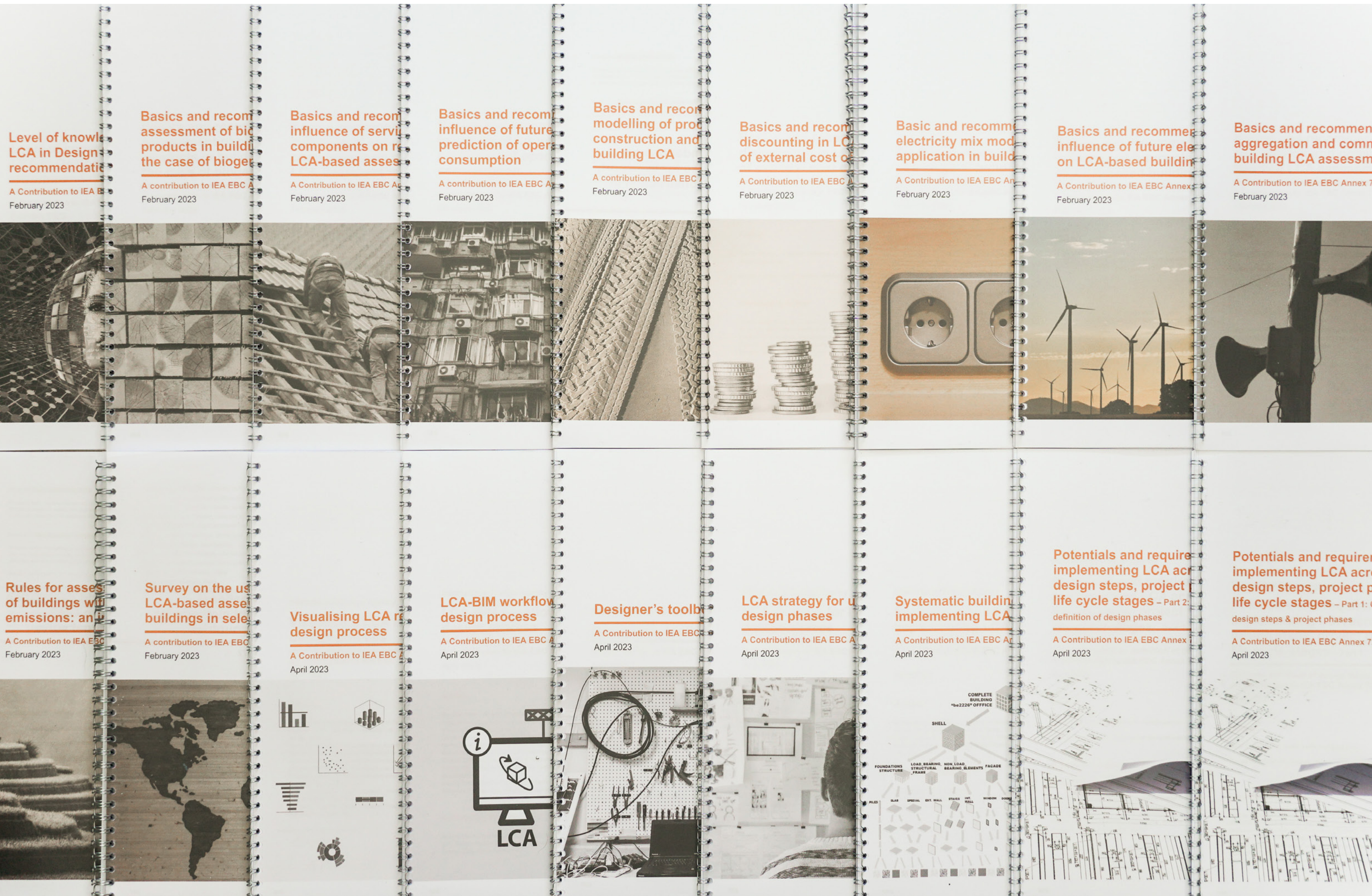
IEA EBC Annex 72

Background information

Assessing life cycle related environmental impacts caused by buildings

May 2023



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Abstract:
The IEA EBC Annex 72 project continued research already conducted under EBC Annex 56 and 57. It extends the scope of Annex 57, which focused on building-related "grey" components of an LCA, to include the operational impacts of building use. In addition to primary energy demand and greenhouse gas emissions, Annex 72 considered other environmental impacts.

The project addressed, among other things, issues of standardization of methodological principles that arise when applying LCA approaches to buildings. It serves as a platform for the exchange of experience and knowledge within the partner countries and promotes the application of LCA to buildings in countries that have little experience.

The objectives of the IEA EBC Annex 72 were:

- Establish and standardize baselines for assessing life-cycle primary energy demand, greenhouse gas emissions, and environmental impacts of buildings, and develop proposals for the development of national or institutional calculation and assessment rules.
- Development of bases for the development, application and interpretation of environmental benchmarks for different building types
- Derive regionally differentiated guidelines and tools to support design decisions for buildings, such as BIM for architects
- Collection and analysis of case studies to support evaluation of real-world application experiences

The results are available in the final and background reports of IEA EBC Annex 72, including the book “IEA EBC Annex 72 Background Information: Assessing life cycle related environmental impacts caused by buildings” collected here.

Kurzfassung:
Das Projekt IEA EBC Annex 72 führte die bereits im Rahmen der EBC Annex 56 und 57 durchgeführten Forschungsarbeiten fort. Es erweitert den Anwendungsbereich von Annex 57, der sich auf gebäudebezogene „graue“ Anteile einer Ökobilanz konzentrierte, um die betriebsbedingten Auswirkungen der Gebäudenutzung. Zusätzlich zum Primärenergiebedarf und den Treibhausgasemissionen wurden im Annex 72 weitere Umweltwirkungen berücksichtigt.

Das Projekt behandelte u.a. Fragen der Vereinheitlichung methodischer Grundlagen, die sich bei der Anwendung von LCA-Ansätzen auf Gebäude ergeben. Es dient als Plattform für den Erfahrungs- und Wissensaustausch innerhalb der Partnerländer und fördert die Anwendung von Ökobilanzen für Gebäude in Ländern, die noch wenig Erfahrung haben.

Die Ziele des IEA EBC Annex 72 waren:

- Erstellung und Vereinheitlichung von Grundlagen zur Bewertung des lebenszyklusbasierten Primärenergiebedarfs, der Treibhausgasemissionen und der Umweltauswirkungen von Gebäuden sowie Erarbeitung von Vorschlägen für die Erarbeitung nationaler oder institutioneller Berechnungs- und Bewertungsregeln
- Entwicklung von Grundlagen für die Entwicklung, Anwendung und Interpretation von umweltbezogenen Benchmarks für verschiedene Gebäudetypen
- Ableitung von regional differenzierten Leitlinien und Instrumenten zur Unterstützung von Entwurfsentscheidungen bei Gebäuden, wie z. B. BIM für Architekten
- Sammlung und Analyse von Fallstudien zur Unterstützung der Auswertung realer Anwendungserfahrungen

Die Ergebnisse sind in den End- und Hintergrundberichten des IEA EBC Annex 72 verfügbar, darunter im hier vorliegenden Buch „IEA EBC Annex 72 Background Information: Assessing life cycle related environmental impacts caused by buildings“ gesammelt.

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Basics and recommendations on aggregation and communication of building LCA assessment results

A Contribution to IEA EBC Annex 72

February 2023

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Basics and recommendations on aggregation and communication of building LCA assessment results

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of the project IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

The practice of aggregating LCA-based building assessment results of multiple midpoint indicators into single-score environmental performance indices is gaining ground, at least for comparing assessment results and for communicating with non-LCA specialist groups of actors, like financial institutions. Indeed, interpreting contradictory results of individual impact indicators is a challenging task, and a single environmental index delivers a clearer message on a building's overall performance. This report helps to provide an improved understanding of the possibilities and limitations of partial or full aggregation of environmental performance assessment results.

To illustrate application, the environmental single scores of five case buildings with varied constructive characteristics were obtained through selected aggregation methods and different impact categories groupings. In general, the performance ranking was maintained, regardless of the aggregation approach used. However, rank reversals are possible, particularly when ecotoxicity categories are considered. This exercise also highlights the importance of standardly reporting not only the same impact categories but also the same building components and of including building services in the analysis, for metals directly influence ecotoxicity results. There is no single best method for aggregating the environmental assessment results of buildings.

If required to facilitate performance communication and report single score building results - in regions or countries with data available to allow weighting - LCA practitioners should choose weighting approaches that ensure coherence to the weighting logic, the underlying regional references used and the problem at hand. The weighting factors shall be thoroughly justified. Sensitivity/uncertainty analyses shall be carried out to assess results robustness, to detect potential ranking reversal risks. Such analyses are also useful to consider the effect of different discount rates and geographic-driven weighting factors on the aggregated result when applying monetization approaches. In all cases, weightings and overall aggregation procedure shall be transparently described, and the result of selected indicators (at the minimum GHG emissions) published in addition to the aggregated assessment result. In selected cases, in which partial aggregation is an alternative to full aggregation, it is recommended that they shall be based on endpoint categories.

A detailed summary of this report is available in the following publication: Gomes et al. (2022)[1].

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[1] See: https://doi.org/10.1088/1755-1315/1078/1/012093

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Abbreviations

Abbreviations	Meaning
ADP	Abiotic Depletion Potential
AHP	Analytic Hierarchy Process
AP	Acidification Potential
AWARE	Available Water Remaining
BAFU	Bundesamt für Umwelt
BDP	Biodiversity Damage Potential
BE	Belgium
BRE	Building Research Establishment
CED	Cumulative Energy Demand
CEN	European Committee for Standardization
CH	Switzerland
CML	Centrum voor Milieuwetenschappen - Leiden (Center of Environmental Science)
CTU	Comparative Toxic Unit
DALY	Disability Adjusted Life Year
DM	Determination Method
DSF	Depleted Stock Fraction
DTT	Distance-to-Target
EBP	Environmental Building Performance
EC-JRC	EU Commission's Joint Research Centre's Institute for Environment and Sustainability
EN	European Standard
EP	Eutrophication Potential
EPD	Environmental Product Declaration
eq.	equivalent
FAETP	Freshwater Aquatic Ecotoxicity Potential
FW	Fresh Water
GDP	Gross Domestic Product
GHG	Green House Gases
GWP	Global Warming Potential
HTP	Human Toxicity Potential
HWD	Hazardous Waste Disposed
IBO	Austrian Institute for Healthy and Ecological Building
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardization
LCA	Life Cycle Assessment

LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
MJ	Mega-Joule (10E+6 Joule)
MMG	Milieugerelateerde Materiaalimpact van Gebouw(element)en
NHWD	Non-hazardous waste disposed
NL	Netherlands
NMD	National Environmental Database
ODP	Ozone Depletion Potential
PEF	Product Environmental Footprint
POCP	Photo-Oxidant Creation Potential (Photochemical oxidation)
POP	Persistent Organic Pollutants
PPP	Purchasing Power Parity
RoW	Rest of World
RTI	Radiotoxicity index
RWDHL	Radioactive waste disposed – high level
Sb	Antimon
SBK	Stichting Bouwkwaliteit (Foundation for Building Quality)
TETP	Terrestrial Ecotoxicity Potential
TNO-MEP	TNO shadow prices (Harmelen, A.K. van, et al., 2004)
UBP	Umweltbelastungspunkten (environmental damage in eco-points)
UK	United Kingdom
WTP	Willingness-to-Pay

1. Introduction

Within the framework of an environmental performance assessment, Life Cycle Assessment (LCA) results are available for several impact categories among other information like inventories and/or aspects. Often, drawing the correct conclusions based on a broad variety of environmental impact and/or aspect-related indicators can be challenging. Sometimes, assessment methods choose to select a single LCA indicator perceived as the most important to focus on. Indeed, optimization towards one variable is much more straightforward than doing the same for more than a dozen indicators, and this partly explains the popularity of single-issue approaches like carbon footprint. However, some assessment methods support their users in interpreting disparate LCA results by applying aggregation methodologies to:

a. combine the assessment results of numerous indicators using weighting factors to form an overall result (or several partial results/scores), which is dimensionless. Benchmarking happens at a mid-point level, i.e., a score is assigned to each indicator based on whether given benchmarks were fulfilled (assessment for individual indicators) and then the scores are weighted and combined to produce an overall single score. This type of aggregation is typical for environmental performance assessment as part of sustainability assessments; and
b. derive a fully aggregated indicator with a unit of measurement (e.g., eco-points) and check the fulfilment of benchmarks set at this aggregated level.

A difference between cases (a) and (b) is that in the former all individual indicators are determined and assessed first and then aggregated, while in the latter only the aggregated indicator is used for the assessment. In that case, all initial information is already transformed into this individual aggregated indicator[2]. Special cases combine aggregated indicators with a few other essential indicators (see Switzerland with its KBOB recommendation 2009/1 on Eco-points, Primary Energy and Greenhouse gas emissions).

Aggregating indicator results into single indexes involves the optional LCIA steps of normalization and weighting (ISO, 2006). In general and simple terms, each indicator result is normalised, i.e. divided by normalisation factors connected to reference information which expresses the total impact of a certain region in a reference year. Then, the normalised values can be multiplied by a weighting factor assigned to each indicator. Once they are all expressed on the same basis, they can be added up into a single value. The weighting applied may be equal for each indicator.

Various options are available for both normalisation and weighting. The purpose of weighting is to ensure that the focus is on aspects considered or perceived most relevant. However, while normalisation can be science-based, this is often not the case for weighting schemes, which inherently involve value choices that depend on policy, value systems, and cultural and other preferences (Sala, Cerutti, & Pant, 2018). This clouds its application for many multi-criteria approaches, including LCA. Additional controversy arises when the partial results are usually no longer visible at the first look, and whether insufficiently robust indicators should be included in external communications or in a weighted result until their robustness is improved (Sala et al., 2018).

Several concepts are applied to weighting across impact categories in LCIA (Figure 1), but distance-to-target (DTT), 'monetization', and the social and expert panel-based methods are most often used (Finnveden, 1996), also within the building sector. Some methods opt for equal weights to aggregate environmental indicators (see e.g., IBO (2011)). Each approach has advantages and drawbacks, and the fittest approach is defined by the application conditions and by preferences of individuals or organisations.

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[2] In some assessment schemes, such as the KBOB recommendation 2009/1, the initial information, the life cycle inventories, as well as the life cycle inventory results remain accessible.

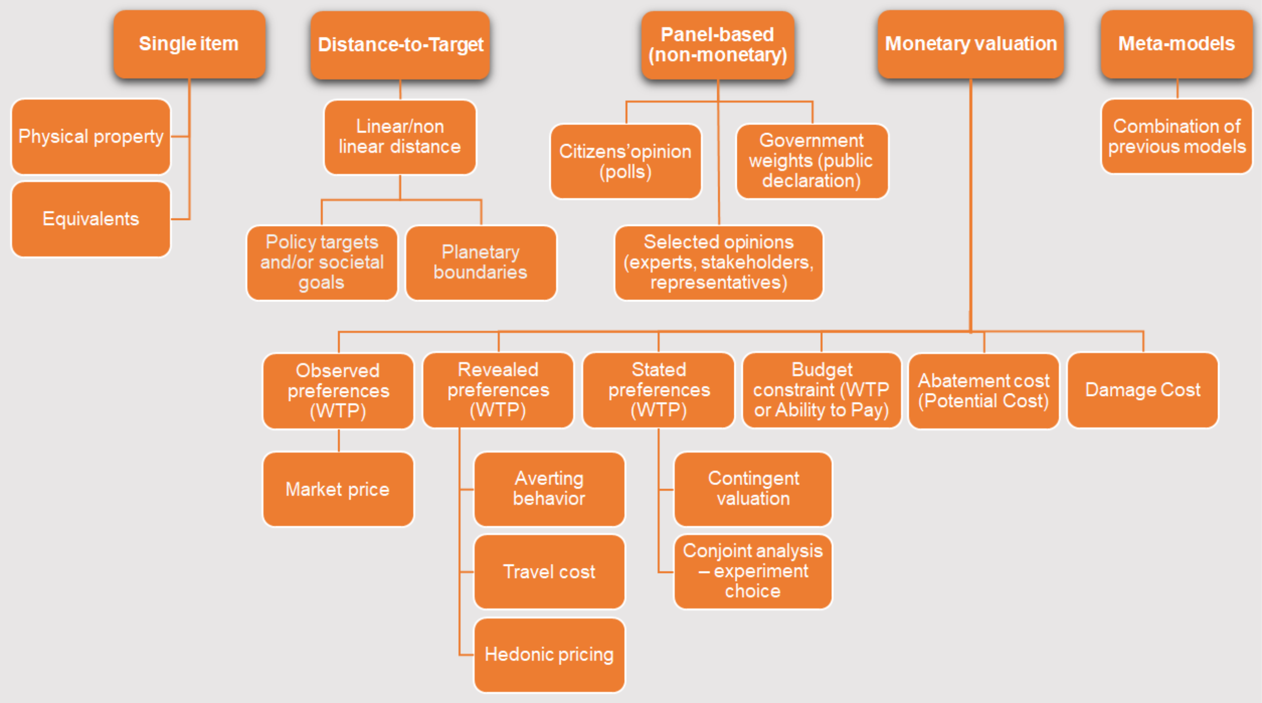

Figure 1: Overview and taxonomy of weighting approaches used in LCIA (Sala et al., 2018)

1.2 Distance to Target

Distance to target (DTT) methods are widely used in LCIA. The ecological scarcity method formed the basis for developing eco-factors for Switzerland (Ahbe, Braunschweig, & Müller-Wenke, 1990; BAFU (Hrsg.), 2021), Germany (Ahbe, Schebek, Jansky, Wellge, & Weihofen, 2014), the European Union and its member states (Ahbe, Weihofen, & Wellge, 2018; Muhl, Berger, & Finkbeiner, 2019).

In distance to target (DTT) methods like the ecological scarcity, critical flows are derived from statistics and policy targets. Weights stem from how far society's activities are from achieving the desired targets. The underlying assumption is that a correlation exists between the seriousness of an effect and the distance between the current and target levels. So, if for achieving a sustainable society impact "A" must be reduced by a factor of 2, and impact "B" must be reduced by a factor of 6, then impact "B" is regarded as three times as serious. An outstanding example in this group is the Swiss eco-factors 2021 method (UBP'21) (BAFU (Hrsg.), 2021), which has been generally applied in Switzerland's policymaking for years and in several applications, including in the building sector. Expressing policy targets in quantitative terms is not always straightforward, though (Castellani, Benini, Sala, & Pant, 2016).

1.3 Monetization

Another way to derive weighting factors in LCA of buildings is through the 'monetary valuation' or 'monetization' of impacts (Pizzol et al., 2016). Monetization is the practice of determining the economic value of non-market goods - i.e., goods for which no market exists - by converting measures of social and biophysical impacts caused by releases of environmentally harmful substances or the use of natural resources into monetary units, based on consideration of external effects that lead to associated (external) costs to society (Arendt, Bachmann, Motoshita, Bach, & Finkbeiner, 2020).

Monetary valuation is applied in cost-benefit analysis to enable the cross-comparison between different impacts and/or with other economic costs and benefits. Such application suggests a great potential to be also applied in the weighting phase of LCA (Pizzol et al., 2016). Indeed, valuing health and environmental impacts as external cost in monetary units for policy-oriented decision support has found increased acceptance worldwide over the past years (Sonnemann, G.; Tsang, 2019).

Monetization is most often based on ‘prevention’ (aka. ‘control or abatement’) or ‘damage’ cost methods. Prevention cost methods value an impact based on marginal cost to securing the relevant policy target for an impact. Doing so requires policy objectives clearly expressed quantitatively (e.g., emission concentration in the air), and cost-effectiveness analyses of all potential prevention measures to enable ranking in monetary terms per prevention (control or abatement) unit, like €/kg emission. The costs of the least cost-efficient measure to meet a given target indicates the value that society is willing to pay or impose on citizens or firms to control that environmental problem (De Nocker & Debacker, 2018). In the construction context, this kind of approach has been used e.g., in the Netherlands by the Dutch Ministry of Public Works’ DuboCalc (for infrastructure works), for comparing the environmental profiles of buildings using GreenCalc, and for LCA of buildings and parts using the Dutch Determination Method (Stichting Bouwkwaliteit, 2019).

As quantitative policy objectives are not always available, and at times defined more on political than on scientific grounds (Castellani et al., 2016), damage cost methods are sometimes preferred, like in environmental priority strategies – EPS (Steen, 1999), the Uniform World Model – UWM (Rabl, Spadaro, & McGavran, 1998), the Environmental prices handbook 2017 (CE Delft, 2018), and – specifically in the building sector - the Belgian ‘Environmental Material Performance of Building Elements’ (MMG) assessment framework (Debacker et al., 2012; Allacker et al., 2020) version valid until July 2021 (MMG2014).

Damage cost methods calculate how emissions or use of resources damage human health and the economy, in terms of additional costs, loss of ecosystem services, reduced income or loss of well-being for current or future generations. Ecosystem damage valuation is based on two elements: first, the damages on nature (say, biodiversity losses) are quantified, then, a value for the loss of biodiversity is needed. Such valuation attempts to estimate the 'demand function' for environmental quality, which is usually determined by how much of their income people are willing to give up for one additional unit of environmental quality or their ‘willingness-to-pay’ (WTP) for damage avoidance.

Similarly, two elements are needed for human health damage valuation: first, the damages on human health are quantified in terms of, e.g. disability-adjusted life years (DALY). Second, a value of life needs to be determined to monetize the damages, expressed in monetary units/DALY for a certain region. Individual indicators results are hence aggregated by multiplying their respective characterization values (e.g., X kg CO_{2eq} or Y DALY) by a monetization factor (e.g., Z €/kg CO_{2eq} or W €/DALY) that indicates the extent of the damage to the environment and/or humans - or the external environmental cost - in monetary terms.

MMG2014 (De Nocker & Debacker, 2018), for example, uses valuation procedures to express eutrophication impacts in €/kg $(PO_4)3\text{-}_{eq}$ that combine various costing methods: willingness to pay for eutrophication impacts avoidance; impacts on biodiversity estimated by fate and impact modelling; and 'restoration costs' and 'prevention costs' to meet the objectives for freshwater quality, as required by the European water framework directive. To account for spatial variability, the value is adjusted for differences in GDP per capita (PPP) between Europe and the rest of the world. That same assessment framework expresses impacts on human health in CTUh (comparative toxic units human health) according with the USEtox method (Rosenbaum et al., 2008). Quantification of loss of life expectancy considers that 1 CTUh cancer case equals 11.5 DALY. The valuation follows Equation 1.

Costs of 1 CTUh cancer = (medical care + loss of production)* + loss of life expectancy** **Equation 1**
= €51,429.60* + (11.5 x €53,363.50***)
= €665,11

Where:
* Estimated based on an EU study (Luengo-Fernandez, Leal, Gray, & Sullivan, 2013)
** Loss of life expectancy = number of DALY x Value of a life year lost / DALY
***W-Europe estimate, assuming 1 DALY related to cancer corresponds to 1 YOLL (year of life lost)

1.4 Panel Approach

Finally, in a panel weighting exercise, a number of experts express their perceived severity of a given impact relatively to others in the local/regional/national/global context. In LCIA, a panel approach has been used, for instance, in damage-oriented (endpoint) methods like eco-indicator 99 (Goedkoop & Spriensma, 1999) and ReCiPe (Goedkoop et al., 2013), which combine a series of individual midpoint indicators into three standardized endpoints - human health, ecosystems quality, and resource scarcity - based on scientific factors. As such, value judgment is applied close to the end of the cause-effect chain. In the context of building LCA, the panel-based approach has been used by UK's BRE EN Ecopoints (Abbe & Hamilton, 2017) to convey single-scores of normalised values of indicators mostly based on EN15804+A1.

2. Weighting Approaches Used in Single Score Results of Buildings LCA

2.1 Swiss Eco-factors (UBP) (distance-to-target method)

The Swiss Eco-factors (UBP) according to the ecological scarcity method were first published in 1990 (Ahbe et al., 1990) and last updated in 2021 (BAFU (Hrsg.), 2021). Based on Swiss environmental policy, it allows for a complete picture of the environmental impacts of the use of energy and material resources, land and freshwater use, of emissions in the air, water bodies and soil, of the deposits of residues from waste treatment, of traffic noise and of marine fish (wild catch), expressed in eco-points. It meets the requirements of a true and fair view in terms of environmental information (BAFU (Hrsg.), 2021).

The ecological scarcity method uses the information on the current annual emissions of pollutants and extraction of resources (current flow, see equation below) in or of a country (here Switzerland) and the maximum allowed annual emissions and extractions (critical flow, see Equation 2) according to environmental legislation in that country.

For every environmental pressure, the eco-factor expresses the distance to target and is defined as follows:

Equation 2

$$\text{Eco-factor} = \underbrace{K}_{\substack{\text{Characterization}\\ \text{(if applicable)}}} \cdot \underbrace{\frac{1\cdot\text{UBP}}{F_n}}_{\text{Normalization}} \cdot \underbrace{\left(\frac{F}{F_k}\right)^2}_{\text{Weighting}} \cdot \underbrace{c}_{\text{constant}}$$

Where: K is the characterization factor of a pollutant or a resource
Flow is the load of a pollutant, quantity of a resource consumed or level of a characterized environmental pressure
F_n is the normalization flow: Current annual flow, with Switzerland as the system boundary
F is the current flow: Current annual flow in the reference area
F_k is the critical flow: Critical annual flow in the reference area
c is a constant (10^{12}/a)
UBP is ecopoint, the unit of the assessed result

Environmental pressures may be individual substances emitted to air, water or soil, radioactive and non-radioactive wastes deposited underground, individual resources extracted, or characterised flows to and from the environment. Characterization factors are determined for pollutants and resources that can be allocated to a specific environmental impact (e.g., global warming potential to quantify the greenhouse gas emissions). Here, the effect of a certain pollutant (e.g., the global warming potential of methane) is placed in relation to the impact of a reference substance (carbon dioxide). Table 1 shows the environmental impacts for which characterisation is used. All other emissions of pollutants and resource extractions are normalised and weighted directly, i.e., without characterisation.

Table 1: Characterization methods used in the 2021 version of the ecological scarcity method (BAFU (Hrsg.), 2021)

Environmental impact	Abbr.	Eco-factor (UBP/ref. unit)	Reference unit	Source for characterisation model
Global warming potential	GWP	1000	kg CO_2-eq.	(IPCC, 2013)
Ozone depletion potential	ODP	25‘000‘000	kg R11-eq.	(UNEP, 2007)
Acidification potential	AP	8‘300	kg SO_2-eq.	(Guinée et al., 2001)
Ecotoxicity potential of heavy metals emitted to air		59'000'000	kg Cd-eq.	(Fantke et al., 2018)
Carcinogenic potential of PAH, dioxin, furan and benzene emissions to air	CTU	2.6 * 10^{11}	CTUh	(Fantke et al., 2018)
Carcinogenic potential of radioactive emissions to air		110’000	GBq C-14-eq.	(Frischknecht, Braunschweig, Hofstetter, & Suter, 2000)
Human toxicity potential of heavy metals emitted to surface water		6’200’000	kg As-eq.	(Fantke et al., 2018)
Carcinogenic potential of radioactive emissions to surface waters		29’000	GBq U-235-eq.	(Frischknecht et al., 2000)
Carcinogenic potential of radioactive emissions to seas		150’000’000	GBq C-14-eq.	(Frischknecht et al., 2000)
Oestrogenic potential of endocrine disruptors		8’700’000’000	kg E2-eq.	(Rutishauser et al., 2004)
Bioconcentration factor of persistent organic pollutants	POP	59’000’000	kg 2,4,6-tribromphenol-eq.	(Ruiz, Ng, Scheringer, & Hungerbuhler, 2012)
Human toxicity potential of heavy metals emitted to soil		2’800’000	kg Zn-eq.	(Fantke et al., 2018)
Impact potential of plant protection products		280’000	kg glyphosate-eq.	(Fantke et al., 2018)
2000-watt society primary energy resources		8.3	MJ oil-eq.	-
Biodiversity damage potential through land use	BDP	630	m^2.a settlement area-eq.	(Chaudhary & Brooks, 2018; Chaudhary, Verones, De Baan, & Hellweg, 2015)
Freshwater consumption	AWARE	22	m3 water-eq.	(Boulay et al., 2017)
Abiotic depletion potential	ADP	150‘000	kg Sb-eq.	(van Oers, Guinée, & Heijungs, 2019)
Depleted Stock Fraction	DSF	1000	kg PS-eq.	(Hélias, Langlois, & Fréon, 2018)
Radiotoxicity of radioactive waste	RTI	54‘000	cm^3 HAA-eq.	(NAGRA, 2014)

2.2 The Determination Method – NL (monetization, prevention costs approach)

The ‘Determination Method of Environmental Performance of Buildings and Civil engineering works’– together with the National Environmental Database (Nationale Milieudatabase – NMD) and the calculation rules – is managed by the Stichting Bouwkwaliteit (SBK - Building Quality Foundation), in the Netherlands.
The NMD database was set up to provide a uniform calculation of the environmental performance of buildings and civil engineering works in the Dutch context. It contains products and activities cards that refer to environmental profiles drawn up in accordance with the Determination Method. These product cards and environmental profiles are used in the various tools to calculate the environmental performance of buildings and civil engineering works.

The Determination Method calculates the material-related environmental performance of buildings and civil engineering works over their entire life cycle in a clear and verifiable manner. The method serves both as PCR that gives instructions for drafting EPDs and the resulting basic profiles and product cards, in a format compatible with EN15804+A1:2013 and suitable for inclusion in the National Environmental Database, and as the calculation rules setting for the computational tools.

The 'Determination Method of environmental performance of buildings and civil engineering works' (Castellani et al., 2016), hereafter 'Determination Method', focuses on the environmental performance of an entire building (or infrastructure work) – the unit to which the performance relates (i.e., the functional equivalent) - instead of on that of individual products. The design and the intended service life define the building products and installations used and the number of replacements over the service life (NMD Foundation, 2020).

The method is structured after the EN 15804:2012 + Amendment A1 standard (CEN, 2013), developed for product-level environmental product declarations (EPDs). Specific rules for drafting and using EPDs for the material-related assessment at building and civil engineering structure level are considered for the Dutch context. The method's monetization approach uses weighting factors (Table 2) to convert the calculated emission values into monetized costs or 'shadow prices', as developed in the RWS report by TNO-MEP (Harmelen, 2004), which supposedly represent the estimated costs that actions to prevent or solve the impact in question would have, i.e., the highest permissible cost level for the government (prevention cost) per unit of emission control.

Each characterized effect score is multiplied by the weighting factor for the corresponding unit, without prior normalization. Once all emission values are collectively expressed in monetary terms, they can be added up into the Environmental Building Performance (EBP), a single score expressed in €/m²GFA*year of lifespan. These weighting factors are determined on a member state level and indicate the (relative) severity of the environmental effects in the country (NMD Foundation, 2020). Only the factor for abiotic depletion (€ 0.16) differs from the original RWS report by TNO-MEP (Harmelen, 2004), which set it to zero.

Until January 1st, 2021, the building environmental profile comprised eleven environmental impact categories (or 'set 1') in accordance with EN 15804+A1 (Table 2). In July 2020, the Determination Method was updated and included a new set of indicators - 'set 2' (NMD Foundation, 2020) to align with EN15804+A2 (CEN, 2019) (Table 3), but the corresponding weighting factors were not found in the searched literature at the time of writing.

Table 2: Indicators describing environmental impact and respective weighting factors ('set 1') within the Dutch Determination Method (Stichting Bouwkwaliteit, 2019)

Environmental indicator	unit	€/unit	
Climate change - GWP 100 yr	kg CO_{2eq}	0,05[3]	emissions
Ozone layer depletion - ODP	kg CFC_{11eq}	30,00	
Photochemical ozone creation - POCP	kg $C_2H_{4\ eq}$	2,00	
Acidification – AP	kg SO_{2eq}	4,00	
Eutrophication – EP	kg $(PO_4)_{3eq}$	9,00	
Human toxicity - HTP	1,4-DCB_{eq}	0,09	
Ecotoxicological effects, aquatic (freshwater) – FAETP	1,4-DCB_{eq}	0,03	
Ecotoxicological effects, aquatic (marine) – MAETP	1,4-DCB_{eq}	0,0001	
Ecotoxicological effects, terrestrial – TETP	1,4-DCB_{eq}	0,06	
Depletion of abiotic resources (excluding fossil energy carriers) - ADP	kg Sb_{eq}	0,16	raw materials[4]
Depletion of fossil fuels - ADP_{ff}	kg Sb_{eq}[5]	0,16	

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[3] Each country has its own damage cost values: the Dutch DM factor is about 25% of the German Federal Environment Agency (UBA) estimate, for example.

[4] The factor for abiotic depletion was set as € 0.16 in the DM, whereas the RWS report set it as € 0.

[5] If 'depletion of fossil energy carriers' is available in MJ, the conversion factor of 4.81E-4 kg of antimony/MJ can be used [CMLIA, Part 2b: Operational Annex, page 52], as indicated in Stichting Bouwkwaliteit (2019).

Table 3: Indicators describing environmental impact ('set 2', valid after January 1st, 2021) within the Dutch Determination Method (NMD Foundation, 2020).

Impact category	Indicator	Unit
Climate change - total	GWP - total	kg CO_{2eq}
Climate change – fossil	GWP – fossil	kg CO_{2eq}
Climate change - biogenic	GWP - biogenic	kg CO_{2eq}
Climate change – land use and change to land use	GWP - luluc	kg CO_{2eq}
Ozone layer depletion	ODP	kg CFC_{11eq}
Acidification	AP	mol $H+_{eq}$
Freshwater eutrophication	EP-freshwater	kg $(PO_4)_{3eq}$
Seawater eutrophication	EP-seawater	kg N_{eq}
Land eutrophication	EP-land	mol N_{eq}
Photochemical ozone formation	POCP	kg $NMVOC_{eq}$
Depletion of abiotic raw materials - minerals and metals	ADP minerals and metals	kg Sb_{eq}
Depletion of abiotic raw materials - fossil fuels	ADP-fossil	MJ, net cal. val.
Water use	WDP	m^3 world $_{eq}$ deprived
Fine particulate emissions	Illness due to PM	Illness incidence
Ionizing radiation	Human exposure	kBq $U235_{eq}$
Ecotoxicity (freshwater)	CTU ecosystem	CTUe
Human toxicity – carcinogenic	CTU human	CTUh
Human toxicity – non-carcinogenic	CTU human	CTUh
Land use-related impact/soil quality	Soil quality index	Dimensionless

2.3 Belgian MMG Assessment Framework (monetization, damage costs approach – up to July 2021[6])

The Belgian MMG assessment framework follows a hierarchical structure in its calculation model, which allows four levels of analysis: materials (e.g., bricks and mortar), work sections (e.g., a masonry wall), building elements (external / internal wall) and whole buildings (Allacker et al., 2020). This way, a simplified evaluation of at building level can be obtained as the sum of material impact of their building elements, as only databases for selected material, work section and element levels are operational.

The MMG assessment framework considers indicators for environmental impacts and external environmental costs. In the MMG2014 version, valid until July 2021, 14 environmental indicators are divided in two subsets (De Nocker & Debacker, 2018). The seven mandatory environmental impact categories for EPDs expressed in the CEN/TC 350 standard EN 15804+A1 (CEN, 2013): Climate change, ozone depletion, acidification for soil and water, eutrophication, photochemical ozone creation, depletion of abiotic resources (elements and fossil fuels) are called 'CEN indicators' (Table 4). Other seven indicators (named 'CEN+') are aligned with recommendations by the ILCD Handbook (EC-JRC, 2011) and the Product Environmental Footprint (PEF) Guide (EC, 2013). Categories like terrestrial and marine ecotoxicity are not yet translated to environmental costs, due to the lack of reliable monetary values in the literature.

The request of Belgian authorities for aggregated building score outputs stem from the inherent difficulty to make decisions when multiple individual impact scores are offered. As the CEN/TC 350 standards do not consider weighting nor aggregation, the MMG developers opted for an environmental external cost-based weighting method (Allacker et al., 2020). Three optional aggregated environmental scores, expressed in

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[6] With the update to CEN/TC 350 standard EN 15804+A2 (CEN, 2019) in July 2021, the MMG assessment approach changed, mainly to be in line with end the European initiatives for LCA of buildings and building products, and to support integration of specific B-EPD data in the TOTEM tool. The current framework considers 19 impact indicators grouped in 12 main impact categories and moved from the previous monetisation approach to adopt the JRC's PEF weighting procedure (Sala et al., 2018). For each individual environmental indicator, the characterised values are first normalised by dividing them with their respective normalisation factors. These factors represent the global impact per capita for a given reference year and allow to express all the results in a dimensionless unit. The normalised results are then multiplied by their respective weighting factors to reflect the perceived relative importance of the environmental impact categories considered. After weighting, the results of the different environmental indicators can be summed up to obtain a single overall score. For details, please see Lam & Trigaux (2021).

monetary value (€) are used: for CEN indicators, for CEN+ indicators, and for an overall single score, which is the sum of both.

Information on damage costs is available for most impact categories, though at different amount and quality. Categories such as terrestrial and marine ecotoxicity are not yet translated to environmental costs, while others like land use impacts on biodiversity, ecotoxicity require proxies such as the costs of typical measures, amount of environmental taxes, or restoration costs (e.g., ecosystems and biodiversity) or configure multi-source and multi-effect problems (e.g., acidification, ozone formation, particulate matter) that complicate prevention cost assessment for single effects, whose targets often reflect short term compromises instead of long term policy objectives, and are seldom used as indicators for social costs (De Nocker & Debacker, 2018).

For most impact indicators, MMG's central estimate is based on damage cost approach and a 3% p.a. discount rate is applied, whilst the low and high estimates account for uncertainty and information from other sources and methods, including that based on prevention costs. External environmental costs may vary regionally, meaning that weight sets derived for Belgium might not apply to other locations. Hence, monetary values have been determined for three regions – Flanders/ Belgium, Western Europe. As most processes related to the life cycle of building products are related to Western Europe (Table 4), only those values are considered for the publicly available version of the method. The monetary values for Flanders/Belgium and the 'rest of the world' are determined for sensitivity analyses sake. MMG explicitly declares that Worldbank's purchasing power parity (PPP[7]) is used to adjust monetary values for differences in GDP/capita between Western Europe and the 'rest of the world' (RoW= 40% of Western Europe values) in cases like acidification of land and water sources, eutrophication, human toxicity and particulate matter impacts (De Nocker & Debacker, 2018).

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[7] PPPs enable to compare the output of economies and the welfare of their inhabitants in 'real' terms, as they control price level differences across nations. The PPP concept is used by multilateral institutions like the UN, Worldbank and IMF, policymakers and private sector agents, among others.

Table 4: "CEN" and "CEN+" environmental indicators used in the MMG assessment framework, respective units and monetary values estimates for the aggregated environmental score: the square root of the uncertainty bandwidth (√BW) is used to calculate the low and high estimates from the central value for Western Europe (Allacker et al., 2020)

Environmental indicator (CEN)	unit	√BW	Estimates (€/unit)		
			Low	Central	High
Global warming	kg CO_{2eq}	2	0.025	0,05	0.10
Ozone depletion	kg CFC_{11eq}	2	25	49.1	100
Acidification for soil and water	kg SO_{2eq}	2	0.22	0.43	0.88
Eutrophication	kg $(PO_4)_{3eq}$	3	6.60	20	60
Photochemical ozone creation	kg ethene $_{eq}$	2	0	0.48	6.60
Depletion of abiotic resources: elements	kg SB_{eq}	4	0	1.56	6.23
Depletion of abiotic resources: fossil fuels	MJ, net calorific value	/	0	0	0.0065
Environmental indicator (CEN+)	**unit**	**√BW**	**Estimates (€/unit)**		
			Low	**Central**	**High**
Human toxicity: cancer effects	CTUh	4	166,277	665,109	2,660,434
Human toxicity: non-cancer effects	CTUh	5	28,816	144,081	720,407
Particulate matter	kg $PM2.5_{eq}$	2.6	12.70	34	85
Ionizing radiation: human health effects	kg $U235_{eq}$	3	3.2E-04	9.7E-04	2.9E-03
Ecotoxicity: freshwater	CTUe	5	7.39E-06	3.7E-05	1.8E-04
Water resource depletion	m^3 $water_{eq}$	3	0.022	0.67	0.20
Land use occupation: soil organic matter	kg C deficit	4	3.4E-07	1.4E-06	0.6E-05
Land use occupation: biodiversity flows, loss of ecosystems service	m^2yr	4			
• from urban			0.07	0.30	2.35
• agricultural			1.5E-03	6.0E-03	2.4E-02
• forestry			5.5E-05	2.2E-04	8.8E-04
Land use transformation: soil organic matter	kg C deficit	4	3.4E-07	1.4E-06	0.6E-05
Land use transformation: biodiversity flows	m^2	4			
• from urban land					
• from agricultural land			n/a	n/a	n/a
• from forest			n/a	n/a	n/a
• from tropical rainforest			n/a	n/a	n/a
			6.90	27	110

2.4 UK BRE EN Ecopoints (panel approach)

In 2015, UK BRE assembled an expert group weighting exercise to create a set of weightings for an aggregated metric (BRE EN Ecopoints) to be reported in addition to the parameters required by EN 15804 standard. The derived weightings can be used in communicating the environmental performance of construction products in BRE decision making tools and building level assessment tools (Abbe & Hamilton, 2017).

The panel assessed the relative importance of eleven EN 15804+A1 environmental indicators (CEN, 2013), preselected as representative of the overall environmental impact of the construction products assessed, whilst ensuring that it reflects the relative importance of the underlying issues within the Western European context (Abbe & Hamilton, 2017). Human and ecotoxicity impacts are excluded, and waste and freshwater use - relevant environmental pressures for construction activities - are counted in (Table 5).

Table 5: Panel-based weighting set derived for the BRE EN Ecopoints aggregation procedure (Abbe & Hamilton, 2017).

Environmental indicator	Indicator	Weighting (%)
Global warming potential (climate change)	GWP	24,1
Net use of fresh water (parameter describing resource use)	FW	15,2
Depletion potential of the stratospheric ozone layer	ODP	13,5
Acidification potential of soil and water	AP	8,4
Eutrophication potential	EP	8,2
Radioactive waste disposed – high level (parameter describing waste categories)	RWDHL	7,0
Abiotic depletion potential for non-fossil resources (elements)	ADP-E	6,6
Formation potential of tropospheric ozone	POCP	5,8
Hazardous waste disposed (parameter describing waste categories)	HWD	5,0
Abiotic depletion potential for fossil resources	ADP-F	4,0
Non-hazardous waste disposed (parameter describing waste categories)	NHWD	2,1

The characterised data for the eleven environmental indicators are referenced to the impact of one European citizen per year, using appropriate normalisation factors. The normalised impact values are then multiplied by the weighting factors for each indicator and their summation gives the single score. The highest BRE EN Ecopoints score indicate the highest environmental impacts. The derived weightings can be used in communicating the environmental performance of construction products in BRE decision making tools and building level assessment tools (Abbe & Hamilton, 2017).

In parallel, a stakeholder panel went through the same survey and procedure used for the expert panel. A multi-criteria decision-making method was used to generate the weights and subsequent prioritisation of the issues in terms of their impact. The chosen option was the analytic hierarchy process (AHP), which uses fuzzy logic to make sense of value judgements, through pairwise comparisons. A detailed description of the weighting exercise consistency, reliability, sensitivity analyses for both the expert and stakeholder panels is provided by (Abbe & Hamilton, 2017).

3. Method

The four approaches for aggregating LCA indicator values into single score results of buildings described in Chapter 2 - distance-to-target Swiss Eco-factors (UBP) 2021 (CH); monetization methods MMG2014 (BE) and Dutch Determination Method (NL); and panel-based weighting method BRE EN Ecopoints (UK) - are examined (Table 6).

Assuming a simplified evaluation at building level as the sum of material impact of their building elements, calculations were illustratively applied to five cases - concrete and masonry school building, a steel-framed laboratory, a concrete-framed and masonry residential high-rise, an office passive building, and a wood-framed building - to shed light on key points to consider when aggregating building scores. These cases had been previously assessed in accordance with the EN15804+A1 (CEN, 2019) and EN15978 (CEN, 2011) standards and using CML-IA baseline and CED methods. Hence, only the corresponding indicators values were available for use, which limited our application. Inventories, LCA assumptions and methodological decisions were the same in all cases, and are not herein detailed, given the focus on aggregation through different perspectives.

Table 6: Aggregation approaches adopted by selected methods used in the building sector

Approach	**Method**			
	UBP'21 (CH)	**MMG2014 (BE)***	**Determination Method (NL)**	**BRE EN Ecopoints (UK)**
Application	📦 🧱 🏠	📦 🧱 🏠 *TOTEM tool*	🏠	📦 🧱 🏠 *BREEAM rating tool*
Weighting	⊕	€ damage costs	€ prevention costs	👥
Partial/total aggregation	environmental areas and total	"CEN", "CEN+" and total*	total	total
Normalization	yes	yes (Flanders, Western Europe, RoW)	no	yes (Western Europe)
Characterization	yes, for env. impacts in Table 1	yes	yes	yes

⊕ distance to target € monetization 👥 expert/stakeholder panel

📦 product level 🧱 element level 🏠 building level

Note: "CEN" and "CEN+" indicators refer to the terminology used by the MMG2014 assessment framework. See Table 4, in section 2.3.

4. Results

Environmental impact categories considered, indicators within them and weighting/monetization factors used in the different methods vary. Some categories – ODP, AP, EP, POCP – are most often used, but only GWP is present in all selected methods. Hence, Table 7 displays all impact factors (1 unit of impact) relatively to the impact of the emission of 1 kg $CO_{2\text{-eq}}$.

The Swiss Eco-factors method has been generally applied in the country's policymaking for long, and specifically addresses the renowned Swiss 2000-watt society goal. The Swiss Eco-factors (UBP) 2021 weighs ODP much heavier than any other approach: one ODP reference unit is about 25,000 times as serious as one GWP reference unit, which is about 25 to 42 times higher than that assigned by monetization approaches used in the building sector. It notably details assessment of impacts on human health. BRE EN Ecopoints, the panel-based method examined, weighs climate change much heavier than any other impact. Regardless of the approach chosen, panel-based weighting sets incorporate values and subjectivity. Users should be aware and encouraged to routinely carry out sensitivity analyses to test the effects of changes in the weighting set on the environmental impact scores.

Though contrasting factors across methods based on different grounds is not meaningful, comparisons within the same aggregation approach reveals variations to some extent expected, as both criticality perception translated into policy goals and mitigation valuation can vary regionally. For example, MMG2014 applies a factor to abiotic depletion potential excluding fossil energy carriers between 10 times higher than its neighbour Dutch DM, which in turn weighs acidification heavier by about the same factor. In this regard, the SBK value attributes all the prevention costs of reducing SO2 emissions to 'acidification', whereas these costs should be shared with health impacts from secondary particles. Other divergences of the kind are noticeable. The Dutch DM breaks down ecotoxicity into terrestrial, marine and freshwater, while MMG2014 considers only the latter, while distinctively attempts to address built environment specifics like land use occupation and transformation.

Aggregated scores were calculated for the four individual midpoint impact categories for which all methods selected provide a quantitative assessment (GWP, ODP, AP, ADP resources); for the seven CEN midpoint categories (MMG2014 and Determination Method) (Table 8). In general, the performance ranking was maintained, regardless of the aggregation approach used. However, rank reversals are possible, particularly when ecotoxicity categories are considered (marked in yellow). Uncertainties on results of this environmental impact indicators, in LCI data and in impact and damage assessment are high, and experience with them is still limited, as disclaimed in EN 15804+A2. One possibility is to aggregate results with and without those categories for now, as recommended by (Sala et al., 2018) for PEF aggregated scores.

Table 7: Relative single score impact factor of the emission of 1 unit of an impact compared to the impact of the emission of 1 kg $CO_{2\text{-eq}}$ in the methods examined.

Environmental impact	Original reference unit	UBP21 CH	MMG2014 BE	DM NL	BRE EN Ept UK
Global warming potential	kg CO_2-eq.	1	1	1	1
Ozone depletion potential	kg R11-eq (CFC-11-eq)	25,000	982	600	0.56
Acidification potential	kg SO_2-eq.	8.3	8.60	80	0.35
Human toxicity potential	1.4-DCB-eq			1.8	
Human toxicity: non-cancer effects	CTUh		2,881,620		
Human toxicity: cancer effects	CTUh		13,302,180		
Carcinogenic potential of PAH, dioxin, furan and benzene emissions to air	CTUh	$2.6 * 10^8$			
Carcinogenic potential of radioactive emissions to air	GBq C-14-eq.	110			
Carcinogenic potential of radioactive emissions to surface waters	GBq U-235-eq.	29			
Carcinogenic potential of radioactive emissions to seas	GBq C-14-eq.	150,000			
Oestrogenic potential of endocrine disruptors	kg E2-eq.	$8.7 * 10^6$			
Bioconcentration factor of persistent organic pollutants	kg 2,4,6-tribromphenol-eq.	59,000			
Impact potential of plant protection products	kg glyphosate-eq.	285			
2000-watt society primary energy resources	MJ oil-eq.	0.0083			
Depletion of abiotic resources: fossil fuels	MJ, net calorific value		0.02		0.17
Depletion of abiotic resources: fossil fuels	kg Sb-eq			3.2	
Abiotic depletion potential (excluding fossil energy carriers)	kg Sb-eq	0.15	31.2	3.2	
Mineral resource extraction	tonnes				0.27
Non-hazardous waste disposed	m^3				0.09
Hazardous waste disposed	m^3				0.21
Radioactive waste disposed (higher level)	m^3 high level waste				0.29
Radiotoxicity of radioactive waste	cm^3 HAA-eq.	54			
Eutrophication	kg $(PO_4)_3$ - eq		400	180	0.34
Photochemical ozone creation	kg (C_2H_4)-eq		9.6	40	0.24
Particulate matter	kg PM2.5-eq		680		
Ionizing radiation: human health effects	kg U235-eq		0.02		
Terrestrial ecotoxicity	1.4-DCB-eq			1.2	
Marine aquatic ecotoxicity	1.4-DCB-eq			0	
Freshwater aquatic ecotoxicity	1.4-DCB-eq			0.6	
Ecotoxicity: freshwater	CTUe		0		
Net use of fresh water	m^3				0.63
Water resource depletion	m^3 water-eq		13.4		
Biodiversity damage potential through land use	m^2.a settlement area-eq.	0.63			
Land use occupation: soil organic matter	kg C deficit		0		
Land use occupation: biodiversity flows. loss of ecosystems service	m^2yr				
from urban			6		
agricultural			6		
forestry			0.12		
Land use transformation: soil organic matter	kg C deficit		0		
Land use transformation: biodiversity flows	m^2				
from urban land			n/a		
from agricultural land			n/a		
from forest			n/a		
from tropical rainforest			540		

Table 8: Environmental LCA single scores of five building cases, considering four categories common to all methods (or seven categories, for MMG2014, Determination Method and BRE EN Ecopoints). The higher the score, the worse (in red) is the performance.

Weighting approach	**DTT**	**Monetization**				**Expert Panel**	
Methods and categories weighted	**Swiss Ecopoints 2021**	**MMG2014 (Western Europe)**		**Determination Method**		**BRE EN Ecopoints**	
	4 common	4 common	7 common	4 common	7 common	4 common	7 common
Weighted score (per m^2GFA·year)	UBP	€				Ecopoints	
School building, concrete-frame, masonry	51,533.15	2.57	4.93	3.63	4.77	1,178.17	3,381.32
Laboratory building, steel-framed, metal cladding	42,061.40	2.10	4.66	2.94	4.16	962.44	2,742.79
Residential high-rise building, concrete-framed, masonry	18,046.26	0.90	1.74	1.25	1.66	414.92	1,144.87
Office passive building	14,010.69	0.70	0.99	0.89	1.04	326.49	974.58
Residential building, wood-framed	8,962,94	0.45	0.66	0.60	0.72	206.69	662.94

4 common categories: GWP, ODP, AP, ADP resources | 7 common categories: GWP, ODP, AP, EP, POCP, ADP resources, ADP ffuels

The adherence of the Determination Method to the available pre-assessed indicators allowed its aggregated score to be fully calculated. When the additional ecotoxicity categories were computed, the school concrete building and the steel-framed laboratory reversed ranks. This is not an inconsistency of the method itself or of the monetization approach, as the methods general structures herein examined are not fully comparable, but rather an expression of how the buildings' materiality (considerably more steel in the lab building) is described by the ecotoxicity indicators added, which also bear high uncertainties, as previously mentioned.

5. Remarks on Discounting when Monetizing Impacts

Monetization approaches may involve discounting after conversion of impacts into financial units, a common practice in economics. Certain impacts take time to manifest themselves into damages that can emerge after years or decades, like air pollutants impacts on human health, while carbon emissions impacts will extend over generations. Hence, in the context of policymaking the costs of mitigation measures taken today are often contrasted with the benefits produced by these actions in the future. Given this short/longer-term trade-off, the way such benefits are valued – i.e., how much guarding against future damage is worth to today's society – guides current policy design and development of cost-effective solutions.

Costs and future benefits differ in their distribution over time and must be brought to a common point in time to become comparable. A centrepiece to do so is discounting, which uses discount rates to put a present value on costs and benefits that will occur at a later date. At an analytic level, the discount rate is therefore a major determinant of the valuation outcomes (i.e., present value of costs and benefits). Its choice greatly influences valuation outcomes when impacts and mitigation measures spread over very long time periods, as for climate change. GHGs long lifespan in the atmosphere requires that the damages expected of their emissions today are valued centuries into the future.

Discounting (using positive discount rates) always gives a lower numerical value to damages in the future than to those happening in the present. This means that using a high discount rate implies that people put less weight on the future and therefore that less investment is needed now to guard against future costs. Contrastingly, when using a low discount rate, more importance is given to future generations' wellbeing in cost–benefit analyses, which supports the view to act now to protect future generations. The notion of discounting ultimately represents a key ethical issue in impact valuation, and becomes critical for issues involving intergenerational equity, such as those referring to environmental degradation and, specially, climate change. Another key ethical parameter is the 'purchase power parity', which indicates if a life-year lost by any world citizen causes the same economic damage regardless of where he/she lives. There is a strong case for using 'social discount rates' (SDR) that factor in both ethical issues (intergenerational and income) equity-and age-weighting. For reflecting the perspective of society, social discount rates are lower than those used by private investors (IPCC, 2007).

There are two reasons for discounting the future. First, because – if the future is wealthier – society may place less weight on future net benefits, and a dollar today is worth more than a dollar received later. This is captured in the 'wealth effect' component ($\eta \times g$, or elasticity of the marginal utility times forecasted growth) in the simple Ramsey Rule for discount[8] (Equation 3).

$$\mathrm{SDR} = \delta + \eta \times g$$

Equation 3

Where:

δ is a rate of pure preference for the present (or rate of impatience)
η is the absolute value of the 'elasticity of marginal utility of consumption', i.e. the change in the value of an additional dollar as society grows wealthier, also referred to as 'intergenerational inequality aversion'
g is the is the growth rate of per capita consumption

Second, to account for people's attitudes to time: human propensity to prefer income today rather than tomorrow, expressed as the pure time preference (δ) component of the discount rate. While g is observable

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[8] Please, see ISO 14008:2019 (ISO, 2019).

(ex post) and determined by the performance of the economy, δ and η require an ethical judgment (National Academies of Sciences Engineering and Medicine, 2017). In an intergenerational framework, the 'pure time preference rate' characterizes the ethical attitude towards future generations.

The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (AR2) notes recommended, as early as 1996, a discount rate of 2-4%, by considering fair to account for a pure time preference rate equal to zero, and a growth rate of GDP per capita of 1-2% per year for developed countries and a higher rate for developing countries that anticipate larger growth rates (IPCC, 2007, p.136). ISO 14008:2019 (ISO, 2019) also suggests that the pure rate of time preference should be set to zero. IPCC's AR5 (Kolstad et al., 2014) reinforced the case for a zero or near-zero pure rate of time preference, suggesting a broad consensus, and citing 2% as the largest value among the approaches reviewed. One argument for a PTP-rate (δ) equal to 0 is that, holding consumption constant, all generations are given equal weight when calculating social welfare. That view stems from the classical impartial utilitarian philosophy, and is supported by luminaries of economics (Drupp, Freeman, Groom, & Nesje, 2018).

Despite the debate regarding the appropriate societal pure time preference rate and social discount rate to apply (De Nocker & Debacker, 2018; Sonnemann, G.; Tsang, 2019), and even on the ethical framework for intergenerational decision-making (Drupp et al., 2018), it is now widely accepted in environmental economics that SDRs must drop with time (Freeman & Groom, 2016). Governments like in the UK and France have adopted this approach to reflect uncertainty about future economic growth, fairness and intra-generational distribution, and observed individual choices (IPCC, 2007). The German Federal Environment Agency (UBA) proposes discount rates of 3% for short-term periods (up to around 20 years), and of 1.5% for claims that extend further into the future and requests a sensitivity calculation with a discount rate of 0% for cross-generational considerations (Schwermer, Preiss, & Müller, 2014, p.37).

Based on these considerations, many authors and governments propose a near zero discount rate when monetizing environmental impacts, especially for long time horizons. The monetizing approaches used for building assessments - MMG2014 and, possibly, the Dutch DM[9] - adopt a discount rate of 3% p.a.

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[9] MMG2014 explicitly declares key monetization decisions, like adoption of purchasing power parity (PPP) to account for GDP/capita variation and of a social discount rate of 3% p.a. – said to be on average in line with declining rates over time used by several governments. Monetary values used by the Dutch Determination Method mainly refer to a study on shadow prices commissioned by the Dutch Ministry of Infrastructure and Environment to TNO in 2006. Shadow prices have been since updated and ultimately replaced by a thorough conceptual update: the 'Environmental prices Handbook 2017' (CE Delft, 2018). The Dutch DM 2020 supporting documentation does not mention the environmental prices concept and only provides the shadow price-based weighting set used, without explicitly declaring key monetisation decisions it relies upon. Hence, the discount rate used is herein inferred to be a 3% p.a. rate, as advised by the Discount Rate Working Group (van Ewijk et al., 2015). No reference to purchase power parity/equity weighting was found.

6. Final Remarks

Alternatives for communicating LCA results of buildings basically comprise (Ströbele & Lützkendorf, 2019):

- Focusing on one or more indicators (e.g., GWP or GWP and PE,nr), with the risk that side effects in other areas and load shifts will not be visible;
- Selecting representative indicators, based on previous studies that show that the result for one or more indicators is representative of the others and leads to reliable statements in the order and sequence of variants;
- Partial aggregation of defined indicators using specific methods; and
- Full aggregation of defined indicators using specific methods.

The last two options above (weighing of environmental impact scores into one or a few scores) are often requested by the target audiences. Using a single-score indicator to express the environmental performance makes it easier to communicate environmental performance of buildings and to compare different buildings. It also provides a comprehensive picture, which allows to identify the important environmental impacts and the most relevant building elements or construction materials. That is why some countries like Switzerland have a long-term tradition in applying single score methods in LCA which are endorsed and authorised by the Swiss Federal Administration.

Weighting factors derived from panel exercises, DTT or monetization estimates have been used to aggregate LCA results of buildings. Both prevention and damage costs monetization approaches have been used. There is no best method for aggregating impact results, though, and each approach has strengths and limitations. Expressing policy targets in quantitative terms is not always straightforward and factors for relevant categories indicators still lack. Value choice-based damage estimations often embeds personal attitude and perspectives of the decision-maker, and monetization costs are established within a virtual market, whose results can involve considerable uncertainty. Indeed, the uncertainty treatment carried out by CE Delft (2018) revealed substantial variations in monetary valuing and weighting environmental goods. Hence, if the concepts underpinning monetization are accepted – that is: financial data is comparable to environmental impacts and those impacts are mutually comparable - users should bear in mind that results can involve considerable uncertainty and take the corresponding precautions when using them.

That said, as general recommendations when pursuing to express the environmental LCA results of a building as a single score:

- Give preference to weighting schemes endorsed by authoritative bodies like national environmental agencies or ministries. Among others, this is expected to ensure that the sets of prices/costs/weights are updated every few years to reflect the latest policies;
- Where appropriate, use conversion factors that comply with scientific or engineering principles first. These normative principles apply to any level of aggregation (see also ISO 21931-1 (ISO, 2010));
- Use a method that explicitly declares all conversion/weighting factors and assumptions made. Aggregation procedures shall be transparently described in easily accessible documents;
- Always provide partially disaggregated information, the life cycle inventory result or, even better, the unit process data shall in addition to the aggregated score;
- If impact category indicators embed high uncertainty (e.g., ecotoxicity), present the aggregated result with and without those individual indicators; and
- If monetization methods are used, choose one that applies zero discount rate and world average equity weighting, in line with IPCC’s recommendations. As impact assessment methods are becoming increasingly regionalized, the monetary valuation of associated impacts should also be region-specific, to deliver meaningful results.

Comparable information is not ubiquitously available, and not all countries and regions have equally developed science, targets and data. LCA practitioners carrying out studies in regions or countries with data and methods that allow weighting are encouraged to report one or more aggregated scores in addition to the detailed environmental profile, for communication’s sake. Target audiences not familiar with the implications of weighting should be made aware of the controversy and objections to do so, of the uncertainties embedded, and of the fact that despite the acknowledged limitations, attempts to evolve are in course to help to fulfil their practical relevance.

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Basics and recommendations on influence of future electricity supplies on LCA-based building assessments

A Contribution to IEA EBC Annex 72

February 2023

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Basics and recommendations on influence of future electricity supplies on LCA-based building assessments

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

Mitigating greenhouse gas (GHG) emissions from buildings is important for combatting climate change because buildings are a major source of GHG emissions, which account for about 30% of global greenhouse gas emissions, and about 40% of energy-related GHG emissions. Different mitigation strategies and scenarios have been developed and implemented in the “energy” and “industry” (including the construction product industry) sectors. This allows us to explore different pathways for the development of future energy supplies, their greenhouse gas emissions, as well as the influences on future manufacturing of building components and construction products. Such scenarios are also of great importance when a transition from static to dynamic life cycle assessment (LCA) of buildings is made throughout their service lives. In particular, the consideration of these scenarios would impose consequences in the life cycle stages (as defined in *EN 15804 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*) including module A1 (product stage - raw material supply) and A3 (product stage - manufacturing) for future new buildings, B4 (use stage - replacement) and B6 (use stage - operational energy use) for both existing and new buildings.

While in the field of energy supply, the possibilities and consequences of decarbonization strategies are being discussed and partly taken into account in the building LCAs in selected countries, corresponding discussions and implementation considering the manufacturing of building components and construction products are still in their infancy. It is necessary to make a transition by including these scenario-based dynamic considerations both on the side of operational and embodied impacts. More importantly, scenarios used to derive these considerations should have a complete global coverage, addressing consistency for both energy systems and underline assumptions between individual countries and regions.

This background report takes an example of considering future electricity supplies based on global Integrated Assessment Models, and discusses the impact of this consideration in building LCAs from both operational and embodied impact perspectives in terms of life cycle greenhouse gas emissions. These considerations are incorporated into the Swiss national building LCA database KBOB. Materials and regional electricity supplies with high emission reduction potentials are identified given different scenarios. In the end, based on this experience, recommendations are made to future national database development that can better accommodate such considerations, and the needs for future research are discussed.

Table of content - B

Abbreviations

Abbreviations	Meaning
CO_2 eq.	CO_2 equivalents
BIPV	Building Integrated Photovoltaics
DQR	Data Quality Requirement
EPD	Environmental Product Declaration
GHG	Greenhouse Gas Emission
IAM	Integrated Assessment Model
IEA	International Energy Agency
KBOB	Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren
kWh	kilowatt hours
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
NDC	Nationally Determined Contributions
PIK	Postdam Institute for Climate Impact Research
PV	Photovoltaics
PVC	Polyvinyl Chloride
REMIND	REgional Model of Investment and Development

1. Introduction

Life cycle assessment (LCA) has been well applied to assess the environmental performances of buildings comprehensively considering all life cycle stages, including the manufacturing of construction products, energy and water required for construction, maintenance, and replacement, the end-of-life treatment and disposal of materials as well as the operation of the building. However, uncertainties in these assessments inherently exist due to the complex supply chain upstream in product manufacturing, unpredictable service life of buildings, building components and materials, variability of electricity supplies, which are often not addressed in most of the deterministic building LCAs (Pomponi et al., 2017). Among these uncertainties, the uncertainties of electricity supplies play in particular an important role, and mainly influence building LCAs due to the energy consumption during the operation of buildings: for example, the mix of electricity supply may vary depending on the time of the consumption, the electricity system transition and potential improvement of generation technologies in the future. It also influences the manufacturing of construction components and products required for the construction as well as the retrofit of buildings, and the infrastructures for the generation of electricity.

Electricity supplies in the future are especially important for building LCA primarily because of their essential role in the transition and decarbonization of the global energy system. Electricity, among other energy supplies, is the supply that experiences the fastest decarbonization in recent decades, partly due to the deep cost reduction of renewable electricity generation, as well as the urgency of halving the greenhouse gas emissions in the next 10 years, and ultimately reaching net-zero global greenhouse gas emissions by 2050 or before in order to keep the global warming to well below 2°C compared to pre-industrial levels.

To understand the influence of future electricity supplies and their impacts on the LCA of buildings, this work will focus on research that answers the following 3 questions (Figure 1):

1. What would be the change of future electricity carbon intensity caused by the transition of electricity system in the future (e.g. based on different energy scenarios, mix of electricity generation technologies) and technology improvement (e.g. efficiency improvement and resulted emissions reduction)?
2. How much will embodied emissions of construction materials change due to the change of carbon intensity of electricity supplies?
3. How uncertain could be the decarbonization of future electricity system, and what influence it would have on the carbon emissions of major construction material supplies in the future?

Note that this study mainly focuses on the effect of future electricity supplies on the embodied emissions of construction materials, while another dedicated subtask (Subtask 1, Activity 1.3) within IEA EBC Annex 72 has focused on the variability and uncertainty of current and future electricity supplies during the operation stage of buildings (see: Peuportier et al., 2023).

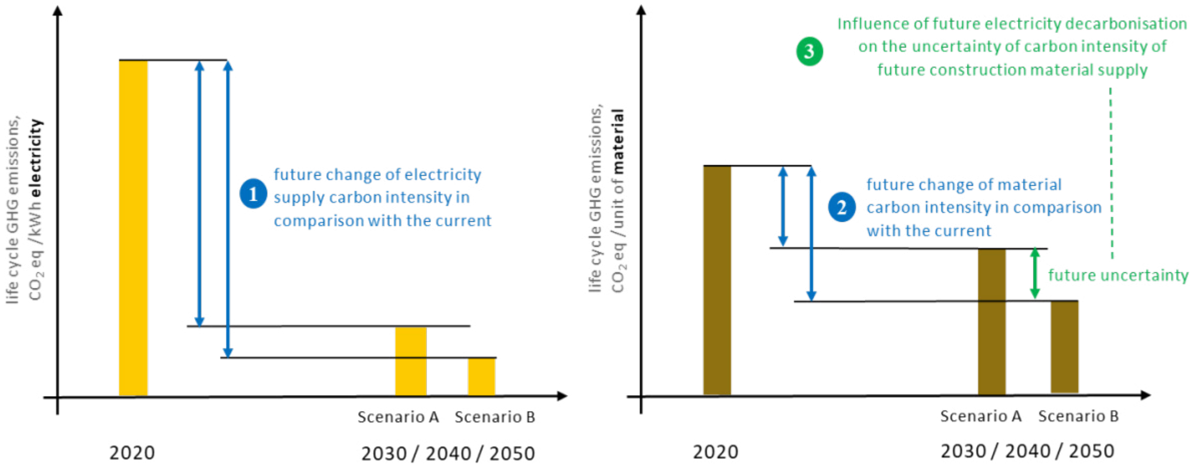


Figure 1: Illustration of the questions of interest in this analysis; “life cycle GHG emissions” are calculated from non-aggregated unit process datasets and LCA including not only the product stage (A1-A3) but also the end-of-life disposal and treatment phase (C3-C4). For electricity supply, the transmission and distribution of electricity is also included.

1.1 Scope of Work

The work will start with a literature review that gives an overview of how the uncertainty of electricity supplies have been addressed in the past literature and practices in building LCA. This will be followed by an analysis of relevant datasets in the latest KBOB (Coordination Group for Construction and Property Services; in German: Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) database. LCI data from KBOB 2016 (KBOB, 2016) will be the basis of the analysis, because in comparison to other available databases which are a mix of LCA results from EPDs (Environmental Product Declaration) and datasets from generic LCA databases (eg. ecoinvent, Gabi), it transparently provides detailed inventory data on the unit process level which allows the scoped analysis. Next, similar to the approach applied in (Cox et al., 2018)(Mendoza Beltran, Cox, Mutel, Vuuren, et al., 2018), an IAM (Integrated Assessment Model) (Pauliuk et al., 2017) REMIND (Postdam Institute for Climate Impact Research (PIK), n.d.) is applied to construct future background database used in KBOB 2016, in order to account for the transition of electricity supply mix and power plant technology advancements in the future. The influence of these transitions will be investigated for the manufacturing of major materials used in buildings and infrastructures, with a focus on life cycle greenhouse gas emissions (GHG). Finally, based on the conclusions drawn from this work, recommendations will be provided on how the uncertainties of life cycle greenhouse gas emissions caused by future electricity supplies shall be addressed in building LCAs. This will be complemented by a recommendation on the requirement of data and tools that support such analysis in the future.

1.2 Literature Review

Depending on the region where the buildings are located and where the construction products or components are manufactured, electricity supply and its GHG intensity could play a key role in the life cycle GHG emissions of buildings (Negishi et al., 2018). The long service life of buildings (i.e. 40 to more than 100 years) indicates the importance of taking future electricity supplies into account. However, this issue is only addressed to a limited extent in the LCA of buildings, mostly focusing on its influence on the environmental impacts of the building operation phase (Ramon & Allacker, 2021), some incorporated high resolution of the temporal electricity mix (Roux et al., 2016)(Kiss et al., 2020), while its influence on building materials production is rarely discussed. Alig et al. 2020 (Alig et al., 2020) is the only study that has addressed this issue, focusing on analyzing the future primary production of construction materials supplied in Switzerland, and their influence of two selected buildings in terms of life cycle cumulated energy demand and greenhouse gas emissions. The study has not only considered future electricity supplies, but also transportation and specific manufacturing process improvements and mitigation measures (eg. carbon capture and storage). For the future electricity supplies, the study has compiled a future scenario representing the time horizon from 2030 to 2050, with information obtained from the Swiss energy perspective 2050 published in 2012, World Energy Outlook in 2018 and Sustainable Development scenario published by the IEA in 2018.

The study in this report has a narrower scope, however, focusing on the influence of future electricity supplies only, but takes into account the future electricity supplies from an IAM at different time horizons (i.e. 2030, 2040, 2050), which ensures the consistency of energy supplies between the regions. The study focuses on investigating the influence of future electricity on the life cycle GHG emissions of buildings in from two perspectives: through the electricity supply during the operation of buildings (section 5.1), and through the electricity supply in building material and component manufacturing (section 5.2).

2. Methodology

Consistent and transparent modification of electricity production datasets in the background database is required to reflect the future development of electricity systems, thus an open-source advanced LCA analytical tool Brightway 2 (Mutel, 2017) is used to support this analysis.

To investigate the impact of the future electricity system development on building life cycle LCA and associated uncertainties, the KBOB list LCA Data 2016 is linked with a prospective background database built based on ecoinvent v3.6, in which electricity production and market (i.e. mix of supply) datasets are modified based on scenarios from the Integrated Assessment Model (IAM) REMIND (Postdam Institute for Climate Impact Research (PIK), n.d.)(Sacchi, n.d.). In order to analyze the influence of future electricity systems on the life cycle environmental impact of construction materials, future scenarios from an IAM (Mendoza Beltran, Cox, Mutel, van Vuuren, et al., 2018) are incorporated, and unit process datasets in the KBOB list data (Frischknecht, 2016) are analyzed. Due to the required systematic changes, analysis has to be performed on the unit process level rather than the static LCIA results (i.e. carbon emissions, primary energy, ecoscarcity points) originally published by KBOB (i.e. KBOB Recommendation 2009/1:2016; as “KBOB LCIA results” hereafter) (Plattform Ökobilanzdaten im Baubereich & Fachgruppe Ökobilanzdaten im Baubereich, 2016), which is what often being used in building LCAs. The relationship between the KBOB list LCA data, published KBOB LCIA results, KBOB LCA database DQR v2: 2016 and ecoinvent databases are illustrated in **Error! Reference source not found.** (on top).

Analysis in this study however cannot be performed to the original KBOB LCA database DQR v2: 2016, as the datasets in the original linked background database are not parameterized (i.e. parameters used in unit process dataset inventory derivation are provided as a feature in the dataset). Thus the background database used in the original KBOB database is migrated into ecoinvent v3.6 to allow the analysis required by this study. This migration results in exclusion of certain sector updates incorporated in KBOB LCA database DQR v2: 2016 in this analysis, which are partially different from what has been updated throughout the ecoinvent releases from version 3+.

In addition, due to the lack of unit process datasets for some material production and disposal processes, 20 (out of 256 materials in total) of such affected materials are excluded from this analysis. A list of all the construction materials in the KBOB database, and whether they are included for this analysis can be found in Appendix A.

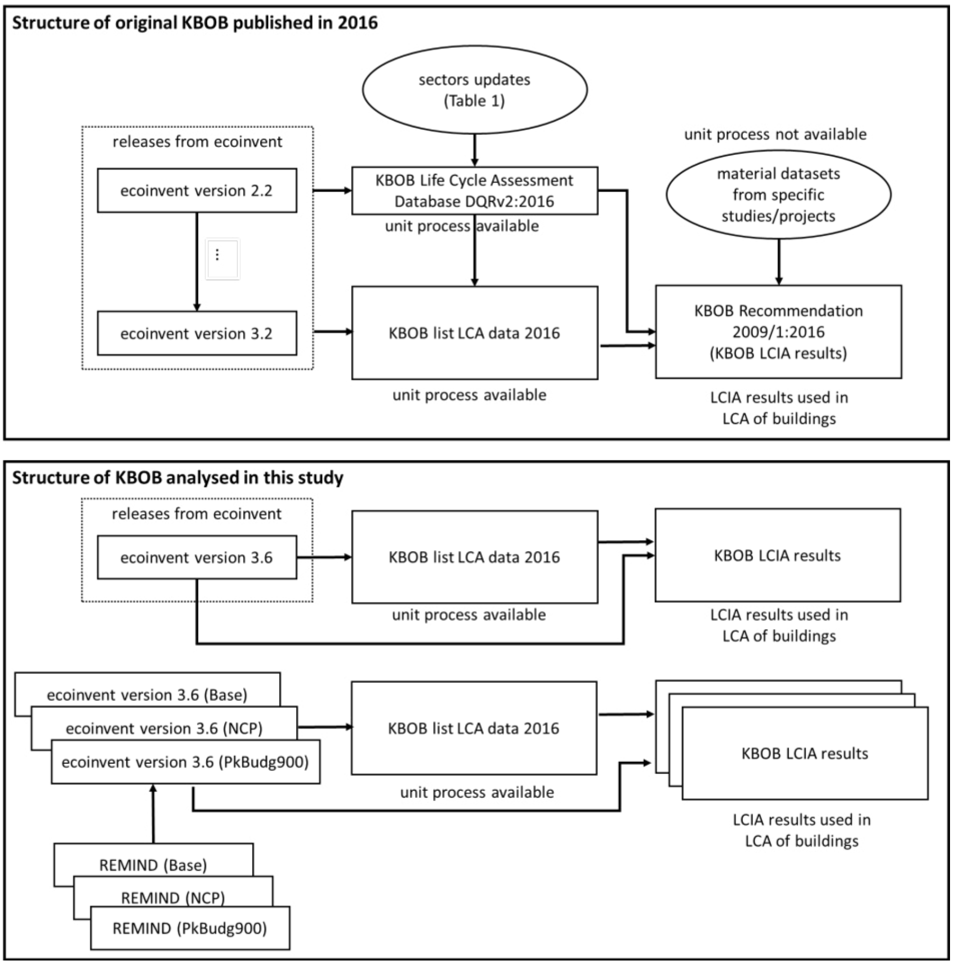


Figure 2: Structure of original KBOB LCA database DQR v2 and list LCA data published in 2016 and analyzed in this study

After linking KBOB with ecoinvent 3.6, future versions of ecoinvent are created using the open-source tool rmnd-lca version 0.0.9 (Sacchi, 2020), with 3 scenarios (CD-Links, 2017) from REMIND IAM (Aboumahboub et al., 2020) :

1. **Base,** which represents counter-factual scenario with no climate policy implemented;
2. **Nationally Determined Contributions (NDC) scenario**, in which emission reductions and other mitigation commitments of the nationally determined contributions under the Paris Agreement are implemented;
3. **PkBudget 900 scenario**, in which climate policies to limit cumulative CO2 emissions to 900 gigatons in the time horizon of 2011-2100. It corresponds to a global temperature of 1.5° increase target.

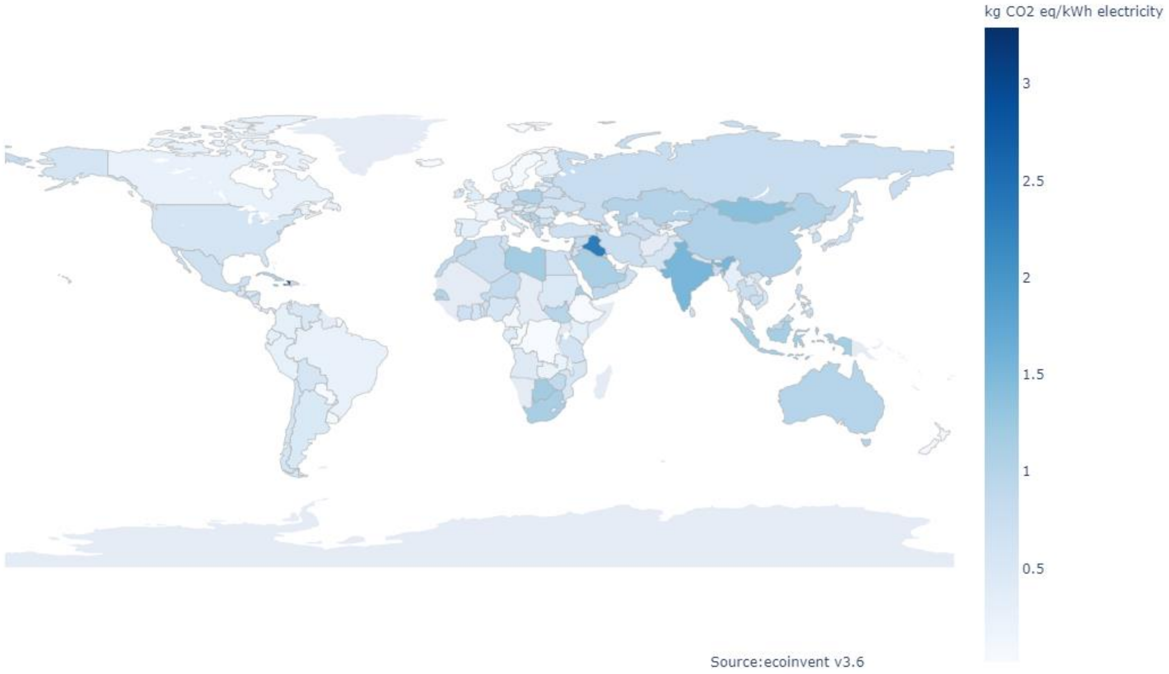
The analysis is performed in three reference years: 2030, 2040 and 2050. The future versions of ecoinvent were created by taking the assumptions of electricity mix as well as the improved electricity production efficiency and resulted decrease of direct emissions from the REMIND IAM in the future. The influence of future electricity systems on construction material is discussed in section 3.2.

3. Results and Discussion

3.1 Future Electricity Supplies During Building Operation

Since buildings are mostly supplied by distribution network, the following results are focused on the low voltage electricity supplies.

shows the GHG emissions for low-voltage electricity supplies by country in current ecoinvent v3.6. Some general regional supplies (such as global, European, rest of the world, etc.) are excluded in this figure as they overlap with the country-specific values. It shows that most of the countries in the world have a grid GHG emissions of less than 1.5 kg CO_2 eq/kWh. Although there are a few outlier countries that exhibit higher emissions (eg. Haiti, Iraq), due to the higher losses of electricity transmission and distribution or not state-of-the-art electricity generation technologies, these countries don't play a key role in the global supply chain of construction materials and their supplies of electricity to buildings are not the focus of this study.



Source:ecoinvent v3.6

Figure 3: Life cycle GHG emissions per kWh of low-voltage electricity supply current ecoinvent v3.6, in kg CO_2 eq/kWh. An interactive version of this figure is available online at: https://plotly.com/~xiaoshir/98/ (Complete table with values for constructing this figure can be downloaded following the link for interactive plot -> data.)

Due to energy transition and technology advancement, the future electricity system will have lower GHG emissions thanks to more generation of renewable electricity and higher efficiency in production technologies. **Error! Reference source not found.** shows the life cycle GHG emissions per kWh of low-voltage electricity supply in the future versions of ecoinvent v3.6 using REMIND scenarios in 2035 and 2050. First, due to the less granularity of geographic definition in REMIND, it can be seen that the results in future background databases are mostly for regions rather than for specific countries as shown in the current ecoinvent v3.6 (

): REMIND has divided the world into 13 geographic regions (Appendix B). Second, by incorporating future scenarios, lower emissions can be observed for low-voltage electricity supply, of up to around 0.6 kg CO_2 eq per kWh world-wide in the Base scenario, and up to 0.3 and 0.05 kg CO_2 eq per kWh in the NCP and the Pkbudg900 scenario respectively. The Pkbudg900 scenario is in particular ambitious as it means most of the world has to be powered by renewable electricity, nuclear power and/or power generation with fossil fuels and carbon capture and storage technologies.[1] This also means that according to the Pkbudg900 scenario, to reach a global temperature increase of 1.5°, some countries will have to decarbonize their electricity system to a tremendous extent to up to 20 times (eg. China, 1.000 g CO2 eq/kWh in current ecoinvent v3.6, vs. 230 g CO2 eq/kWh in NDC scenario and 50 g CO2 eq/kWh in Pkbudg900 scenario by 2050), which would be influential to the life cycle GHG emissions during operation of buildings in those countries.

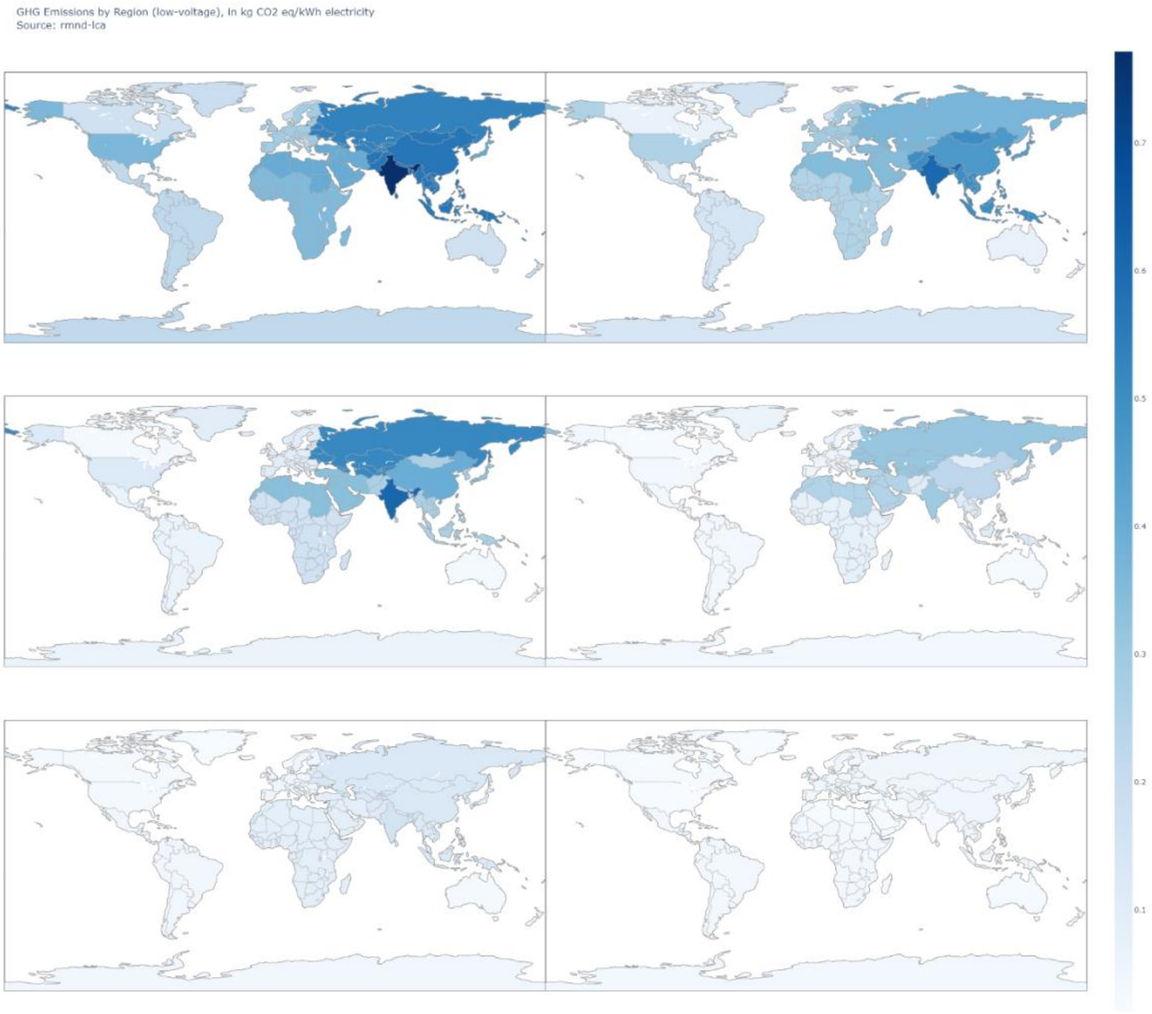


Figure 4: Life cycle GHG emissions per kWh of low-voltage electricity supply in the future, in kg CO_2 eq/kWh. Top: Base scenarios; middle: NCP scenarios; bottom: Pkbudg900 scenarios. left: reference year 2030; right: reference year 2050. An interactive version of this figure is available online at: https://chart-studio.plotly.com/~xiaoshir/152/ (Complete table with values for constructing this figure can be downloaded following the link for interactive plot -> data.)

3.2 Influence of Future Electricity System on Selected Construction Materials and Components

The percentage of life cycle GHG emissions difference is calculated for each material in the KBOB database linked with future versions of ecoinvent (future KBOB) in comparison with current KBOB

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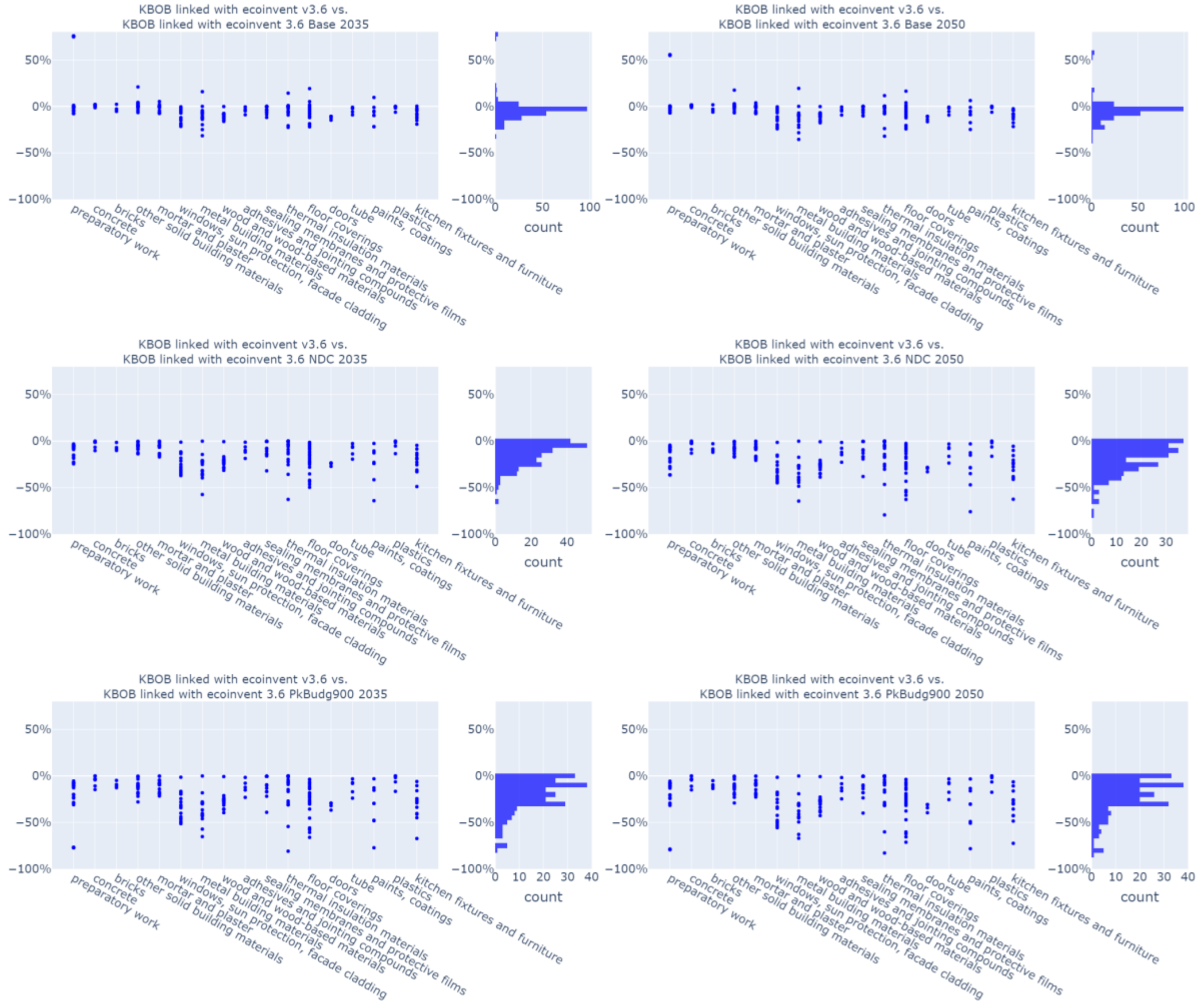
database linked with ecoinvent v3.6 (current KBOB; as thereafter), as shown in



. The formula applied to calculate the difference is as follows:

$$D_m = \frac{LG_{current\ KBOB,\ m} - LG_{future\ KBOB,\ m}}{LG_{current\ KBOB,\ m}}$$

in which,
D: difference in percentage
LG: life cycle GHG emissions for unit amount of material;
m: material

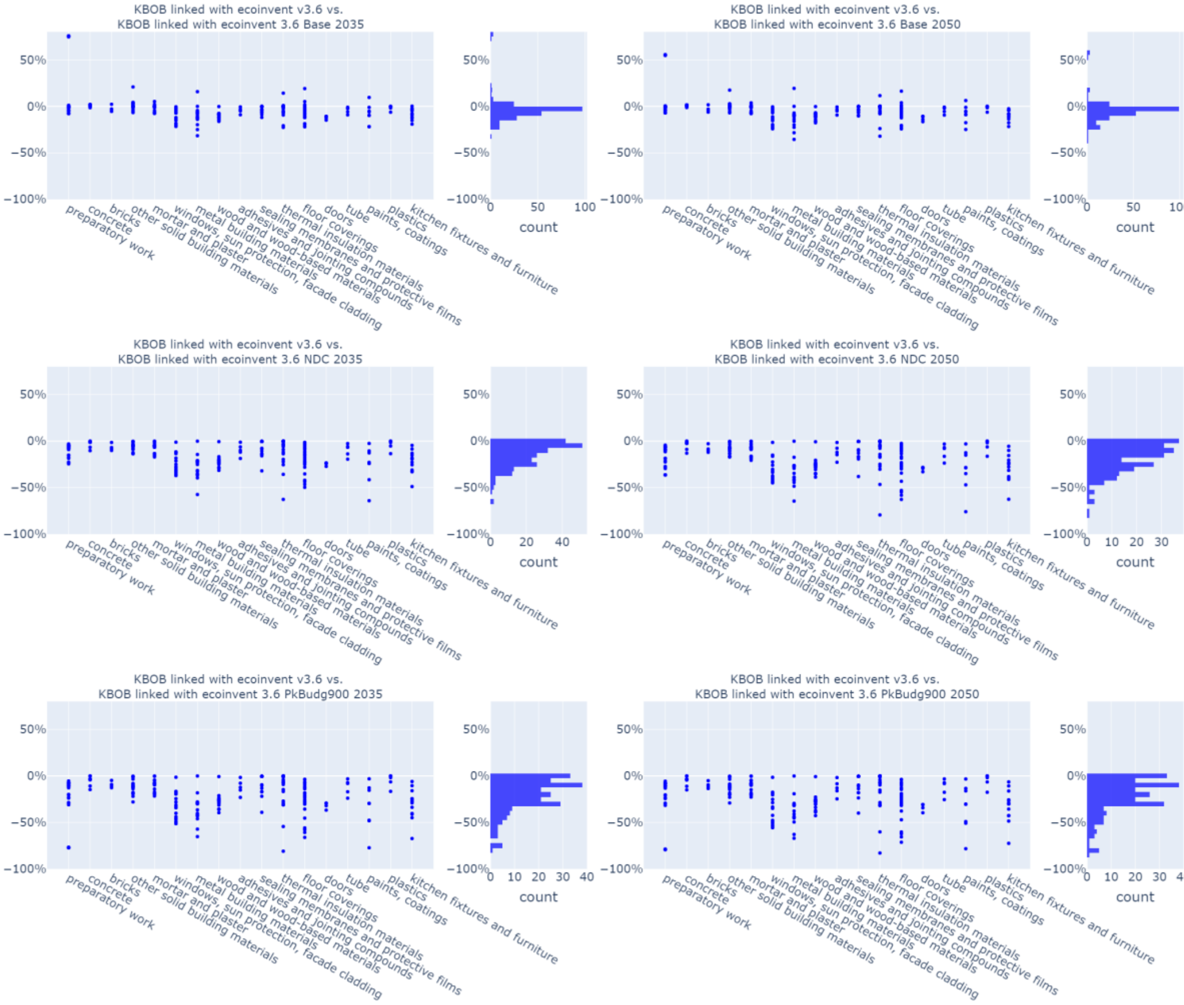


Figure 5: Percentage difference in climate change LCIA results: between KBOB linked with ecoinvent v3.6 and the ecoinvent integrated with future scenarios of IAM; each point in the figure represents the percentage difference between current and future KBOB in terms of life cycle GHG emissions, which is calculated based on the formula above; from top to bottom: Base-, NCP-, and PkBudg900- scenario; years from left to right: 2035 and 2050. An interactive version of this figure is available online at: https://plotly.com/~xiaoshir/156/, with correspondence between each scatter point and specific material. (Complete table with values for constructing this figure can be downloaded following the link for interactive plot -> data.)

As expected, most materials show reduced GHG emissions in both 2035 and 2050 regardless of the scenarios, because the electricity supplies in most of countries have lower GHG emissions (**Error! Reference source not found.**) than the current supplies in ecoinvent v3.6 (

). In Base scenarios, the range of difference for most of the materials fall into a range of -20% to 5%, while with the NCP and Pkbudg900 scenarios, few materials could achieve much higher GHG reductions of up to around 80%. Four data points under the category of preparation work (in German: “Vorbereitungsarbeiten”, very close to each other on top) in the Base scenarios show more than 50% higher emissions than in the current KBOB database (i.e. linked with ecoinvent v3.6). Similarly, in the Pkbudg900scenario, when the GHG emissions of Swiss electricity supply is reduced to about 21-23 g CO_2 eq/kWh in 2035 and 2050 (low-voltage), the emissions of these processes could be greatly reduced by about 80% accordingly.

Besides the dewatering process in the preparation work, other processes and materials also exhibit different extent of sensitivity to the future transition of electricity system. Materials from six sectors exhibit greater reduction in GHG emissions of more than 50% in the NDC scenario in 2050 as well as the Pkbudg900 in both 2035 and 2050: namely windows, sun protection, facade cladding (in German: “Fenster”, “Sonnenschutz”, “Fassadenverkleidungen”), metal construction materials (in German “Metalbaustoffe”), thermal insulation materials (in German “Wärmedämmstoffe”), floor coverings (in German “Bodenbeläge”), paints and coatings (un German “Antrichstoffe”, “Beschichtungen”) and kitchen fittings and furniture (in German “Kücheneinbauten und –möbel”). In the category of floor coverings, kitchen fittings and furniture, the high emission reduction potential are all related to natural stone materials. This is rather expected, as electricity is a major GHG emission contributor in natural stone cutting process. In paints and coatings, the great GHG emission reduction potential is led by one process named “enamelling”, which is electricity-intensive (14 kWh/m^2) to manufacture.

Since not all the materials/element/process as shown above will be needed in buildings with significant amount, the following section will zoom into a selection of specific materials, which are split into two groups: major materials for future new construction and renovation of buildings respectively (**Error! Reference source not found.**).

Table 1: List of major materials/components for future new construction and renovation.

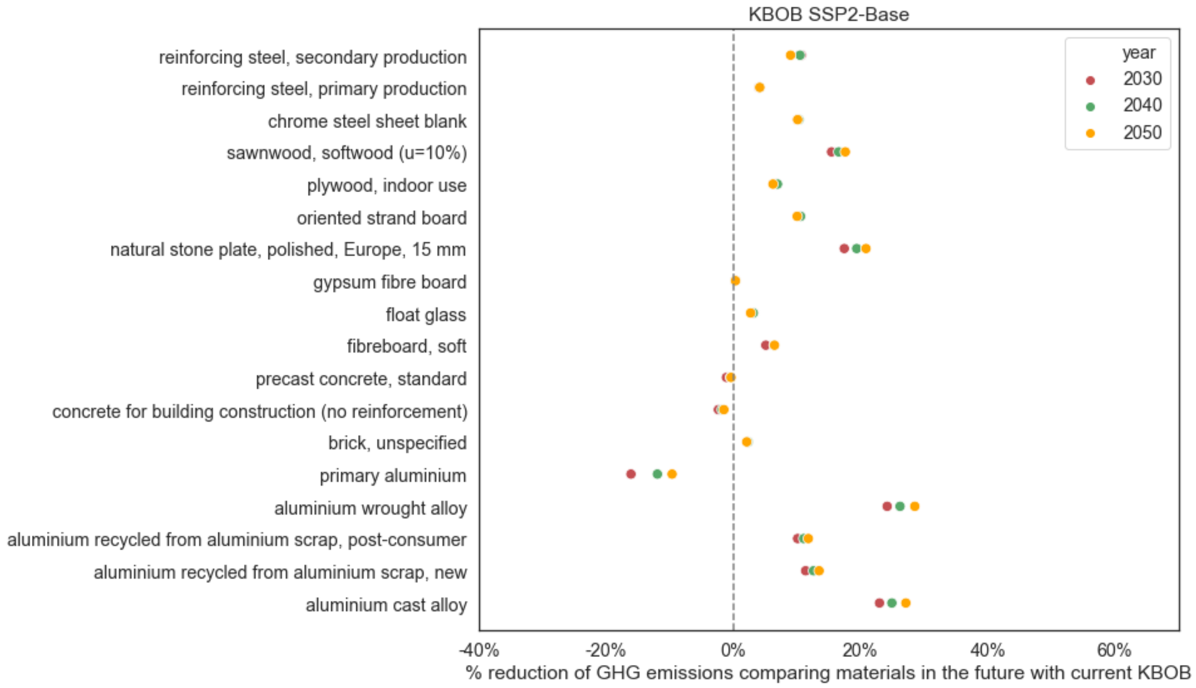
Future new construction	**Future renovation and replacement of building components**
1. Cement and Concrete	1. Windows with frames made from:
2. Steel, reinforcing	– wood
3. Steel, stainless	– PVC
4. Brick	– wood-aluminium
5. Aluminium	– aluminium
6. Float glass	2. Insulation materials:
7. Softwood, solid	– rock wool
8. Plywood, softwood	– foam glass
9. Oriented strand board (OSB) panel	3. PV systems
10. Fibreboard, soft	4. Cement mortar
11. Natural stones	

[*] glass wool and gypsum fibreboard had to be excluded despite being a major insulation material, because they are represented by aggregated datasets (i.e. dataset consisting of cumulated elementary flows, directly exchanged with the environment) in KBOB, whose LCIA score cannot be affected by the change of electricity system in the background database as performed in this analysis.

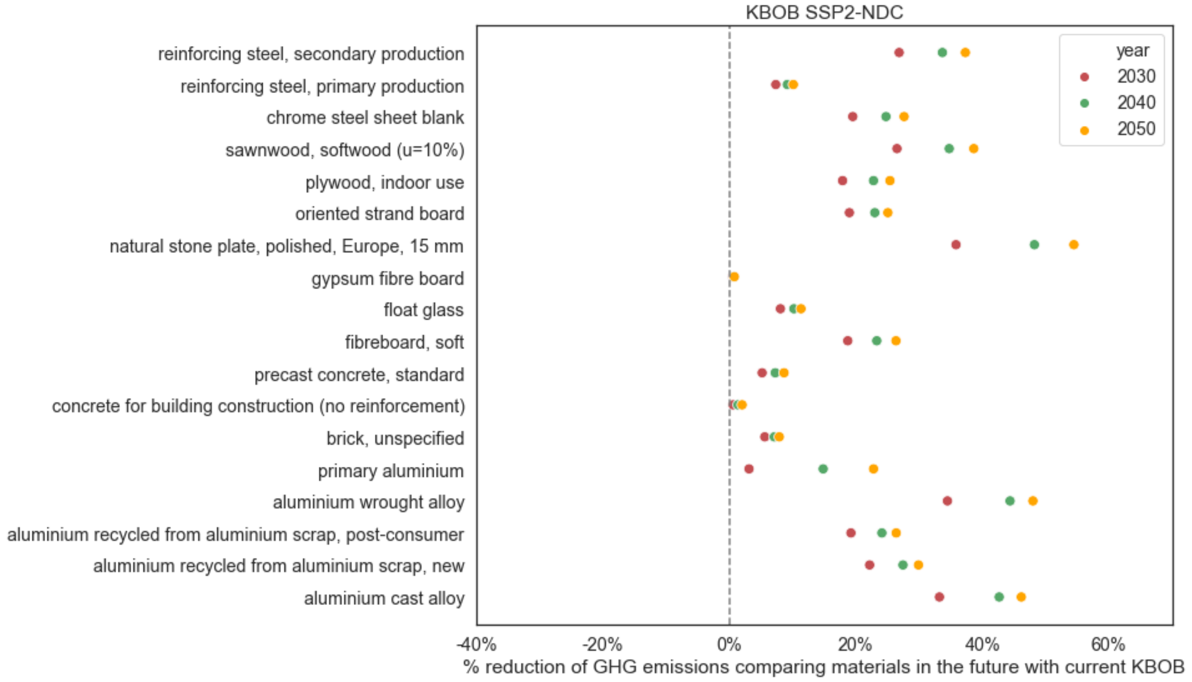
The percentage reductions of life cycle GHG emissions for major materials/components in new construction are shown in **Error! Reference source not found.**, while the absolute life cycle GHG emissions for each listed item in both current KBOB linked with ecoinvent v3.6 and future ecoinvent versions will be included in Appendix C.

Overall, in the Base scenario, increased emissions in the future have been observed for primary aluminium, and slightly for concretes. This is caused by the phase out of nuclear power in selected countries and the continuously increased share of fossil fuels in the power generation sector in the rest part of world. Since the future electricity mix from the IAM model is region-specific and not sector-specific (eg. specific to aluminium industry), so the electricity supply for primary aluminium production is only determined by the region, which is a limitation of the method. In the most climate-ambitious scenario (PdBudg900), the percentage of emissions reduction in 2040 is very close to 2050, which shows that if the world would follow an ambitious path towards power decarbonization, the resulted emission reductions can be mostly achieved by 2030 for most of materials, indicating the vital role of progress in the next 10 years.

a)


KBOB SSP2-Base
reinforcing steel, secondary production
reinforcing steel, primary production
chrome steel sheet blank
sawnwood, softwood (u=10%)
plywood, indoor use
oriented strand board
natural stone plate, polished, Europe, 15 mm
gypsum fibre board
float glass
fibreboard, soft
precast concrete, standard
concrete for building construction (no reinforcement)
brick, unspecified
primary aluminium
aluminium wrought alloy
aluminium recycled from aluminium scrap, post-consumer
aluminium recycled from aluminium scrap, new
aluminium cast alloy
year
2030
2040
2050
-40%
-20%
0%
20%
40%
60%
% reduction of GHG emissions comparing materials in the future with current KBOB

b)


KBOB SSP2-NDC
reinforcing steel, secondary production
reinforcing steel, primary production
chrome steel sheet blank
sawnwood, softwood (u=10%)
plywood, indoor use
oriented strand board
natural stone plate, polished, Europe, 15 mm
gypsum fibre board
float glass
fibreboard, soft
precast concrete, standard
concrete for building construction (no reinforcement)
brick, unspecified
primary aluminium
aluminium wrought alloy
aluminium recycled from aluminium scrap, post-consumer
aluminium recycled from aluminium scrap, new
aluminium cast alloy
year
2030
2040
2050
-40%
-20%
0%
20%
40%
60%
% reduction of GHG emissions comparing materials in the future with current KBOB

c)

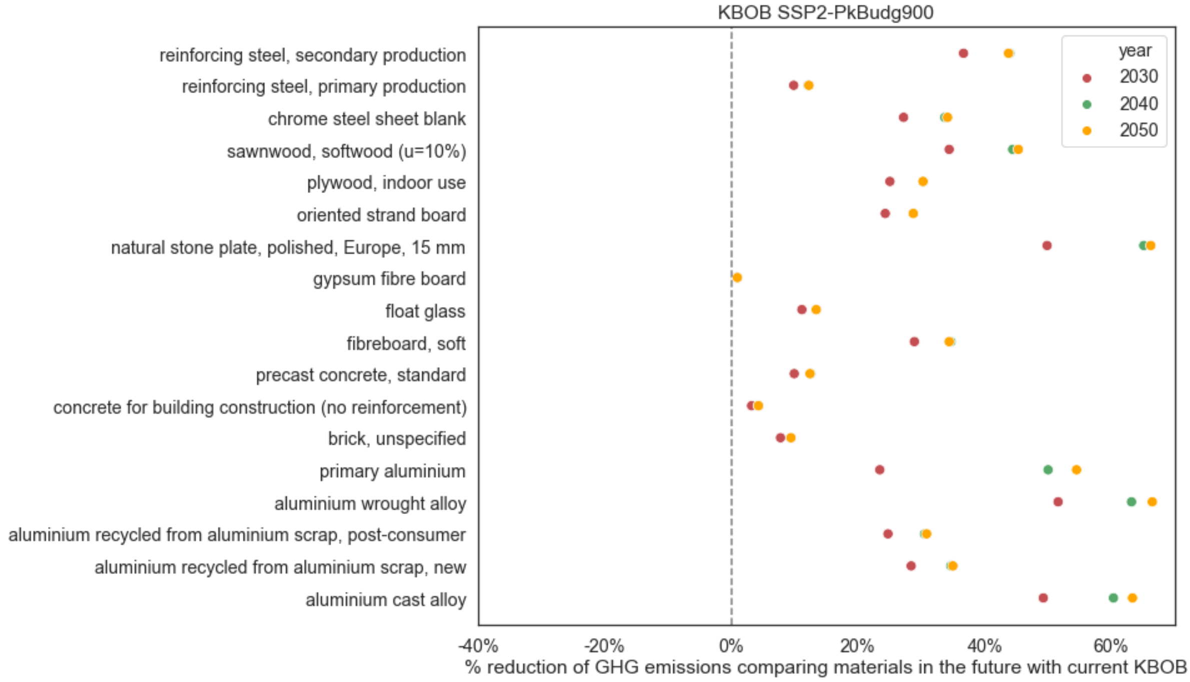


Figure 6: Percentage reduction of life cycle GHG emissions for major materials in new construction in different scenarios

In the scenario of PdBudg900, the highest future emission reduction potentials of up to more than 60% have been observed in natural stone and aluminium alloys (i.e. wrought- and cast- alloy). This is followed by sawnwood, secondary reinforcing steel and primary aluminium, which exhibit up to 40% to 60% of future emission reduction potential.

Comparing recycled steel (i.e. secondary reinforcing steel) and aluminium with their primary production, it shows that secondary reinforcing steel has much higher future emission reduction potential (i.e. in terms of percentage of emission reduction) than its primary material, whereas the GHG reduction potential for recycled aluminium is slightly lower than that of primary aluminium (**Error! Reference source not found.**). This is due to the contribution of electricity consumption in overall life cycle GHG emissions (11%) for primary steel being much lower than its contribution in the life cycle GHG emissions of secondary steel, secondary aluminium (27%-31%) and primary aluminium (44%). This also shows that a higher amount of life cycle electricity consumption alone does not indicate higher emissions reduction potential in the future, but the contribution of electricity consumption in the life cycle GHG emissions also matter.

It is also interesting that the percentage of emission reduction potential for primary aluminium is lower than that of aluminium alloys, although it has higher cumulative electricity consumption than aluminium alloys on a kilogram basis (Similarly, the percentage reduction of life cycle GHG emissions for major materials/components in retrofitted buildings are shown in **Error! Reference source not found.**. Solar PV systems exhibit the highest GHG emissions reduction potential, of up to more than 60%, led by mono-silicon PV system among the selected PV technologies. This is due to the electricity-intensive manufacturing processes upstream, such as the purification of metallurgical grade silicon to solar-grade silicon. However, due to the fast increase of manufacturing and installed capacity of solar PV systems worldwide, the upstream supply chain processes have been constantly improving (e.g., less electricity consumption in solar-grade silicon production, less material waste as a result of improved wafer sawing process and greater cell size), which is partly not considered in the dataset used for this analysis (e.g. the state-of-art electricity consumption manufacturing solar-grade silicon from metallurgical grade silicon by key players in China is about 70 kWh/kg of solar-grade silicon production (China Photovoltaic Industry Association, 2020), whereas the dataset used in this analysis assumes 110 kWh/kg). Thus, the actual emission reduction potential of solar PV systems in the future is believed to be lower than projected in this analysis, given that only the influence of the future electricity system is considered.

Table 3: Cumulative electricity consumption by material/component

Sector	Construction material-English	Unit	electricity supply
Aluminium	aluminium cast alloy	kg	4.78
	aluminium recycled from aluminium scrap, new	kg	0.46
	aluminium recycled from aluminium scrap, post-consumer	kg	0.57
	aluminium wrought alloy	kg	11.86
	primary aluminium	kg	17.34
Brick	brick, unspecified	kg	0.06
Concrete	concrete for building construction (no reinforcement)	kg	0.02
	precast concrete, standard	kg	0.09
Fibreboard, soft	fibreboard, soft	kg	0.67
Float glass	float glass	kg	0.39
Gypsum panel	gypsum fibre board	kg	0.01
Natural stones	natural stone plate, polished, Europe, 15 mm	m2	37.52
Oriented strand board (C	oriented strand board	kg	0.40
Plywood, softwood	plywood, indoor use	kg	0.72
Softwood, solid	sawnwood, softwood (u=10%)	kg	0.18
Stainless steel	chrome steel sheet blank	kg	1.98
Steel, reinforcing	reinforcing steel, primary production	kg	0.55
	reinforcing steel, secondary production	kg	0.76

This is because the 66% of the life cycle electricity supply for aluminium alloys are from China, where a great GHG emission reduction potential is expected for the electricity grid supply, whereas for primary aluminium, the percentage of electricity supply from Iceland and Norway remains dominant, where the potential of future grid emission reduction is relatively low. Recycled aluminium, stainless steel, plywood and fibreboard are materials among the third highest level of emission reduction potential, of up to 20% to 40%.

Table 2: Comparison between primary and secondary aluminium and steel

	Life cycle electricity consumption (kWh/kg)	% GHG reduction potential by 2050 (PkBudg900 2050)	Absolute GHG emissions (kg CO2 eq/kg), KBOB linked with ecoinvent v3.6	Absolute GHG emissions (kg CO2 eq/kg), KBOB linked with ecoinvent v3.6 modified with SSP2 PkBudg900 2050
Aluminium, primary	16.6	41%	7.3	4.3

Aluminium, recycled from scrap[*]	0.5-0.6	31%-35%	0.6-0.9	0.4-0.6
Reinforcement steel, primary	0.6	12%	2.2	1.9
Reinforcement steel, recycled	0.8	44%	0.71	0.4

[*] range reflecting value ranges considering aluminium recycled from both post-consumer and new scrap.

As expected, concrete is the material with the least emission reduction potential, since only the decarbonized electricity system in the future is incorporated in this analysis, whereas the majority of emissions in concrete is contributed by process emissions and combustion of fuels from clinker production (Habert et al., 2020), regardless of the type of cement used and different mixtures in concrete production. Precast concretes have slightly higher reduction potential due to four times higher life cycle electricity consumption than standard (Similarly, the percentage reduction of life cycle GHG emissions for major materials/components in retrofitted buildings are shown in **Error! Reference source not found.**. Solar PV systems exhibit the highest GHG emissions reduction potential, of up to more than 60%, led by mono-silicon PV system among the selected PV technologies. This is due to the electricity-intensive manufacturing processes upstream, such as the purification of metallurgical grade silicon to solar-grade silicon. However, due to the fast increase of manufacturing and installed capacity of solar PV systems worldwide, the upstream supply chain processes have been constantly improving (e.g., less electricity consumption in solar-grade silicon production, less material waste as a result of improved wafer sawing process and greater cell size), which is partly not considered in the dataset used for this analysis (e.g. the state-of-art electricity consumption manufacturing solar-grade silicon from metallurgical grade silicon by key players in China is about 70 kWh/kg of solar-grade silicon production (China Photovoltaic Industry Association, 2020), whereas the dataset used in this analysis assumes 110 kWh/kg). Thus, the actual emission reduction potential of solar PV systems in the future is believed to be lower than projected in this analysis, given that only the influence of the future electricity system is considered.

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Brick	brick, unspecified	kg	0.06
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	precast concrete, standard	kg	0.09
Fibreboard, soft	fibreboard, soft	kg	0.67
Float glass	float glass	kg	0.39
Gypsum panel	gypsum fibre board	kg	0.01
Natural stones	natural stone plate, polished, Europe, 15 mm	m2	37.52
Oriented strand board (C	oriented strand board	kg	0.40
Plywood, softwood	plywood, indoor use	kg	0.72
Softwood, solid	sawnwood, softwood (u=10%)	kg	0.18
Stainless steel	chrome steel sheet blank	kg	1.98
Steel, reinforcing	reinforcing steel, primary production	kg	0.55
	reinforcing steel, secondary production	kg	0.76

Despite 45 kWh of electricity consumption is required per cubic meter of precast concrete, its emissions reduction potential (in percentage of current emissions) is relatively low in comparison with other materials, as the main contributor to its life cycle GHG emissions is not electricity consumption (partially also due to the electricity supply from Switzerland, where the carbon intensity of grid supply is low, thanks to great share of hydropower and nuclear power), but rather the consumption of cement and reinforcing steel.

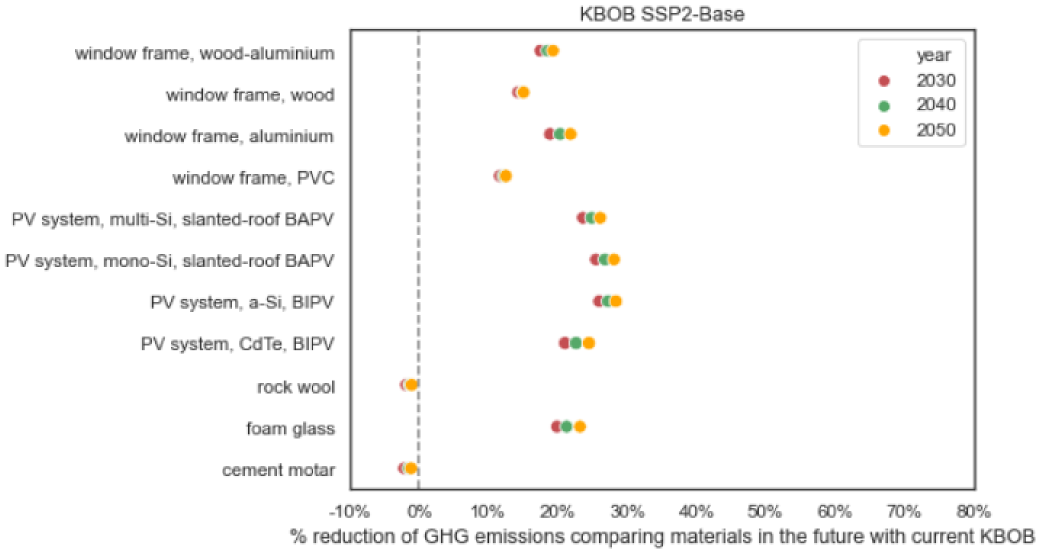
Similarly, the percentage reduction of life cycle GHG emissions for major materials/components in retrofitted buildings are shown in **Error! Reference source not found.**. Solar PV systems exhibit the highest GHG emissions reduction potential, of up to more than 60%, led by mono-silicon PV system among the selected PV technologies. This is due to the electricity-intensive manufacturing processes upstream, such as the purification of metallurgical grade silicon to solar-grade silicon. However, due to the fast increase of manufacturing and installed capacity of solar PV systems worldwide, the upstream supply chain processes have been constantly improving (e.g., less electricity consumption in solar-grade silicon production, less material waste as a result of improved wafer sawing process and greater cell size), which is partly not considered in the dataset used for this analysis (e.g. the state-of-art electricity consumption manufacturing solar-grade silicon from metallurgical grade silicon by key players in China is about 70 kWh/kg of solar-grade silicon production (China Photovoltaic Industry Association, 2020), whereas the dataset used in this analysis assumes 110 kWh/kg). Thus, the actual emission reduction potential of solar PV systems in the future is believed to be lower than projected in this analysis, given that only the influence of the future electricity system is considered.

Table 3: Cumulative electricity consumption by material/component

Sector	Construction material-English	Unit	electricity supply
Aluminium	aluminium cast alloy	kg	4.78
	aluminium recycled from aluminium scrap, new	kg	0.46
	aluminium recycled from aluminium scrap, post-consumer	kg	0.57
	aluminium wrought alloy	kg	11.86
	primary aluminium	kg	17.34
Brick	brick, unspecified	kg	0.06
Concrete	concrete for building construction (no reinforcement)	kg	0.02
	precast concrete, standard	kg	0.09
Fibreboard, soft	fibreboard, soft	kg	0.67
Float glass	float glass	kg	0.39
Gypsum panel	gypsum fibre board	kg	0.01
Natural stones	natural stone plate, polished, Europe, 15 mm	m2	37.52
Oriented strand board (C	oriented strand board	kg	0.40
Plywood, softwood	plywood, indoor use	kg	0.72
Softwood, solid	sawnwood, softwood (u=10%)	kg	0.18
Stainless steel	chrome steel sheet blank	kg	1.98
Steel, reinforcing	reinforcing steel, primary production	kg	0.55
	reinforcing steel, secondary production	kg	0.76

Insulation material foam glass is also shown to have high emission reduction potential of up to more than 60%, due to its high electricity consumption of 1.5 kWh/kg in comparison with only 0.2 kWh/kg of electricity consumption in rock wool production. This is closely followed by different types of window frames, especially the one with the consumption of aluminium, due to reasons explained above for aluminium cast alloy.

a)



b)

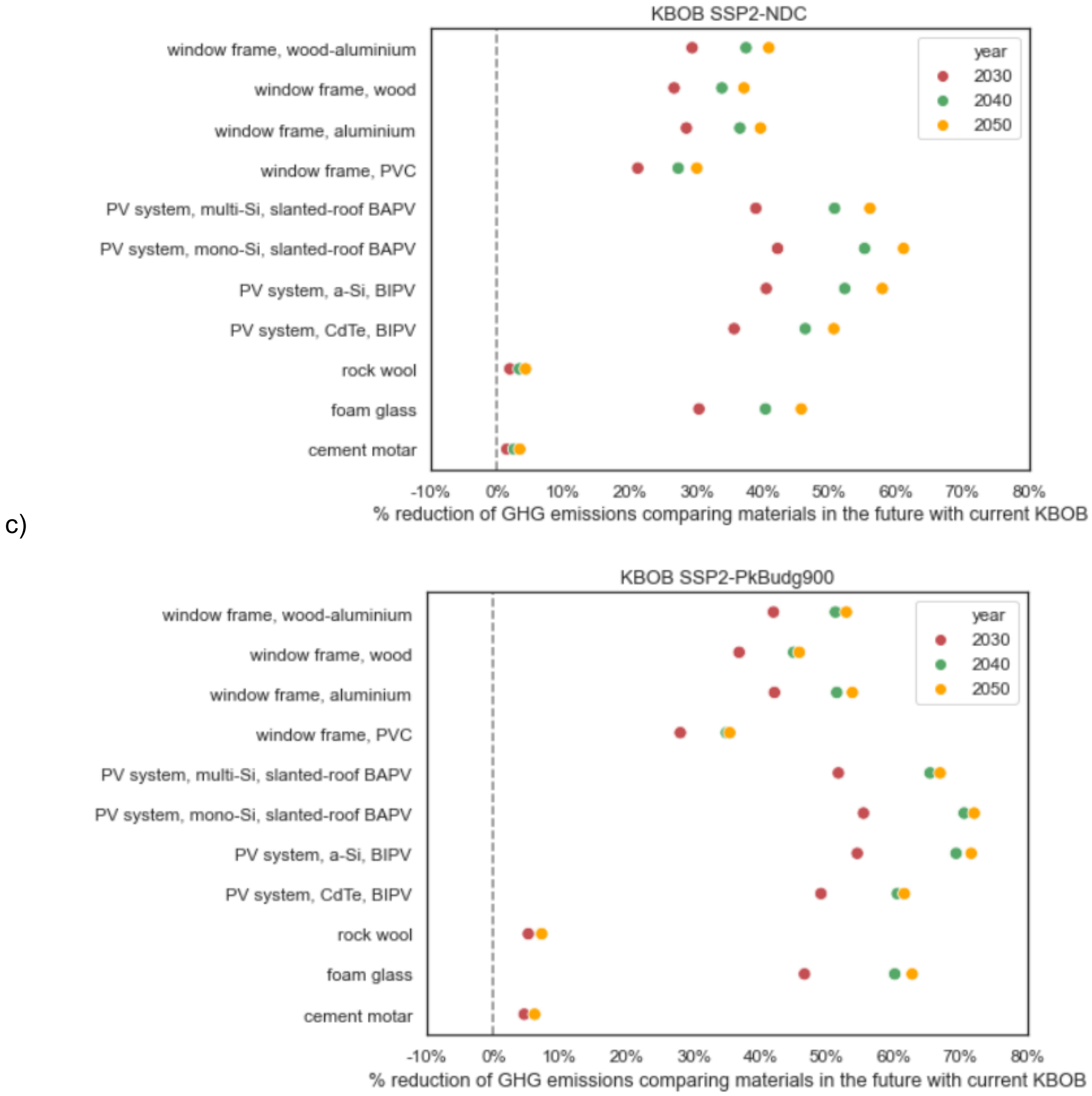


Figure 7: Percentage reduction of life cycle GHG emissions for major materials for retrofitted buildings

Although most of the materials/components selected have the reference unit of kilogram, some materials have different reference units, such as square meter (e.g. natural stones, windows) and unit of system of a certain size (e.g. PV systems at the power capacity of 3 kWp). To investigate whether there is an indicator that can reflect the sensitivities of life cycle GHG emissions to future electricity system decarbonization across different materials/components, even if the future background database is not in place, the amount of cumulative electricity consumption is normalized by the amount of cumulative fossil energy demand (**Error! Reference source not found.**). Although for PV systems and natural stone, the higher values for this indicator reflect the high emission reduction potential, it is found that this indicator alone in the current database (**Error! Reference source not found.**a) does not always indicate the sensitivity of embodied emissions of materials/components to future electricity system decarbonization (e.g. primary aluminium vs. aluminium alloys), because it does not reflect the geographical distribution of the upstream processes including their electricity supplies, thus their future emission reduction potentials cannot be estimated. This can be partly compensated by estimating this indicator in the future scenario (**Error! Reference source not found.**b), for which a great increase in its value hints a great reduction of fossil fuel consumption upstream in the future, but it still does not reflect if the consumption of electricity dominates the overall life cycle GHG emissions or not in comparison with other contributions, which is also key for a great percentage reduction of GHG emissions. In conclusion, the sensitivity of materials/components' embodied emissions to future electricity system decarbonization is determined not only by the amount of cumulative electricity consumption, but also the contribution of electricity consumption in its current life cycle GHG emissions, as well as the main countries of electricity supplies upstream where the majority of electricity is consumed and its future potential for decarbonization.

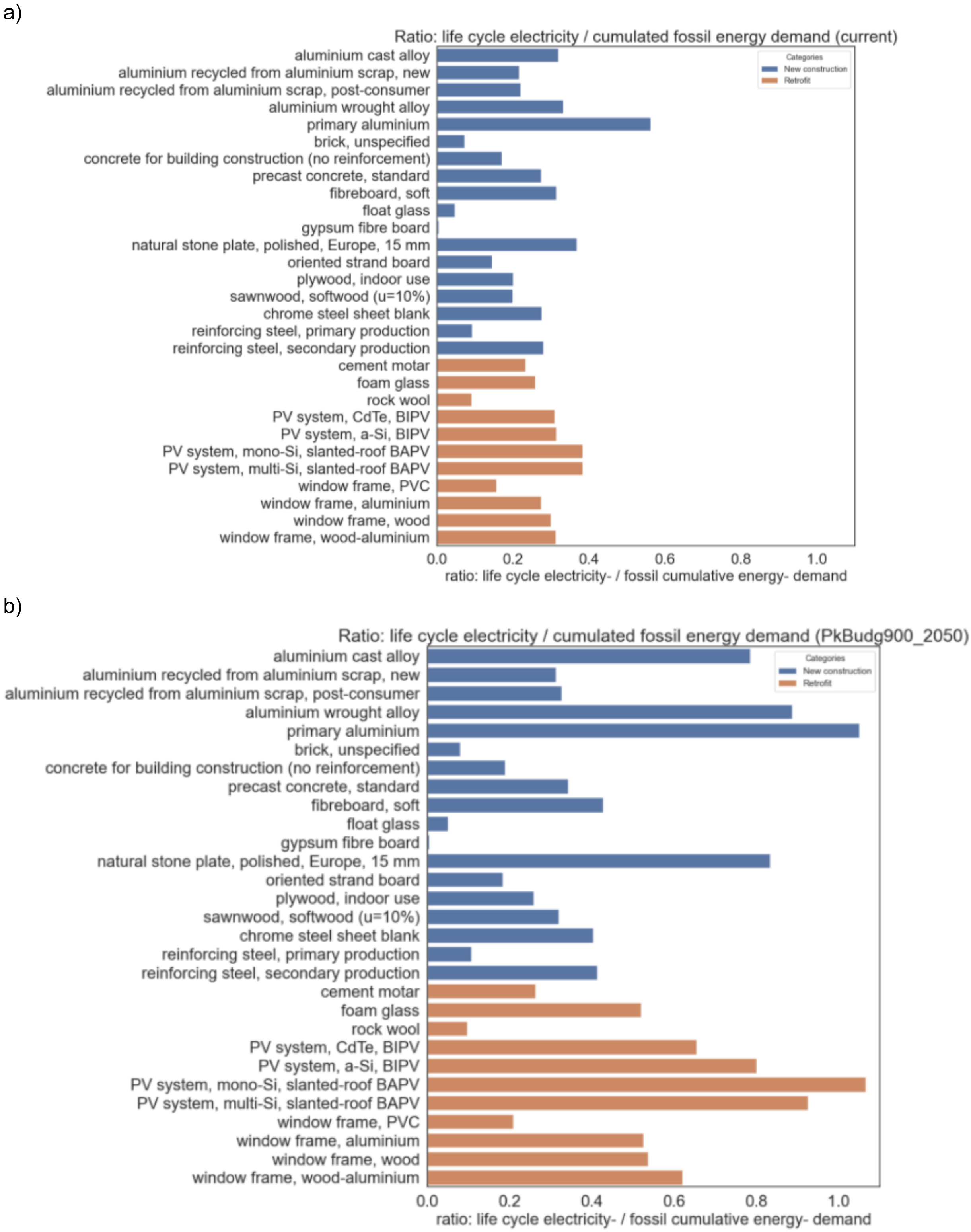


Figure 8: Ratio of life cycle electricity (in the processes from which life cycle GHG emissions are calculated based on explanation in Figure 1) and fossil cumulative energy demand, in kWh/kWh oil-eq: a) KBOB linked with ecoinvent v3.6 (current); b) KBOB linked with future ecoinvent v3.6 modified using scenario PdBudg900 in 2050. The value

of ratio increases in b) in comparison with a), due to decreased fossil energy demand in the supply chain of the materials upstream, as a result of decarbonized power system in the future

4. Conclusions and Outlook

The main results produced from this analysis is the life cycle GHG emissions per kWh of electricity supply (**Error! Reference source not found.**) and per unit amount of material or component, considering different future scenarios and time horizons. The table below includes selected results of life cycle GHG emissions of material or component, for base scenario from 2030 to 2050 at a 10-year interval, while the complete results for all scenarios for the same time horizons can be found in Appendix C.

Table 4: Life cycle GHG emissions (in kg CO_2 eq) per unit amount of material/component in KBOB, linked with ecoinvent v3.6, and with ecoinvent v3.6 incorporating global electricity system decarbonization from selected scenarios

New Construction /Retrofit	Index	Material/ Components	Material/Components displayed name in Figures	Unit	Life cycle GHG emissions per unit amount of material/component			
					KBOB linked with ecoinvent v3.6	**KBOB SSP2-Base_2030**	**KBOB SSP2-Base_2040**	**KBOB SSP2-Base_2050**
New construction	N1	Concrete	concrete for building construction (no reinforcement)	kg	9.49E-02	9.72E-02	9.66E-02	9.63E-02
	N2	Concrete	precast concrete, standard	kg	1.67E-01	1.69E-01	1.68E-01	1.67E-01
	N3	Steel, reinforcing	reinforcing steel, secondary production	kg	7.12E-01	6.36E-01	6.37E-01	6.48E-01
	N4	Steel, reinforcing	reinforcing steel, primary production	kg	2.20E+00	2.11E+00	2.11E+00	2.11E+00
	N5	Brick	brick, unspecified	kg	2.59E-01	2.53E-01	2.53E-01	2.54E-01
	N6	Aluminium	primary aluminium	kg	9.59E+00	1.11E+01	1.07E+01	1.05E+01
	N7	Aluminium	aluminium wrought alloy	kg	1.31E+01	9.91E+00	9.65E+00	9.34E+00
	N8	Aluminium	aluminium cast alloy	kg	5.41E+00	4.17E+00	4.06E+00	3.94E+00
	N9	Aluminium	aluminium recycled from aluminium scrap, new	kg	6.24E-01	5.53E-01	5.46E-01	5.40E-01
	N10	Aluminium	aluminium recycled from aluminium scrap, post-consumer	kg	9.09E-01	8.17E-01	8.09E-01	8.02E-01
	N11	Stainless steel	chrome steel sheet blank	kg	2.25E+00	2.03E+00	2.02E+00	2.02E+00
	N12	Float glass	float glass	kg	1.18E+00	1.14E+00	1.15E+00	1.15E+00
	N13	Natural stones	natural stone plate, polished, Europe, 15 mm	m2	2.86E+01	2.36E+01	2.31E+01	2.27E+01
	N14	Softwood, solid	sawnwood, softwood (u=10%)	kg	2.48E-01	2.10E-01	2.07E-01	2.05E-01
	N15	Plywood, softwood	plywood, indoor use	kg	9.32E-01	8.69E-01	8.68E-01	8.74E-01
	N16	Oriented strand board (OSB) panel	oriented strand board	kg	7.08E-01	6.34E-01	6.33E-01	6.37E-01
	N17	Fibreboard, soft	fibreboard, soft	kg	5.76E-01	5.47E-01	5.39E-01	5.39E-01
	N18	Gypsum panel	gypsum fibre board	kg	5.24E-01	5.22E-01	5.22E-01	5.22E-01

Retrofit	R1	Windows	window frame, aluminium	m2	6.00E+02	4.87E+02	4.78E+02	4.69E+02
	R2	Windows	window frame, wood	m2	1.74E+02	1.49E+02	1.48E+02	1.48E+02
	R3	Windows	window frame, wood-aluminium	m2	3.27E+02	2.70E+02	2.67E+02	2.64E+02
	R4	Windows	window frame, PVC	m2	3.31E+02	2.92E+02	2.91E+02	2.90E+02
	R5	Insulation material	foam glass	kg	1.78E+00	1.43E+00	1.40E+00	1.37E+00
	R6	Insulation material	rock wool	kg	1.09E+00	1.11E+00	1.10E+00	1.10E+00
	R7	Cement motar	cement motar	kg	2.09E-01	2.13E-01	2.12E-01	2.11E-01
	R8	PV system	PV system, multi-Si, slanted-roof BAPV	unit	6.54E+03	4.99E+03	4.91E+03	4.83E+03
	R9	PV system	PV system, mono-Si, slanted-roof BAPV	unit	7.60E+03	5.66E+03	5.56E+03	5.46E+03
	R10	PV system	PV system, a-Si, BIPV	unit	4.83E+03	3.58E+03	3.51E+03	3.46E+03
	R11	PV system	PV system, CdTe, BIPV	unit	4.28E+03	3.38E+03	3.31E+03	3.23E+03

4.1 Conclusions and Recommendations

It shows that incorporating future electricity supplies in the background database for construction material database can be crucial for materials with electricity-intensive manufacturing process upstream in the supply chain and which are used in building elements that need replacement during the service life of buildings. Depending on the material, its upstream processes and the selected future scenarios, the changes of life cycle GHG emission from -80% to +20% in comparison with the materials as in current KBOB database can be achieved, which is significant.. The life cycle GHG emissions of construction materials that are sensitive to future electricity supplies are concentrated in aluminium- (up to -60% emissions reduction), natural stones-related materials (up to -60%~-71% emissions reduction), as well as certain insulation (eg. aerogel vilies, up to -83% emissions reduction) and coating materials (eg. enamelling, up to -78% emissions reduction). The percentage of life cycle GHG emission variations for electricity supply itself in the future is much higher, which indicates prominent influence on the operation phase of buildings.

Given the high variability of the electricity system in terms of time and geographical regions currently (*ElectricityMap | Live CO_2 Emissions of Electricity Consumption*, n.d.) and its uncertainty in the future, this analysis shows the importance of using non-aggregated unit process datasets in the background when establishing building LCA databases for designers and architects such as the KBOB recommendation 2009/1:2016. Especially for those materials with relatively electricity-intensive manufacturing process, transparent non-aggregated unit process datasets allow such analysis changing background database, which can facilitate a more up-to-date and precise understanding of life cycle GHG emissions of construction materials. On the other hand, close and up-to-date linkages material datasets have with the background databases should be better addressed in the future, so that updated, more diverse and detailed material datasets can be utilized by sectors other than building industry, for example, cement and steel consumption in large infrastructures such as power plants or general infrastructure required in industry sectors.

4.2 Limitations and Future Research

While this analysis demonstrates the possibility of incorporating future electricity supplies in assessing the life cycle GHG emissions of construction materials, it has also a few limitations that should be further investigated.

There are few limitations in the analysis arise from applying IAM in the background database. First of all, only future electricity system has been considered, while other sectors such as transport, specific industry sectors are excluded. In addition, the IAM considered in this analysis is only one of the IAM available in literature (Pauliuk et al., 2017), future research should investigate what variation of results it would bring by incorporating other IAMs in the analysis. In addition, IAM often has aggregated global regions than considering specific countries or regions smaller than countries (which can bring great varieties especially for large countries like the USA and China). The most climate-ambitious scenario (eg. PkBudget 900 scenario in this analysis) also exhibits very ambitious targets of decarbonization (**Error! Reference source not found.**), for which a path towards the future is less addressed, which might make potential GHG emission reductions analyzed in this study optimistic.

Additionally, diverse future scenarios for specific sectors (eg. heat supply, recycling) and industries should also be further investigated and incorporated in such analysis, in order to better understand the specific conditions and challenges that are faced in reality. Further analysis can be also performed looking into the upstream supply chains for critical materials in terms of their geographical distribution and dependencies, which can help to understand the supply of security for specific countries. At last, results generated from this analysis have only focused on materials alone, and they can be further applied in different types of building case studies to take into account the relative consumption amount, which could help to form priorities in the making of national policies and strategies.

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Appendix

A. List of datasets excluded due to lack of unit process datasets

Sector	Material name
Fenster, Sonnenschutz, Fassadenverkleidungen	Fassade, Pfosten-Riegel, Alu/Glas
Fenster, Sonnenschutz, Fassadenverkleidungen	Fensterrahmen Aluminium, WICLINE 75evo
Fenster, Sonnenschutz, Fassadenverkleidungen	Isolierverglasung 2-fach, VSG, Ug-Wert 1.1 W/m2K
Fenster, Sonnenschutz, Fassadenverkleidungen	Isolierverglasung 3-fach, VSG, Ug-Wert 0.6 W/m2K
Fenster, Sonnenschutz, Fassadenverkleidungen	Fassadenplatte, Kalkstein, 30 mm
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne, kammergetr., Vollholzhaus holzpur
Holz und Holzwerkstoffe	Brettschichtholz, MF-gebunden, Feuchtbereich, Produktion Schweiz
Holz und Holzwerkstoffe	Brettschichtholz, UF-gebunden, Trockenbereich, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Buche / Eiche, kammergetrocknet, gehobelt, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Buche / Eiche, kammergetrocknet, rau, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Buche / Eiche, luftgetrocknet, rau, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne / Lärche, kammergetr., gehobelt, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne / Lärche, luftgetr., gehobelt, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne / Lärche, luftgetrocknet, rau, Produktion Schweiz
Dichtungsbahnen und Schutzfolien	Dichtungsbahn Polyolefin (FPO)
Wärmedämmstoffe	Glaswolle, Isover
Wärmedämmstoffe	Strohballenwand
Mauersteine	Kalksandstein, FBB
Andere Massivbaustoffe	Kalksteinplatte
Rohre	Polypropylen (PP), rezykliert, Rehau

B. List of countries & regions

Country	Country Code	Region Code	Alpha-3 Code
Aruba	AW	LAM	ABW
Afghanistan	AF	OAS	AFG
Angola	AO	SSA	AGO
Anguilla	AI	LAM	AIA
Aland Islands	AX	EUR	ALA
Albania	AL	NEU	ALB
Andorra	AD	NEU	AND
United Arab Emirates	AE	MEA	ARE
Argentina	AR	LAM	ARG
Armenia	AM	REF	ARM
American Samoa	AS	OAS	ASM
Antarctica	AQ	LAM	ATA
French Southern Territories	TF	OAS	ATF
Antigua and Barbuda	AG	LAM	ATG
Australia	AU	CAZ	AUS
Austria	AT	EUR	AUT
Azerbaijan	AZ	REF	AZE
Burundi	BI	SSA	BDI
Belgium	BE	EUR	BEL
Benin	BJ	SSA	BEN
Bonaire, Sint Eustatius and Saba	BQ	LAM	BES
Burkina Faso	BF	SSA	BFA
Bangladesh	BD	OAS	BGD
Bulgaria	BG	EUR	BGR
Bahrain	BH	MEA	BHR
Bahamas	BS	LAM	BHS
Bosnia and Herzegovina	BA	NEU	BIH
Saint Barthelemy	BL	LAM	BLM
Belarus	BY	REF	BLR
Belize	BZ	LAM	BLZ
Bermuda	BM	LAM	BMU
Bolivia, Plurinational State of	BO	LAM	BOL
Brazil	BR	LAM	BRA
Barbados	BB	LAM	BRB
Brunei Darussalam	BN	OAS	BRN
Bhutan	BT	OAS	BTN
Botswana	BW	SSA	BWA
Central African Republic	CF	SSA	CAF
Canada	CA	CAZ	CAN
Cocos (Keeling) Islands	CC	OAS	CCK
China	CN	CHA	CHN

Switzerland	CH	NEU	CHE
Chile	CL	LAM	CHL
Cote d Ivoire	CI	SSA	CIV
Cameroon	CM	SSA	CMR
Congo, the Democratic Republic of the	CD	SSA	COD
Congo	CG	SSA	COG
Cook Islands	CK	OAS	COK
Colombia	CO	LAM	COL
Comoros	KM	SSA	COM
Cape Verde	CV	SSA	CPV
Costa Rica	CR	LAM	CRI
Cuba	CU	LAM	CUB
Curacao	CW	LAM	CUW
Christmas Island	CX	OAS	CXR
Cayman Islands	KY	LAM	CYM
Cyprus	CY	EUR	CYP
Czech Republic	CZ	EUR	CZE
Germany	DE	EUR	DEU
Djibouti	DJ	SSA	DJI
Dominica	DM	LAM	DMA
Denmark	DK	EUR	DNK
Dominican Republic	DO	LAM	DOM
Algeria	DZ	MEA	DZA
Ecuador	EC	LAM	ECU
Egypt	EG	MEA	EGY
Eritrea	ER	SSA	ERI
Western Sahara	EH	MEA	ESH
Spain	ES	EUR	ESP
Estonia	EE	EUR	EST
Ethiopia	ET	SSA	ETH
Finland	FI	EUR	FIN
Fiji	FJ	OAS	FJI
Falkland Islands (Malvinas)	FK	LAM	FLK
France	FR	EUR	FRA
Faroe Islands	FO	EUR	FRO
Micronesia, Federated States of	FM	OAS	FSM
Gabon	GA	SSA	GAB
United Kingdom	GB	EUR	GBR
Georgia	GE	REF	GEO
Guernsey	GG	EUR	GGY
Ghana	GH	SSA	GHA
Gibraltar	GI	EUR	GIB
Guinea	GN	SSA	GIN
Guadeloupe	GP	LAM	GLP

Gambia	GM	SSA	GMB
Guinea-Bissau	GW	SSA	GNB
Equatorial Guinea	GQ	SSA	GNQ
Greece	GR	EUR	GRC
Grenada	GD	LAM	GRD
Greenland	GL	NEU	GRL
Guatemala	GT	LAM	GTM
French Guiana	GF	LAM	GUF
Guam	GU	OAS	GUM
Guyana	GY	LAM	GUY
Hong Kong	HK	CHA	HKG
Honduras	HN	LAM	HND
Croatia	HR	EUR	HRV
Haiti	HT	LAM	HTI
Hungary	HU	EUR	HUN
Indonesia	ID	OAS	IDN
Isle of Man	IM	EUR	IMN
India	IN	IND	IND
British Indian Ocean Territory	IO	OAS	IOT
Ireland	IE	EUR	IRL
Iran, Islamic Republic of	IR	MEA	IRN
Iraq	IQ	MEA	IRQ
Iceland	IS	NEU	ISL
Israel	IL	MEA	ISR
Italy	IT	EUR	ITA
Jamaica	JM	LAM	JAM
Jersey	JE	EUR	JEY
Jordan	JO	MEA	JOR
Japan	JP	JPN	JPN
Kazakhstan	KZ	REF	KAZ
Kenya	KE	SSA	KEN
Kyrgyzstan	KG	REF	KGZ
Cambodia	KH	OAS	KHM
Kiribati	KI	OAS	KIR
Saint Kitts and Nevis	KN	LAM	KNA
Korea, Republic of	KR	OAS	KOR
Kuwait	KW	MEA	KWT
Lao People's Democratic Republic	LA	OAS	LAO
Lebanon	LB	MEA	LBN
Liberia	LR	SSA	LBR
Libya	LY	MEA	LBY
Saint Lucia	LC	LAM	LCA
Liechtenstein	LI	NEU	LIE
Sri Lanka	LK	OAS	LKA

Lesotho	LS	SSA	LSO
Lithuania	LT	EUR	LTU
Luxembourg	LU	EUR	LUX
Latvia	LV	EUR	LVA
Macao	MO	CHA	MAC
Saint Martin (French part)	MF	LAM	MAF
Morocco	MA	MEA	MAR
Monaco	MC	NEU	MCO
Moldova, Republic of	MD	REF	MDA
Madagascar	MG	SSA	MDG
Maldives	MV	OAS	MDV
Mexico	MX	LAM	MEX
Marshall Islands	MH	OAS	MHL
Macedonia, the former Yugoslav Republic of	MK	NEU	MKD
Mali	ML	SSA	MLI
Malta	MT	EUR	MLT
Myanmar	MM	OAS	MMR
Montenegro	ME	NEU	MNE
Mongolia	MN	OAS	MNG
Northern Mariana Islands	MP	OAS	MNP
Mozambique	MZ	SSA	MOZ
Mauritania	MR	SSA	MRT
Montserrat	MS	LAM	MSR
Martinique	MQ	LAM	MTQ
Mauritius	MU	SSA	MUS
Malawi	MW	SSA	MWI
Malaysia	MY	OAS	MYS
Mayotte	YT	SSA	MYT
Namibia	NA	SSA	NAM
New Caledonia	NC	OAS	NCL
Niger	NE	SSA	NER
Norfolk Island	NF	OAS	NFK
Nigeria	NG	SSA	NGA
Nicaragua	NI	LAM	NIC
Niue	NU	OAS	NIU
Netherlands	NL	EUR	NLD
Norway	NO	NEU	NOR
Nepal	NP	OAS	NPL
Nauru	NR	OAS	NRU
New Zealand	NZ	CAZ	NZL
Oman	OM	MEA	OMN
Pakistan	PK	OAS	PAK
Panama	PA	LAM	PAN
Pitcairn	PN	OAS	PCN

Peru	PE	LAM	PER
Philippines	PH	OAS	PHL
Palau	PW	OAS	PLW
Papua New Guinea	PG	OAS	PNG
Poland	PL	EUR	POL
Puerto Rico	PR	LAM	PRI
Korea, Democratic People's Republic of	KP	OAS	PRK
Portugal	PT	EUR	PRT
Paraguay	PY	LAM	PRY
Palestine, State of	PS	MEA	PSE
French Polynesia	PF	OAS	PYF
Qatar	QA	MEA	QAT
Reunion	RE	SSA	REU
Romania	RO	EUR	ROU
Russian Federation	RU	REF	RUS
Rwanda	RW	SSA	RWA
Saudi Arabia	SA	MEA	SAU
Sudan	SD	MEA	SDN
Senegal	SN	SSA	SEN
Singapore	SG	OAS	SGP
South Georgia and the South Sandwich Islands	GS	LAM	SGS
Saint Helena, Ascension and Tristan da Cunha	SH	SSA	SHN
Svalbard and Jan Mayen	SJ	NEU	SJM
Solomon Islands	SB	OAS	SLB
Sierra Leone	SL	SSA	SLE
El Salvador	SV	LAM	SLV
San Marino	SM	NEU	SMR
Somalia	SO	SSA	SOM
Serbia	RS	NEU	SRB
South Sudan	SS	SSA	SSD
Sao Tome and Principe	ST	SSA	STP
Suriname	SR	LAM	SUR
Slovakia	SK	EUR	SVK
Slovenia	SI	EUR	SVN
Sweden	SE	EUR	SWE
Swaziland	SZ	SSA	SWZ
Sint Maarten (Dutch part)	SX	LAM	SXM
Seychelles	SC	SSA	SYC
Syrian Arab Republic	SY	MEA	SYR
Turks and Caicos Islands	TC	LAM	TCA
Chad	TD	SSA	TCD
Togo	TG	SSA	TGO
Thailand	TH	OAS	THA
Tajikistan	TJ	REF	TJK

Turkmenistan	TM	REF	TKM
Timor-Leste	TL	OAS	TLS
Tonga	TO	OAS	TON
Trinidad and Tobago	TT	LAM	TTO
Tunisia	TN	MEA	TUN
Turkey	TR	MEA	TUR
Tuvalu	TV	OAS	TUV
Taiwan, Province of China	TW	CHA	TWN
Tanzania, United Republic of	TZ	SSA	TZA
Uganda	UG	SSA	UGA
Ukraine	UA	REF	UKR
United States Minor Outlying Islands	UM	OAS	UMI
Uruguay	UY	LAM	URY
United States	US	USA	USA
Uzbekistan	UZ	REF	UZB
Holy See (Vatican City State)	VA	NEU	VAT
Saint Vincent and the Grenadines	VC	LAM	VCT
Venezuela, Bolivarian Republic of	VE	LAM	VEN
Virgin Islands, British	VG	LAM	VGB
Virgin Islands, U.S.	VI	LAM	VIR
Viet Nam	VN	OAS	VNM
Vanuatu	VU	OAS	VUT
Wallis and Futuna	WF	OAS	WLF
Samoa	WS	OAS	WSM
Yemen	YE	MEA	YEM
South Africa	ZA	SSA	ZAF
Zambia	ZM	SSA	ZMB
Zimbabwe	ZW	SSA	ZWE
Kosovo	XK	EUR	XKX
Rest of the world	RoW	CAZ	#N/A
Europe	RER	EUR	#N/A
Northern America	RNA	USA	#N/A
Latin America	RLA	LAM	#N/A
Africa	RAF	SSA	#N/A
Asia	RAS	OAS	#N/A
Oceania	UN-OCEANIA	CAZ	#N/A
World	GLO	World	#N/A

Appendix C: Life cycle GHG emissions per material/component in KBOB linked with ecoinvent v3.6 and with ecoinvent v3.6 incorporating global electricity system decarbonization from different SSP scenarios

New Construction /Retrofit	Index	Material/ Components	Material/Components displayed name in figures	Unit	Life cycle GHG emissions / unit			
					KBOB linked with ecoinvent v3.6	KBOB SSP2-Base_2030	KBOB SSP2-Base_2040	KBOB SSP2-Base_2050
New construction	N1	Concrete	concrete for building construction (no reinforcement)	kg	9.49E-02	9.72E-02	9.66E-02	9.63E-02
	N2	Concrete	precast concrete, standard	kg	1.67E-01	1.69E-01	1.68E-01	1.67E-01
	N3	Steel, reinforcing	reinforcing steel, secondary production	kg	7.12E-01	6.36E-01	6.37E-01	6.48E-01
	N4	Steel, reinforcing	reinforcing steel, primary production	kg	2.20E+00	2.11E+00	2.11E+00	2.11E+00
	N5	Brick	brick, unspecified	kg	2.59E-01	2.53E-01	2.53E-01	2.54E-01
	N6	Aluminium	primary aluminium	kg	9.59E+00	1.11E+01	1.07E+01	1.05E+01
	N7	Aluminium	aluminium wrought alloy	kg	1.31E+01	9.91E+00	9.65E+00	9.34E+00
	N8	Aluminium	aluminium cast alloy	kg	5.41E+00	4.17E+00	4.06E+00	3.94E+00
	N9	Aluminium	aluminium recycled from aluminium scrap, new	kg	6.24E-01	5.53E-01	5.46E-01	5.40E-01
	N10	Aluminium	aluminium recycled from aluminium scrap, post-consumer	kg	9.09E-01	8.17E-01	8.09E-01	8.02E-01
	N11	Stainless steel	chrome steel sheet blank	kg	2.25E+00	2.03E+00	2.02E+00	2.02E+00
	N12	Float glass	float glass	kg	1.18E+00	1.14E+00	1.15E+00	1.15E+00
	N13	Natural stones	natural stone plate, polished, Europe, 15 mm	m2	2.86E+01	2.36E+01	2.31E+01	2.27E+01
	N14	Softwood, solid	sawnwood, softwood (u=10%)	kg	2.48E-01	2.10E-01	2.07E-01	2.05E-01
	N15	Plywood, softwood	plywood, indoor use	kg	9.32E-01	8.69E-01	8.68E-01	8.74E-01
	N16	Oriented strand board (OSB) panel	oriented strand board	kg	7.08E-01	6.34E-01	6.33E-01	6.37E-01
	N17	Fibreboard, soft	fibreboard, soft	kg	5.76E-01	5.47E-01	5.39E-01	5.39E-01
	N18	Gypsum panel	gypsum fibre board	kg	5.24E-01	5.22E-01	5.22E-01	5.22E-01
Retrofit	R1	Windows	window frame, aluminium	m2	6.00E+02	4.87E+02	4.78E+02	4.69E+02
	R2	Windows	window frame, wood	m2	1.74E+02	1.49E+02	1.48E+02	1.48E+02
	R3	Windows	window frame, wood-aluminium	m2	3.27E+02	2.70E+02	2.67E+02	2.64E+02
	R4	Windows	window frame, PVC	m2	3.31E+02	2.92E+02	2.91E+02	2.90E+02
	R5	Insulation material	foam glass	kg	1.78E+00	1.43E+00	1.40E+00	1.37E+00
	R6	Insulation material	rock wool	kg	1.09E+00	1.11E+00	1.10E+00	1.10E+00
	R7	Cement motar	cement motar	kg	2.09E-01	2.13E-01	2.12E-01	2.11E-01
	R8	PV system	PV system, multi-Si, slanted-roof BAPV	unit	6.54E+03	4.99E+03	4.91E+03	4.83E+03
	R9	PV system	PV system, mono-Si, slanted-roof BAPV	unit	7.60E+03	5.66E+03	5.56E+03	5.46E+03
	R10	PV system	PV system, a-Si, BIPV	unit	4.83E+03	3.58E+03	3.51E+03	3.46E+03
	R11	PV system	PV system, CdTe, BIPV	unit	4.28E+03	3.38E+03	3.31E+03	3.23E+03

New Construction /Retrofit	Index	Material/ Components	Material/Components displayed name in figures	Unit	Life cycle GHG emissions / unit					
					KBOB SSP2-NDC_2030	KBOB SSP2-NDC_2040	KBOB SSP2-NDC_2050	KBOB SSP2-PkBudg900_ 2030	KBOB SSP2-PkBudg900_ 2040	KBOB SSP2-PkBudg900_ 2050
New construction	N1	Concrete	concrete for building construction (no reinforcement)	kg	9.44E-02	9.36E-02	9.30E-02	9.19E-02	9.08E-02	9.09E-02
	N2	Concrete	precast concrete, standard	kg	1.58E-01	1.55E-01	1.52E-01	1.50E-01	1.46E-01	1.46E-01
	N3	Steel, reinforcing	reinforcing steel, secondary production	kg	5.21E-01	4.72E-01	4.46E-01	4.51E-01	3.99E-01	4.00E-01
	N4	Steel, reinforcing	reinforcing steel, primary production	kg	2.04E+00	2.00E+00	1.98E+00	1.99E+00	1.94E+00	1.93E+00
	N5	Brick	brick, unspecified	kg	2.44E-01	2.41E-01	2.39E-01	2.39E-01	2.35E-01	2.35E-01
	N6	Aluminium	primary aluminium	kg	9.29E+00	8.17E+00	7.41E+00	7.34E+00	4.80E+00	4.37E+00
	N7	Aluminium	aluminium wrought alloy	kg	8.57E+00	7.27E+00	6.80E+00	6.33E+00	4.82E+00	4.39E+00
	N8	Aluminium	aluminium cast alloy	kg	3.61E+00	3.10E+00	2.92E+00	2.75E+00	2.15E+00	1.99E+00
	N9	Aluminium	aluminium recycled from aluminium scrap, new	kg	4.86E-01	4.53E-01	4.38E-01	4.47E-01	4.08E-01	4.06E-01
	N10	Aluminium	aluminium recycled from aluminium scrap, post-consumer	kg	7.35E-01	6.90E-01	6.70E-01	6.85E-01	6.32E-01	6.29E-01
	N11	Stainless steel	chrome steel sheet blank	kg	1.81E+00	1.69E+00	1.63E+00	1.64E+00	1.49E+00	1.48E+00
	N12	Float glass	float glass	kg	1.09E+00	1.06E+00	1.05E+00	1.05E+00	1.02E+00	1.02E+00
	N13	Natural stones	natural stone plate, polished, Europe, 15 mm	m2	1.84E+01	1.48E+01	1.30E+01	1.44E+01	9.99E+00	9.68E+00
	N14	Softwood, solid	sawnwood, softwood (u=10%)	kg	1.83E-01	1.62E-01	1.52E-01	1.63E-01	1.38E-01	1.36E-01
	N15	Plywood, softwood	plywood, indoor use	kg	7.66E-01	7.20E-01	6.96E-01	6.99E-01	6.50E-01	6.50E-01
	N16	Oriented strand board (OSB) panel	oriented strand board	kg	5.74E-01	5.45E-01	5.31E-01	5.36E-01	5.05E-01	5.05E-01
	N17	Fibreboard, soft	fibreboard, soft	kg	4.69E-01	4.42E-01	4.25E-01	4.10E-01	3.77E-01	3.78E-01
	N18	Gypsum panel	gypsum fibre board	kg	5.21E-01	5.20E-01	5.20E-01	5.20E-01	5.19E-01	5.19E-01
Retrofit	R1	Windows	window frame, aluminium	m2	4.29E+02	3.81E+02	3.62E+02	3.47E+02	2.91E+02	2.77E+02
	R2	Windows	window frame, wood	m2	1.28E+02	1.15E+02	1.09E+02	1.10E+02	9.57E+01	9.42E+01
	R3	Windows	window frame, wood-aluminium	m2	2.31E+02	2.05E+02	1.94E+02	1.90E+02	1.59E+02	1.54E+02
	R4	Windows	window frame, PVC	m2	2.61E+02	2.41E+02	2.32E+02	2.38E+02	2.15E+02	2.14E+02
	R5	Insulation material	foam glass	kg	1.24E+00	1.06E+00	9.67E-01	9.52E-01	7.10E-01	6.64E-01
	R6	Insulation material	rock wool	kg	1.07E+00	1.05E+00	1.04E+00	1.03E+00	1.01E+00	1.01E+00
	R7	Cement motar	cement motar	kg	2.06E-01	2.03E-01	2.01E-01	1.99E-01	1.96E-01	1.96E-01
	R8	PV system	PV system, multi-Si, slanted-roof BAPV	unit	3.99E+03	3.22E+03	2.87E+03	3.15E+03	2.26E+03	2.16E+03
	R9	PV system	PV system, mono-Si, slanted-roof BAPV	unit	4.39E+03	3.40E+03	2.95E+03	3.38E+03	2.24E+03	2.12E+03
	R10	PV system	PV system, a-Si, BIPV	unit	2.88E+03	2.30E+03	2.03E+03	2.20E+03	1.48E+03	1.37E+03
	R11	PV system	PV system, CdTe, BIPV	unit	2.75E+03	2.29E+03	2.11E+03	2.18E+03	1.69E+03	1.64E+03

Basic and recommendations on electricity mix models and their application in buildings LCA

A Contribution to IEA EBC Annex 72

February 2023

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A Contribution to IEA EBC Annex 72

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of the project IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations on aggregation and communication of building LCA assessment results (Gomes et al. 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

The evolution of electricity systems is one of the key issues to progress towards net zero GHG emissions, as shown in the IEA roadmap for the global energy sector[1]. Because a large part of the produced electricity is consumed in buildings, and because electricity consumption is an important contributor in life cycle impacts of buildings, it is essential to properly account for the electricity system when performing a Building LCA.

This document was written for method and tool developers, and policy makers (regulation). Existing (official and individual) approaches in different countries are first reviewed. Users are invited to follow the recommendations provided by the developers (e.g. certification scheme, design tools). Some of the recommendations are case specific. We propose to distinguish the following four cases:

a. Assessments against benchmarks defined by voluntary certification schemes and regulation
b. Environmental reporting of facility management companies and assessment of private lifestyles:
c. LCA in building design tools (building optimisation independent of voluntary schemes or regulation)
d. LCA in building research

These recommendations address electricity related impacts. Methodological choices should be consistent across energy sources. Thus, the following recommendations should be applied on fuels as well. For instance, if a future renewable scenario is applied for electricity production, the same level of ambition should preferably be applied for gas (future supply with biogas and/or synthetic gases produced with biogenic carbon and renewable electricity) and liquid fuels.

Even if it is sometimes difficult to express recommendations that are relevant in all situations, this document explains the choices made in different contexts. The following Table 2: Synthesis tabl an overview of the recommendations. To ensure transparency in LCA results, the assessment method of electricity related emissions must be described by indicating clearly the corresponding methodological choices.

Table S: Synthesis of the 10 recommendations. "Gray" indicates than no specific choice is recommended.

Type of choice	Application cases			
	Regulation/ certification	Design tool	Facility assessment	Research
1_Generic vs provider-specific electricity mix	generic	generic	specific	
2_Geographic scope	national	national	national	
3_Production mix vs supply mix	supply mix	supply mix	supply mix	
4_Nature of trade flows	commercial or physical flows, explain the choice			
5_Modelling choice for the supply mix	production-export+import or production+import, explain the choice			
6_End uses dependence	universal if same temporal variation in buildings as national consumption, use-specific recommended otherwise (e.g. winter peak demand for heating)			
7_Time dimension	present, near future or long-term future mix, explain the choice			
8_LCA modelling approach	average, short-term marginal or long-term marginal, explain the choice			
9_Time granularity	annual or hourly, explain the choice			

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[1] IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

Annexes present in more detail models corresponding to different temporal resolution (from hourly to annual), models used in national methods, example methodological choices in various tools, and models for local renewable electricity production (particularly photovoltaics).

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Abbreviations

Abbreviations	Meaning
ADEME	Agency for energy management and environment (France)
AIB	Association of Issuing Bodies
BAU	Business As Usual scenario
BIPV	Building Integrated Photovoltaics
BREEAM	Building Research Establishment Environmental Assessment Method
BWR	Boiling Water Reactor technologies
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
DGNB	German Sustainable Building Council
DHW	Domestic Hot Water
EAM	European attribute mix
EEMM	European Electricity Market Model
EKZ	Energy company for the canton of Zurich
ELCAB	Electricity in Life Cycle Assessments of Buildings
ENTSO-E	European Network of Transmission System Operators for Electricity
GHG	Greenhouse Gas
GOs	Guarantees of Origin
HP	Heat Pump
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
NEP	Energy policies
NRE	Non-Renewable Primary Energy
NVEs	Norwegian Energy Regulatory Authority
POM	Political Measures
PV	Photovoltaic
PWR	Pressurized Water Reactor
RE	Renewable Primary Energy
RE-DISS	Reliable disclosure systems for Europe
REKK	Regional Centre for Energy Policy Research
RSP	Renewable Portfolio Standard
RTE	French Transmission System Operator
SFOE	Swiss Federal Office for Energy
TMY	Typical Meterorological Years
TSO	Transmission System Operators
Abbreviations	Meaning

UCTE	Union for the Co-ordination of Transmission of Electricity
WWB	Business as usual
ZEB	Zero-Emission Buildings

Definitions

Electricity production mix: % of different processes from which electricity is produced. For instance the global world electricity production mix in 2020 is[2] : 35% coal, 29% renewables, 23% gas, 10% nuclear and 3% others.

Electricity supply mix: % of different processes from which supplied electricity is produced.

Specific mix: supply mix of a specific electricity provider

Generic mix: average supply mix of all electricity providers

Use-specific mix: supply mix for a specific use (e.g. heating, cooling, lighting…)

Universal mix: average supply mix for all uses

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[2] https://www.iea.org/data-and-statistics/charts/global-electricity-generation-mix-2010-2020

1. Introduction

The evolution of electricity systems is one of the key issues to progress towards net zero GHG emissions, as shown in the IEA roadmap for the global energy sector[3]. Because a large part of the produced electricity is consumed in buildings, it is useful to address related models in the Annex 72 methodology reports.

Electricity consumption during the operation of buildings is one important factor determining the environmental impacts, greenhouse gas emissions and primary energy demand during its life cycle. The assessment of one, rather energy efficient, building with electricity being the only energy carrier consumed during its operation by several research organisations using their respective national method revealed two things: firstly, the operation phase contributes at least one third to the total greenhouse gas emissions; secondly, the differences in life cycle greenhouse gas emissions vary by a factor of more than 5 (see **Error! Reference source not found.** and report of activity 1.2,Frischknecht et al. 2019).

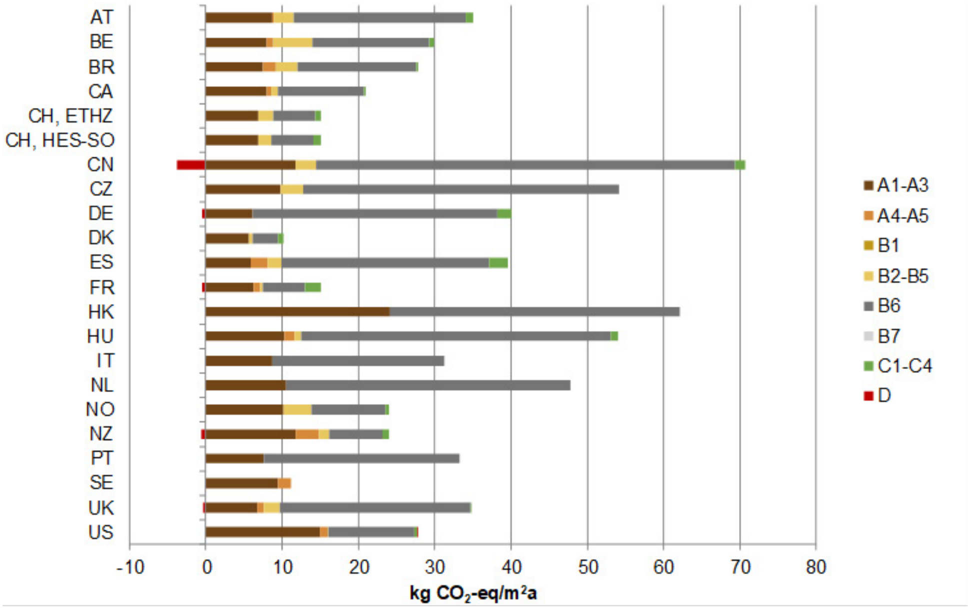

Figure 1: Greenhouse gas emissions in kg CO_2-eq. per m^2 and year of the reference building "be2226" assessed according to the national/regional approaches of the countries listed,Frischknecht et al. 2019.

The provenience and the technologies used to generate the electricity are key determining factors for the greenhouse gas intensity of electricity. That is why it is considered very important to choose the most appropriate electricity model in the life cycle assessment of buildings.

Temporal variation of the electricity production mix and related impacts may be large in some countries. For instance, in France CO_2 emissions are higher during peak demand due to the operation of thermal power plants during these periods. **Error! Reference source not found.** (Roux et al. 2016b) shows the difference in environmental impacts per m^2 and year of electricity use in a so called "plus energy house" when applying an hourly mix (plain line) and a yearly average mix method (dotted line), respectively in the case of electric space heating (a) and all uses including a PV production (b). Compared to modelling electricity supply on a yearly average basis, an hourly based electricity mix increases the space heating related CO_2 emissions of the building per m^2 and year by 20% in graph a) and the whole electricity related emissions with PV production by 40% in graph b). The difference is more pronounced with building integrated PV because more PV

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[3] IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

electricity is produced than consumed in summer and the excess production is fed into the grid (which potentially gives rise for avoided emissions[4]) and more electricity is consumed than produced in winter and the greenhouse gas emission intensity of the avoided electricity mix during summer is lower than that of the consumption during winter.

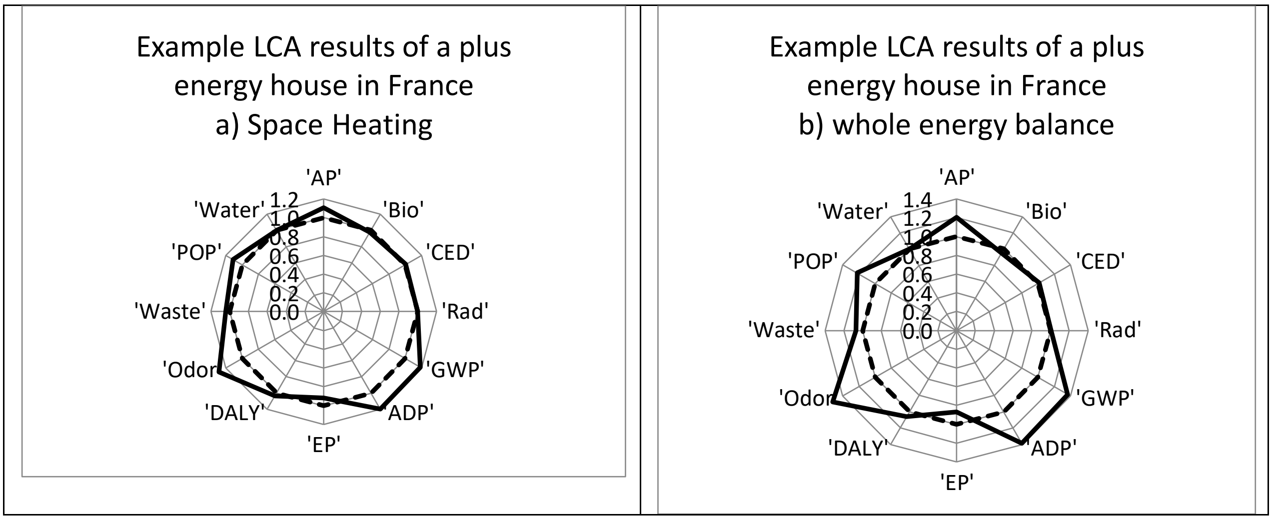

Figure 2: Impacts of electricity use in a Plus energy house in France (Roux et al. 2016b), Comparison between an hourly mix (plain line) and a yearly average mix method (dotted line)

Considering an average or a longterm marginal electricity mix may also have a large influence on the resulting environmental impacts of a building, e.g. the carbon footprint of a house comparing electric and natural gas heating as shown in **Error! Reference source not found.** (Roux et al. 2016a). Two aspects are varied and combined into four future scenarios: climate change (temperature rise; 1 and 2) and legal framework (A and B): Climate change is more severe in scenarios 1 than in scenarios 2, A corresponds to business as usual and B to more renewables and carbon tax.

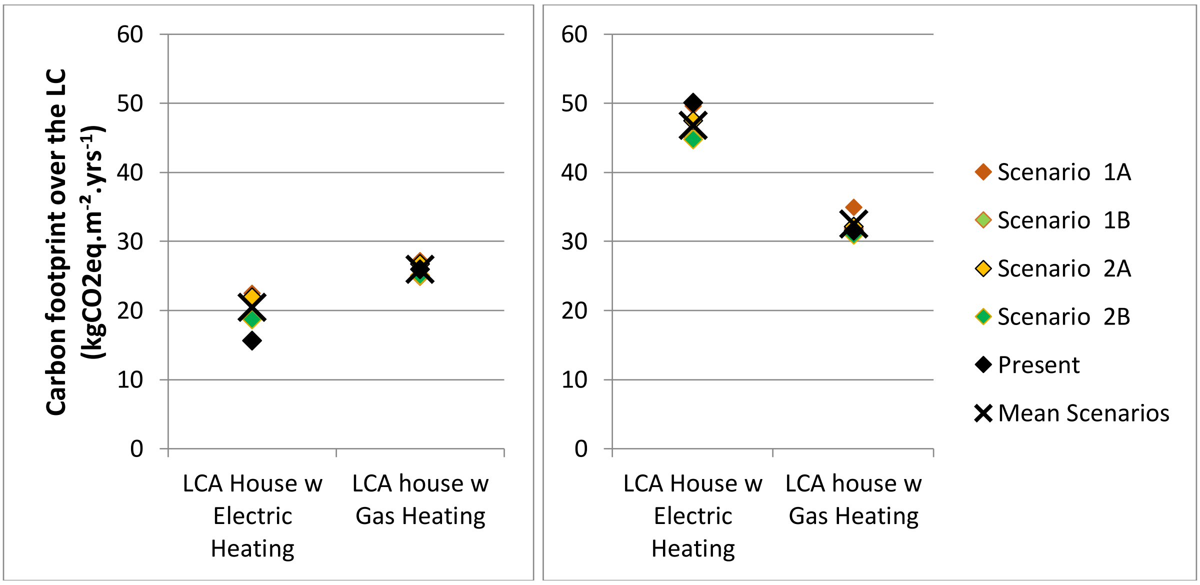

Figure 3: CO2 emissions of a house considering natural gas or electricity alternatives for space and water heating (Roux et al. 2016a), using an attributional (left) or a consequential approach (right)

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[4] This is one possible modelling option, see Chapter XXX on « exported energy » for a discussion on the various approaches.

In this case, the choice between attributional or consequential LCA reverts the ranking of the alternatives and thus may change the decision between natural gas and electric heating. The choice of one particular long term scenario has less influence on the emission intensity and no influence on the ranking.
The question of long term technology development occurs with material manufacture (including resource extraction), technical performance of building elements such as windows or photovoltaic panels and fuel supply chains and finally electricity mix and power plant performance. This chapter focuses on modelling the electricity mix during the operation of buildings. That is why technology developments in other fields related to buildings are not covered in this chapter.

The background report is structured as follows: In Chapter **Error! Reference source not found.** an overview of main questions related to the design of buildings are listed. Chapter **Error! Reference source not found.** contains the state of art of scope dependent modelling electricity mix in the operation phase of buildings in different countries. Chapter 4 contains a description of the proposed harmonised approach for each of the five questions and Chapter **Error! Reference source not found.** contains illustrations of the proposed scope dependent harmonised approaches. In Annex A in Chapter 0, the different basic types of electricity mixes are explained and Annex B in Chapter 0 contains descriptions of the most recent national electricity mixes according to the typology described in Annex A.

2. Status of Discussion and Questions

The considerations in this Chapter are limited to the question of the electricity mix appropriate to be used in the environmental assessment of buildings. Hereby it is proposed to distinguish the following application oriented questions:

1. Quantify the environmental impacts of a building and compare it to national benchmark values (in view of certification or labelling) – based on conventions/agreements (Special case: proof/certification of (net) zero GHG emission buildings)

2. Quantify the environmental impacts of different alternatives for a given building specification and use this information to select and build one of the alternatives.

3. Identify the optimum (minimum) environmental impacts of construction and dismantling of the building on one hand and operation of the building on the other (trade off).

4. Assess whether to act now or to wait for better (less electricity consuming) technologies based on a comparison of the environmental performance of different options.

5. Calculation of environmental payback time in the case of investment measures which lead to reduced electricity demand in the use phase (electricity demand in operation or maintenance).

We did not identify research work on nor applications answering questions 4 and 5. We therefore do not address them in this report.

3. Existing (official and individual) Approaches in Different Countries

3.1 Introduction

Environmental life cycle assessment is applied on buildings and provides answers to the different questions listed in Chapter **Error! Reference source not found.**. In this subchapters the state of application of environmental assessments of buildings in different countries is described, grouped according to the five main questions identified.

3.2 Benchmarking for Buildings

3.2.1 Denmark

In current building code, only the operational phase of buildings is considered. However, the building authorities have introduced a voluntary sustainability class, including requirements for LCA of buildings. It was implemented as a set of voluntary requirements in May 2020, and which are planned to be implemented as a part of the building code in January 2023. In order to prepare for the introduction of LCA in the building code, development of an LCA tool for buildings was initiated by the authorities. Thus the national tool, LCAbyg has been developed and several analyses have been and are being performed in order to develop benchmarks.

The LCA benchmarks for buildings that are alrady in use in Denmark relates to DGNB certification. DGNB has been used in Denmark since 2012. From the beginning, an Excel tool developed by the Danish Building Research Institute was used for performing LCA, applying static energy approach for the operational energy. The final results from the tool were based on a combination of two reference study periods:

a. 50 years calculating both embodied impacts and impacts related to the operational energy. The results weighting 70% of the final result.

b. 80-120 years calculating only the embodied impacts. The results weighing 30% of the final result.

In year 2015, the LCAbyg tool was released in order to prepare for the voluntary sustainability class in the building code, and since 2018, DGNB certifications can be performed with either the Excel tool (and the RSP and energy approach described above) and LCAbyg (with RSP and energy approach described below). The aim is that LCA for future DGNB certifications will be performed in LCAbyg and according to similar methods and requirements as introduced in the voluntary sustainability class.
For several years, the recommended reference study period for building LCA in Denmark has been from 80 to 120 years depending on the building type (Aagaard et al. 2013). **Error! Reference source not found.** shows the reference values for the embodied GHG emissions, according to DGNB 2018. The voluntary sustainability class has introduced the use of a reference study period of 50 years, and the DGNB will use the same in the newest update of DGNB 2020 manual by the end of 2020. The voluntary sustainability class introduced in May 2020 does not include reference values. However, the necessary analysis to prepare for the possibility to include benchmarks have been conducted and published (Zimmermann et al., 2020). Here, reference values for both embodied and operational impacts together and separated have been calculated. DGNB will be using these analyses to prepare updated reference values for the DGNB 2020 manual.

Table 1: RSP and reference values for LCA in DGNB, when LCAbyg is used for certification in DGNB 2018 manual (Rasmussen & Birgisdottir 2018; Rasmussen et al. 2019)

		Reference values (GHG emissions)	
New buildings	RSP (years)	Construction	Operation
Modules according to EN 15978		A1-A3, B4, C1-C4	B6
Residential buildings	120	6,0 kg CO_2/m^2/year	The reference values for B6 is dynamic and depending on both building type and building specific supplementary demand. In addition, the emissions are based on a forecasting scenario for the future electricity supply.
Office buildings	80	5,3 kg CO_2/m^2/year	

The building code determines the energy requirements for buildings, which differentiate by building type. By regulation, some buildings are allowed an additional supplementary demand. The supplement is assigned for buildings with e.g. extended in-use hours, extra lighting and/or ventilation demand and extra floor height. The data for the environmental impacts of the operational energy in LCAbyg represent the Danish energy grids and includes data for the average Danish electricity production, district heating and natural gas for heating, which were developed for LCAbyg (COWI 2016, COWI 2020). LCAbyg allows the user to choose between the use of static energy data based on dataset from year 2015 and forecasting of electricity and district heating according to the political goals until year 2050 (Birgisdottir & Rasmussen 2019). The forecasting scenario is based on estimation of the expected development of the energy composition in 5 data points (2015, 2020, 2025, 2035 and 2050) and the corresponding expected environmental impacts (see Section 0). Use of the forecasting scenario for energy use is required when performing LCA in the voluntary sustainability class and DGNB.

Since the recommended reference study period in building LCA in Denmark has until May 2020 been from 80 to 120 years depending on building type, a building LCA scenario calculated in 2018 represents a period ending in 2098-2138. In the forecasting scenario, data for 2050 is used for the remaining years after year 2050.

Error! Reference source not found. shows the results for the greenhouse gas emissions for a typical office building calculated in LCAbyg based on the approach described above (Birgisdottir & Stenholt Madsen 2017).

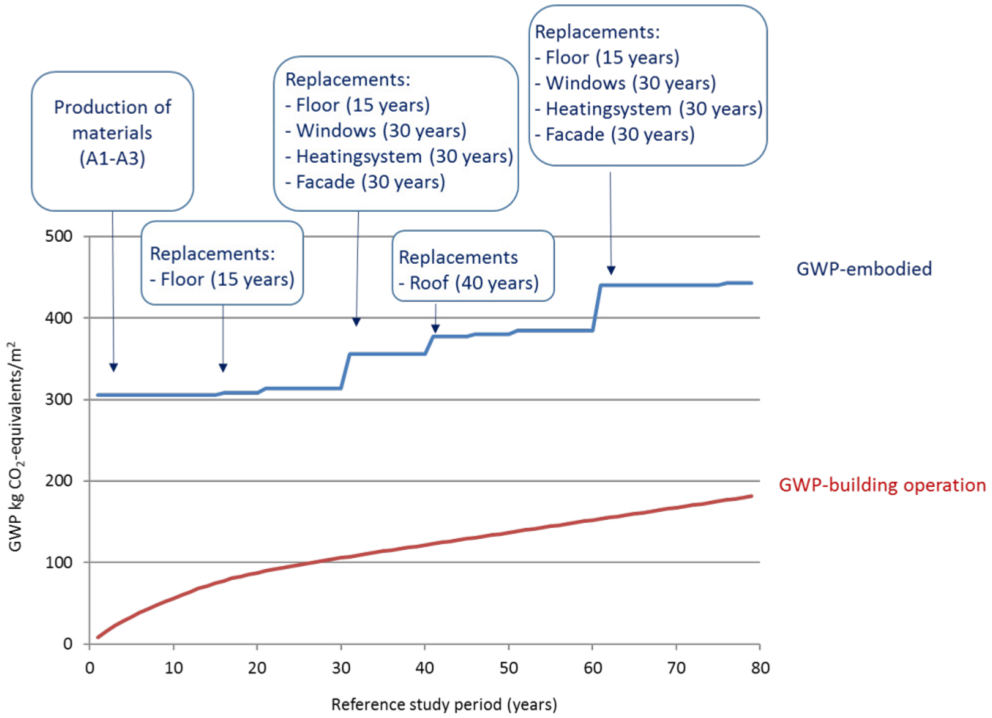

Figure 2: Greenhouse gas emissions for an office building, results accumulated over the reference study period of 80 years. Blue line showing the embodied greenhouse gas emissions (A1-A3, B4, C3-C4), red line showing the GHG emissions from the operational energy use (B6) - (Birgisdottir & Stenholt Madsen 2017)

3.2.2 France

Two main approaches were developed. One as a voluntary label in order to study the next building regulation, and one as a design tool aiming at a more science based evaluation.

In the "E+C-" label[5] which will be the basis for the next building regulation "RE 2020", a recent electricity mix is used but in order to account for the temporal variation of this mix, it is different for heating, cooling, domestic hot water, lighting and other uses, for housing and tertiary buildings. There are two benchmark levels regarding CO_2 equivalent (GHG) emissions per m^2 of building, C1 and C2, which depend on the type of building (houses, apartment buildings, offices and other buildings), the climate zone (North of France, Mediterranean coast etc.). The threshold for the next regulation is not chosen at the moment.

In the EQUER design tool, part of the Pleiades software used by 2,500 users (engineers, architects, contractors, teachers, students etc.) and approved e.g. in the BREEAM label, there are two possibilities regarding the electricity mix: one corresponds to a recent annual average electricity mix (e.g. for 2017), and the second to an hourly electricity mix model (see annex A §1.6.5). Benchmarks have been elaborated for three building types: single family houses, apartment buildings, and office buildings. There are two performance levels for each type, corresponding to the best and worst performance of the sample on each LCA indicator (per m^2 and per year), so that a designer knows how his/her project performs compared to references. Each performance level has two possible values: one corresponds to the recent annual average electricity mix, and the second to an hourly electricity mix model as the user can choose between these two options.

3.2.3 Hungary

In current building energy regulations, only the operational phase of buildings is considered. There are different primary energy requirements for residential buildings, offices, educational buildings and a reference building approach is used for other building uses. Primary energy demand is calculated using primary energy

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[5] E+C-: means: higher energy efficiency, lower CO2 emissions

factors. For electricity, there are two factors available for peak and off-peak use. These factors are not entirely based on physical flows, but also involve some political and energy strategy considerations. The next revision of the building code is in progress. It is expected that besides primary energy factors also a CO_2 emission indicator will be introduced and there is a recommendation to base these values on a life cycle approach. There is no intention, however, to include the construction phase in the short-term, although this has been recommended by researchers.

In current Hungarian LCA studies, an annual average electricity mix is used for benchmarking.

3.2.4 Switzerland

The SIA technical bulletin 2040 (SIA 2017), a voluntary standard, regulates the procedure for determining the greenhouse gas emissions and the primary energy demand, non renewable for the construction (construction, servicing and deconstruction including waste management), the operation (energy requirements for heating, hot water, ventilation, lighting and operating equipment) and the daily mobility induced by the building. For each of the three components reference values are given which serve as benchmarks. The benchmarks do not have to be met individually but help identifying where measures to improve the energy efficiency or reduce greenhouse gases are most needed. The target values for the primary energy demand, non-renewable and the greenhouse gas emissions correspond to the sum of the reference values of the three components. The SIA bulletin 2040 defines target and reference values as well as additional requirements for residential buildings, office buildings, school buildings, specialist shops, grocery shops and restaurants, both for new and retrofit buildings. Table 1 shows the greenhouse gas emission target and reference values and additional requirements for new buildings.

The modelling of the construction phase is done according to the technical bulletin SIA 2032 “Embodied energy: Life cycle assessment of the construction of buildings” (SIA 2020) and the modelling of the building induced mobility is based on the technical bulletin SIA 2039 “Mobility – energy demand in function of the building location” (SIA 2016).

Table 1 : Reference and target values for greenhouse gas emissions in kg CO_2-eq per m^2 energy reference area and year, applied on residential, office and school buildings, specialists and grocery shops as well as restaurants, both new and retrofit. Reference service life: 60 years
Additional requirement: partial sum of “construction” and “operation” shall not exceed the amounts listed in this column

New buildings	Construction	Operation	Mobility	Total	Additional requirement
Modules according to EN 15978	A1-A3, B4, C1-C4	B6	not available		A1-A3, B4, B6, C1-C4
Residential buildings	9.0	3.0	4.0	16.0	12.0
Office buildings	9.0	4.0	7.0	20.0	13.0
School buildings	9.0	2.0	3.0	14.0	11.0
Specialist shops	9.0	6.0	6.0	21.0	15.0
Grocery shops	9.0	29.0	20.0	58.0	38.0
Restaurants	9.0	10.0	24.0	43.0	19.0

The target and reference values published in the technical bulletin SIA 2040 are aligned with the 2050 milestone target of a 2000-watt society (EnergieSchweiz für Gemeinden et al. 2014a, b).

Electricity used during the operation phase of a building is modelled using the Swiss average annual supply mix, excluding renewable electricity sold with dedicated, certified electricity products. In case the electricity consumption of a building is covered with certified renewable electricity and this supply is guaranteed with longterm contracts, the environmental profile of this certified electricity may be applied on up to 50 % of the total electricity consumption of the building. For the remaining share the environmental profile of the Swiss average annual supply mix applies (SIA 2017, clause 2.3.1.4).

In situ production of electricity and electricity consumption of the building are balanced on an annual basis. In situ produced and exported electricity has the environmental impacts of the in situ production. Exported electricity does not give rise for any environmental benefits from potentially avoiding electricity production elsewhere (see also Chapter XXX on exported electricity and Chapter XXX on zero emission building definitions).

The only instance where future developments are partly taken into account is daily individual mobility: the passenger cars are supposed to have a fuel efficiency of 3 litres gasoline per 100 km, which is about half of the current specific fuel consumption (according to New European Driving Cycle) of new passenger cars registered in 2019 in Switzerland.

3.2.5 Sweden

Sweden does not currently have a fully standardized approach for building LCA. Assessments are meant to follow the standards EN 15804 and EN 15978, but there is still room for manoeuvre regarding methodological choices in building LCA. Several significant initiatives can however be noted.

First, a mandatory declaration of greenhouse gas emissions for all new buildings has been introduced in 2022 (Swedish National Board of Housing, Building and Planning, 2018). This declaration, at the time of its introduction, will be limited to the impact of the product and construction stages (modules A1-5). Currently (during Spring 2020), a new proposal is being developed, regarding the future implementation of a mandatory declaration based on a more complete LCA. However, decisions regarding which life cycle stages to include and regarding methodological choices for this LCA declaration have not yet been taken.

Second, a number of voluntary certification systems are currently used on the Swedish market. The most used certification system in Sweden is Miljöbyggnad (Sweden Green Building Council, 2017). Miljöbyggnad is not based on an LCA approach, but the latest version (3.0) includes a criterion related to the calculation of greenhouse gas emissions from the building frame for modules A1-A4. The Nordic Swan Label for Buildings (Nordic Ecolabelling, 2016) does not either include an LCA-based assessment of greenhouse gas emissions. The LEED points system rewards initiatives that carry out an LCA and initiatives that show a 10% reduction in several impact categories compared to a reference building defined by the architect. However, there are not many methodological specifications as long as the same LCA method is used for the baseline and the reference building (United States Green Building Council, 2018). The BREEAM-SE system includes an assessment of energy performance, and a separate assessment of life cycle environmental impacts limited to construction materials (BRE Global & Sweden Green Building Council, 2017). Overall, none of the certification schemes commonly used in Sweden include an assessment of greenhouse gas emissions from operational energy use.

Third, actors from the building and infrastructure industry are contributing to the national initiative “Fossile Free Sweden” (Fossilfritt Sverige[6]). This voluntary initiative entails the development of a roadmap aiming for a climate neutral building sector by 2045, as well as a harmonized life cycle-based method to assess greenhouse gas emissions from building sector companies and individual measures or projects. As of Spring 2020, discussions are ongoing regarding various methodological aspects of this upcoming common assessment method, including how to assess greenhouse gas emissions from electricity and district heating.

Finally, new and upcoming certification systems will include a more complete life cycle assessment, including greenhouse gas emissions from operational energy use. The Citylab certification system for neighbourhoods was launched at the end of 2019. It includes, among other criteria, limit values for greenhouse gas emissions from operational energy use per dwelling in residential buildings, and per m^2 heated area in other facilities (excluding lighting and office equipment) (Sweden Green Building Council, 2019). The recently introduced

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[6] http://fossilfritt-sverige.se/fardplaner-for-fossilfri-konkurrenskraft/fardplaner-for-fossilfri-konkurrenskraft-byggbranschen/

NollCO$_2$ (Zero CO$_2$) certification system includes an assessment of life cycle greenhouse gas emissions (Sweden Green Building Council, 2020). Following guidelines from the Swedish Energy Agency, the assessment of greenhouse gas emissions from electricity use in Citylab and the pilot version of NollCO$_2$ is based on a yearly Swedish electricity mix, calculated following the method of the EU Joint Research Center (JRC) (Moro & Lonza, 2018). The original JRC calculation was based on values for 2013. In NollCO$_2$, the JRC method is used to calculate updated emission factors for electricity, for the year 2018. In a previous pilot version of NollCO$_2$, the assessment was meant to be based on a hourly Nordic electricity mix instead.

3.3 Comparison of Alternative Concepts (e.g. architectural competition)

3.3.1 Denmark

Alternatives can be compared with LCAbyg, by using static energy approach vs. forecasting (for electricity and district heating), and by looking into the consequences of different energy supply for heating (district heating, natural gas, electricity). Figure 1 shows an example where calculations of the consequenses of using static vs. forecasting approach for both electricity and district heating have been calculated in a report about embodied energy and GHG emissions (Birgisdottir & Stenholt Madsen 2017).

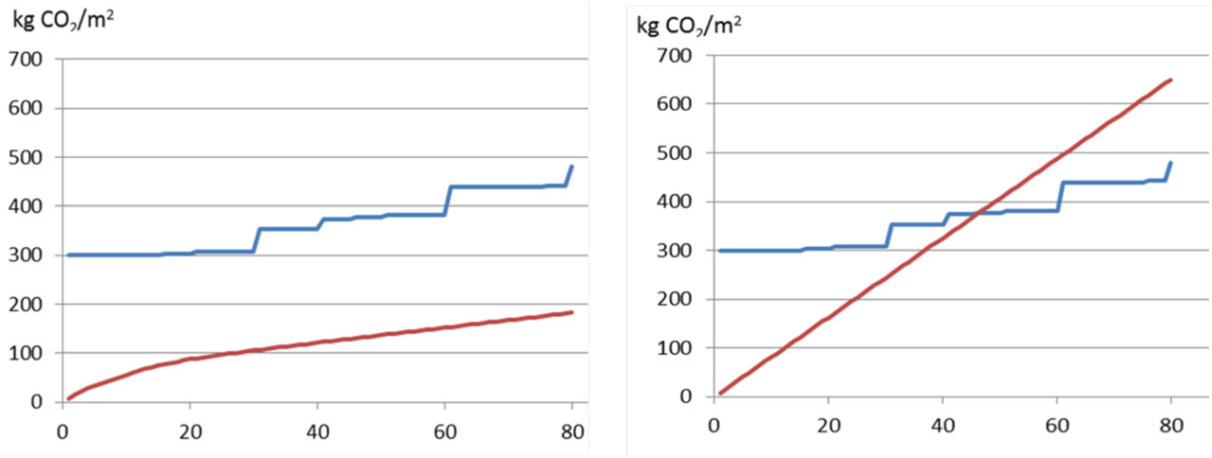


Figure 1: Embodied GHG emissions for an office building calculated over 80 years reference study period using forecasting scenario vs. static energy approach (Birgisdottir & Stenholt Madsen 2017).

If comparisons of alternatives are performed, they are most probably done in relation to DGNB certification or in research projects. However, there are no known documented examples of comparisons of alternative concepts for energy scenarios.

3.3.2 France

Alternatives can be compared either using the E+C- scheme (present electricity mix according to the building type and use of electricity) or the EQUER model (considering an annual average or an hourly model), see benchmark.

3.3.3 Hungary

Alternatives are generally compared using a recent annual average electricity mix. In architectural competitions, application of a LEED/Breeam rating scheme is sometimes required.

3.3.4 Switzerland

The technical bulletin SIA 2040 “SIA energy efficiency path” offers a calculation device for the early design stage which is being used to assess alternative concepts, for example submitted in an architectural competition. Hence the methodology specified in the technical bulletin SIA 2040 is also applied in comparisons, which implies that it is common practice to apply the average annual Swiss supply mix in comparisons of alternative concepts and architectural competitions.

Yet, depending on the context of use, other modelling approaches of the electricity mixes can also be relevant. In that context, two application cases are presented below to illustrate the influence of alternative modelling approaches for the comparison of design alternatives:

- Use of the current average annual Swiss supply mix (SIA 2040 approach) vs. the use of longterm consequential & residual mixes
- Use of the current average annual Swiss supply mix (SIA 2040 approach) vs. the use of an hourly Swiss supply mix

Application case 1:

In a project commissioned by a Swiss municipality the question was analysed and answered about the appropriate electricity mix to be used when comparing the environmental impacts of different strategies retrofitting existing buildings. In its ordinance, the municipality adheres to the 2000 Watt and 1 ton CO_2-eq-society. The city-owned public utility is vertically integrated (owns and runs power plants and power lines) and relies heavily on renewable energy. It is recommended to apply consequential electricity mixes complementary to the traditional attributional annual average electricity mix because the traditional approach favours inefficient retrofitting solutions. Energy inefficient buildings would however counteract the efforts of reaching 2000-Watt-society goals and lead to a substantial increase in electricity demand.

The environmental assessment of the decision about the appropriate measures in a retirements home owned by a Swiss municipality has been performed using consequential (long term marginal) electricity mixes. The retirements home has a gross and energy reference area of about 10’000 m^2 and an energy demand today of 435 MJ/m^2a for space heating and 50 MJ/m^2a for hot water supply. In a retrofitted state (new triple glazed windows, insulation of rooftop, façades and ground floor, ventilation with energy recovery), the energy demand is 68 MJ/m^2a for space heating, 50 MJ/m^2a for hot water supply and 10 MJ/m^2a electricity for ventilation. Electricity demand for further equipment (lighting, elevators) is disregarded for the sake of simplicity.

The climate change impact as well as the overall environmental impacts differ substantially depending on the electricity mix used (see

Figure 2, Frischknecht 2016). It shows that the solution of just replacing the heating system (from district heat to a heat pump operated with green electricity, the standard electricity product of this municipality) would be most beneficial, whereas retrofit solutions (substantially increasing the energy efficiency of the building) show higher impacts than the current situation. In its constitution the municipality committed itself to the 2’000 Watt society and a 1 ton CO_2-society, goals which are out of reach if the buildings are not refurbished, including an increase in their energy efficiencies. The utility of the municipality forecasted its electricity production and supply volume in 2050. The different scenarios show that natural gas fired power plants will be used in case the annual electricity demand is higher than the production capacity of renewables available.

Hence, favouring low energy efficiency building solutions contradicts the overarching goal of the municipality and urges the utility to purchase fossil based electricity or invest in fossil fuelled power plants. An assessment using longterm marginal electricity mixes is appropriate which shows the environmental benefits of retrofitting in comparison to solutions with just substituting the heating system.

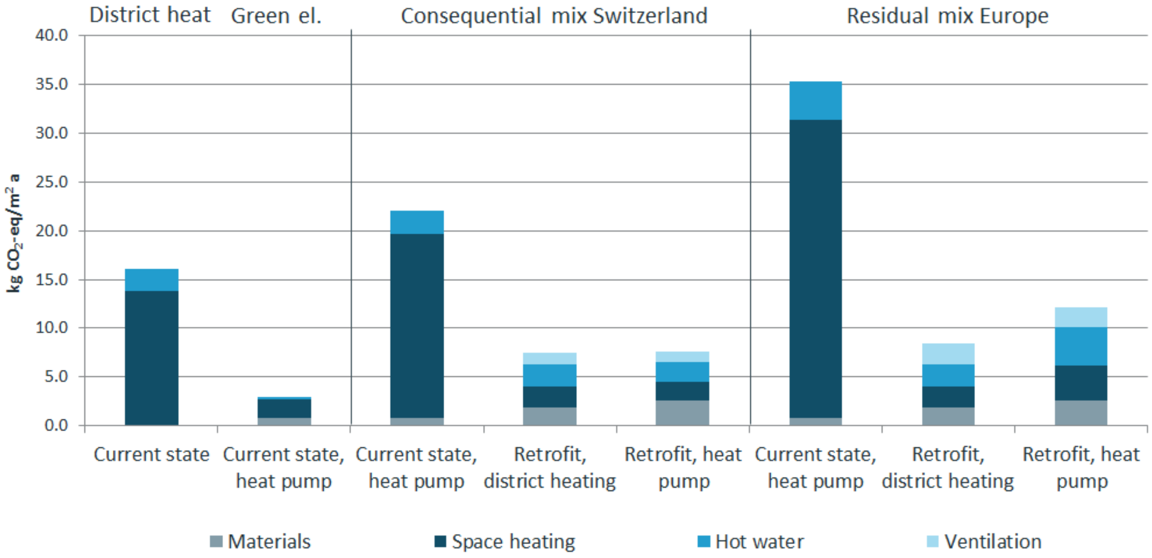


Figure 2: Greenhouse gas emissions of a retirements home in a Swiss municipality (Frischknecht & Stolz 2015), in kg CO_2-eq/m^2 and year

A similar effect can be observed when quantifying the overall environmental impacts according to the ecological scarcity method 2013 (Frischknecht & Büsser Knöpfel 2013).

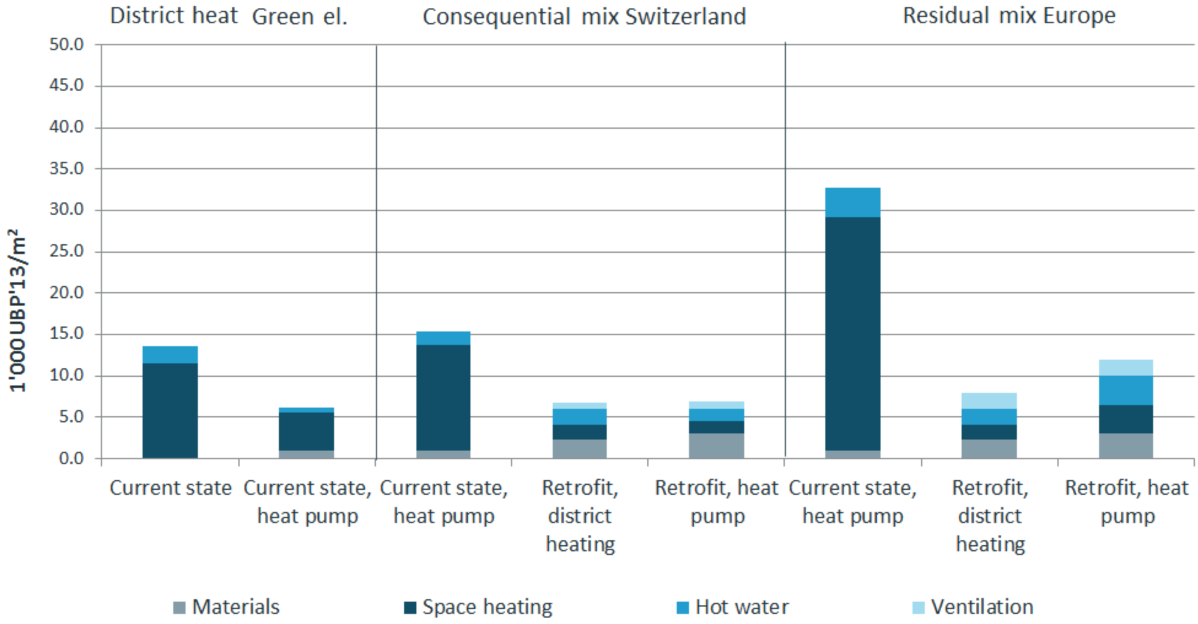


Figure 3: Overall environmental impact of a retirements home in a Swiss municipality (Frischknecht & Stolz 2015), in UBP/m^2 and year, ecological scarcity method 2013 (Frischknecht & Büsser Knöpfel 2013)

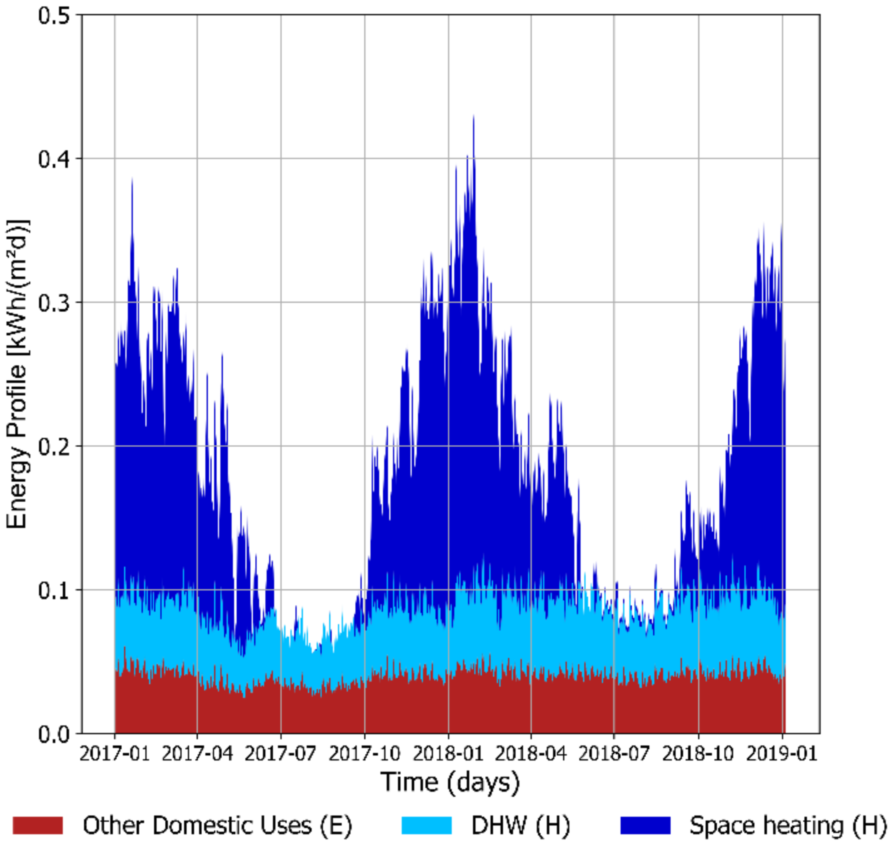
Application case 2:

The case study is based on the results of the EcoDynBat research project funded by the Swiss Federal Office of Energy in 2018-2020. It aims at assessing the influence of the various intra-annual time steps of the environmental impact of the energy demand in the Swiss buildings (i.e., monthly, daily and hourly time steps).

Background research question & motivations:
The methodology for the electricity mixes in buildings specified in the technical bulletin SIA 2040 is used for both benchmarking purpose[7] and comparisons of design alternatives. In each of these contexts, it is a common practice to apply the average annual Swiss supply mix according to the KBOB 2009/1:2016 data. However, such approach does not provide the carbon emissions at a higher time resolution of the year (month, day or hour). Such approach may however be relevant to compare different energy supply for buildings (decentralized or from the grid). For the supplied electricity mix, in winter a substantial share of electricity is imported from Germany to fulfil the demand. It is thus important to know the level of “carbon” emissions in the electricity used in Swiss buildings (e.g., to cover the space heating) at each hour, day and month of the year.

A preliminary study, focusing on the determination of the hourly Swiss supply mix, already showed the high variability of the hourly GHG emissions during the year[8]. In order to obtain this hourly profile, the electricity mix has been calculated with a matrix-based computational approach considering the physical flows for the mix calculation and gross cross boarder exchanges (see description in the section 1.7.5), leading to significantly different results than the actual reference values used in the SIA 2040 technical bulletin in Switzerland.

Then these hourly electricity mixes with different time steps have been applied to different building case studies in order to check the LCA results of the electricity used. To do so, a multi-family building composed of 20 apartments is used as an exemplary case study. The electricity mix data is based on the 2017 and 2018 years. Building measurements were taken every hour, for the energy consumption of the 20 apartments and more specifically for the energy of the heating system (kWh), the total energy (kWh), the electricity (kWh) and the domestic hot water - DHW (L). The energy profile is given in the Figure 4:



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[7] See the details in section 1.3.2, Switzerland

[8] cf. **Figure 20** page 46 page where the GHG emissions of the Swiss supply mix are presented for different time steps is presented

Figure 4: Swiss MFH consumption profile considered for the EcoDynBat case study

Based on this energy demand profile, four scenarios were considered, **Table 2**:

Scenario	**Heat pump**	**District heating network**	**PV**		**Grid Electricity**	Time step
			Yes	**No**		
Reference		Heatingt & DHW		■	■	Annual, monthly, daily, hourly
B		Heatingt & DHW	■		■	
C	Heating & DHW			■	■	
D	Heating & DHW		■		■	

Table 2: Scenario considered for the time step influence within the Swiss project EcoDynBat

The reference case corresponds to the current building situation. The energy for space heat and DHW is provided by a district heating network operated by a gas fuelled cogeneration unit. The electricity is consumed from the grid. The case B adds a photovoltaic (PV) installation of 21kWp to cover the entire roof surface (all other things being equal as the reference case). Thus the PV self-consumption will decrease the amount of electricity imported from the grid. The scenario C assumes the use of an air-water heat pump (HP) to supply energy for space heat and DHW. For each time step, the HP performances (COP) are calculated as a function of the heat source and the distribution temperatures. The electricity is taken from the grid. Finally, the scenario D uses HP but, an additional PV installation (21kWp) is added, reducing the electricity consumed from the grid.

For all scenarios, the impacts of the electricity from the grid is considered according to the method and results (for the LCA data of the electricity supply mix) presented in the chapter 1.7.5.

Table 3 presents the LCA results of scenarios A, B, C, and D for the different time steps (yearly, monthly, daily and hourly) for the following indicators:

- greenhouse gas emissions (GHG),
- non-renewable primary energy (NRE),
- Renewable Primary energy (RE)
- Total environmental impact (UBP) according to the Ecological Scarcity method 2013

Figure 5 graphically reports the relative time step influence on the GHG emissions for the four scenarios[9].

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[9] Relative time step influence is calculated by comparing the hourly, daily and monthly results to the reference yearly result

		Annual			Sum	Monthly			Sum	Daily			Sum	Hourly			Sum
		Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating		Other Domestic Uses	DHW	Space Heating	
Reference	GHG	2.36	4.34	8.95	**15.65**	2.23	4.34	8.95	**15.52**	2.3	4.34	8.95	**15.59**	2.3	4.34	8.95	**15.59**
	NRE	89.27	73.48	151.39	**314.14**	85.28	73.48	151.39	**310.15**	87.95	73.48	151.39	**312.82**	89.83	73.49	151.39	**314.7**
	RE	35.41	0.49	1	**36.9**	36.42	0.49	1	**37.91**	35.73	0.49	1	**37.22**	35.61	0.49	1	**37.1**
	UBP	3934.58	2657.03	5474.14	**12065.75**	3713.58	2657.03	5474.14	**11844.75**	3895.89	2657.03	5474.14	**12027.06**	3884.44	2657.029	5474.14	**12015.609**
Scenario B	GHG	1.93	4.34	8.95	**15.22**	1.913	4.34	8.95	**15.203**	1.97	4.34	8.95	**15.26**	2	4.34	8.95	**15.29**
	NRE	62.21	73.48	151.39	**287.08**	59.99	73.48	151.39	**284.86**	61.4	73.48	151.38	**286.26**	63.95	73.48	151.39	**288.82**
	RE	46.38	0.49	1	**47.87**	46.88	0.49	1	**48.37**	46.48	0.49	1	**47.97**	46.02	0.49	1	**47.51**
	UBP	3318.8	2657.029	5474.12	**11449.949**	3208.72	2657.03	5474.14	**11339.89**	3343.31	2657.029	5474.14	**11474.479**	3363.88	2654.03	5474.14	**11492.05**
Scenario C	GHG	2.36	1.34	2.94	**6.64**	2,23	1,3	3,14	**6,67**	2,3	1,34	3,25	**6,89**	2.3	1.34	3.4	**7.04**
	NRE	89.27	35.66	81.64	**206.57**	85,27	34,15	79,75	**199,17**	87,95	35,3	81,4	**204,65**	89.83	31.16	87.72	**208.71**
	RE	35.41	14.13	32.32	**81.86**	36,42	14,5	32,45	**83,37**	35,73	14,2	31,92	**81,85**	35.61	14.21	30.42	**80.24**
	UBP	3934.6	1783.97	4023.72	**9742.29**	3713,6	1703	3968	**9384,6**	3895,89	1790	4257,56	**9943,45**	3884.44	1780.03	4370.8	**10035.27**
Scenario D	GHG	2.03	1.23	2.96	**6,22**	0.75	2	1.23	**6,29**	2.08	1.25	3.14	**6,47**	2,1	1,26	3,29	**6,65**
	NRE	68.18	28.44	75.95	**172,57**	7.47	65.71	27.44	**167,36**	67.32	28.13	75.68	**171,13**	70,07	29,31	81,72	**181,1**
	RE	43.96	17.06	34.62	**95,64**	66.27	44.51	17.26	**96,52**	44.06	17.07	34.26	**95,39**	43,62	16,98	32,78	**93,38**
	UBP	3454.4	1622.7	3953.5	**9030,7**	1154.2	3331.5	1570.4	**8758,2**	3485.1	1644	4118.5	**9247,6**	3502,5	1645,1	4225,7	**9373,3**

Table 3: Results of the EcoDynBat case study for the assessment of the time step influence on the environmental impacts of the energy consumed in a MFH building located in Switzerland

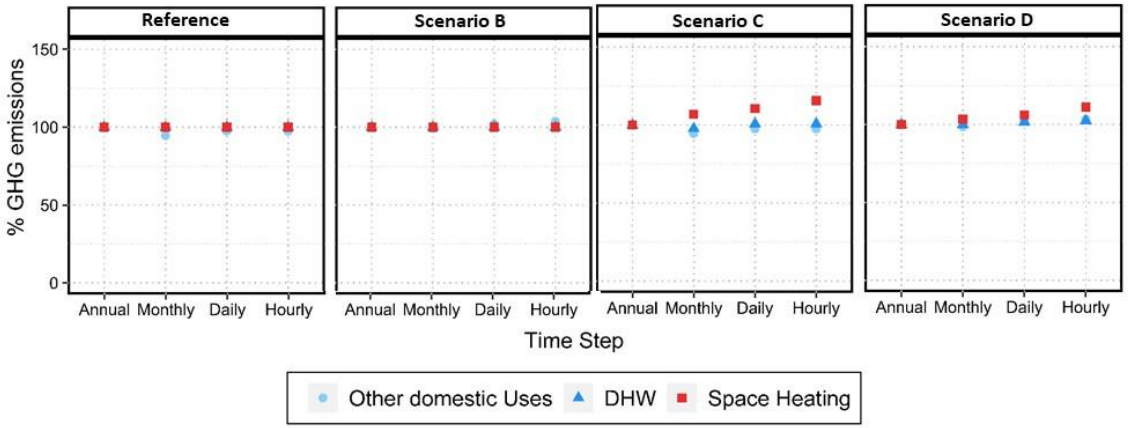

Figure 5: Influence of the time step for the four scenarios for the GHG emissions

According to the results presented in the Table 3, the time step influence is found to be very small for the NRE, RE, and UBP indicators for all the scenarios. As a result, calculating on an annual basis according to the SIA 2040 provide a sufficient accuracy.

For the GHG emissions, the impacts are found to be slightly more influenced by the time step choice, see Figure 5. Influence depends on the energy uses and scenarios. The time step influence is more important in scenarios C and D, where the electricity is used for all the uses (including the heating, DHW and the other uses), than in the reference scenario and in scenario B, where the electricity is used only for the other uses.

The detailed interpretations are reported below:
In the reference scenario, supplied by a district heating network operated with a gas cogeneration unit, the time step influence for the other electricity uses is 2.5% when considering the hourly time step compared to the yearly time step. For the total building energy demand, the overall time step influence drops to only 0.3%.

For the case B, i.e reference case + PV, the time step influence is about 3.5% (hourly compared to yearly) at the maximum for the other domestic uses which also negligible. For the total building energy demand, the deviation between an hourly and annual balance decreases to 0.5%.
Thereby, it appears that the time step influence is small when considering the domestic appliances electricity demand solely and when the space heating & DHW is supplied by a non-electric energy carrier. Moreover, the electricity demand related to the domestic uses is not fluctuating over the year and thereby an annual time step is sufficient to perform the calculation.

Regarding two other scenarios (C & D), the trends are similar for the relative deviations for the other electricity uses (about 2.5% to 3.5% in the two scenarios). The time step influence between an hourly and an annual balance is again not significant for these uses. The situation is however different for the space heating.

In scenario C, where the space heat and DHW is supplied by an air/water HP and thereby electricity, the variation for the space heating is now found to be 13.5% when considering the hourly rather than the yearly step. The DHW impact is not influenced by the time step. Globally, regarding the overall impact of the energy demand, the time step influence is found to be 5.7% since the space heat electricity demand represent 42% of the overall building energy demand.

Regarding the scenario D, i.e. scenario C + PV, the difference between hourly to annual is found to be 10%. On the overall energy demand impact, the time step influence is 6.5% because the PV also influence the impacts related to the domestic use and DHW electricity demand.

These results confirm that the choice of the time step can be rather influential when the electricity demand show a high seasonality. In the case study, the building is recent and has a low energy demand profile. For renovated buildings with higher energy demand for space heat, the time step could thereby be more significant.

Considering the four indicators used in the EcoDynBat project and in the case of Switzerland and its electricity supply mix pattern the electricity demand seasonality will drive the time step influence only for the GHG emissions. High seasonality usage and high share of this usage (such as for a renovated building operated with a HP) may significantly influence the time step while, logically, the impact of a constant electricity demand will not be influenced by any time step consideration.

Finally, from the EcoDynBat project, it can be also stated that the assumptions regarding the electricity mix is key and strongly influence the environmental impacts of the supply electricity mix. This aspect is one of the key outcome of the EcoDynBat project.

Application case 3: ELCAB

Goal of the case study:

The case study is based on the results of the ELCAB (**E**lectricity in **L**ife **C**ycle **A**ssessments of **B**uildings) research project funded by the Swiss Federal Office of Energy in 2018-2020 (Frischknecht et al. 2020). Similar to the EcoDynBat project it aims at assessing different electricity mix models on the environmental impact of the electricity demand in Swiss residential and office buildings.

Several electricity mixes were defined and established. In particular, annual and seasonal electricity mixes were derived matching the hourly generic use profile of a residential and an office building with the technology mix producing the electricity in Switzerland and the technology mixes used to produce the electricity imported from neighbouring countries. The building specific annual electricity mixes are compared to the Swiss electricity mix matching the national hourly consumption profile with the technology mixes as decribed above, to the Swiss consumer and supply mixes based on guarantees of origin 2018, to the average future Swiss electricity mix 2020-2050 (to cover 30 years of operation of a building erected today), to a long term marginal power plant technology (natural gas fired gas combined cycle power plant), and to the mix 2017 of the city of Zürich.

Furthermore, the influence of self generation of electricity with PV system and of on site battery storage on the specific electricity mix of the residential building was evaluated and quantified.

On the basis of the life cycle inventories established the specific environmental impacts of these electricity mixes were quantified. Finally, the different electricity mixes were applied in the use phase of the life cycle assessments of a residential and an office building to show the consequences of the choice of the electricity mix model on their environmental performance.

Methods:

Several electricity mix models were developed and applied in this project:

1. Annual and seasonal attributional electricity mixes of Switzerland in 2018. These electricity mixes were established by determining the hourly production, subtracting the hourly commercial exports and adding the hourly commercial imports of Switzerland. The resulting technology mix profiles were matched with the load (consumption) profiles of a residential and an office building (see Figure 6**Error! Reference source not found.**) and with the consumption profile of Switzerland in 2018. The technology mixes of the imports and the exports represent the country mix of the respective hours.
2. The Swiss consumer mix based on guarantees of origin 2018, the Swiss supply mix based on guarantees of origin 2018[10] and the ewz (utility of the City of Zürich) electricity mix based on guarantees of origin 2017.
3. The average future electricity mix of Switzerland according to the “New Energy Policy” scenario of the Energy Strategy 2050 was determined in 5 years time steps from 2020 until 2050. It does not include commercial trade but only imports required to satisfy the domestic demand.
4. The long term marginal electricity mix of Switzerland and of ewz was derived comparing the electricity demand and production volumes of the Business as Usual and the New Energy Policy

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[10] The Swiss GO consumer mix represents the mix of GOs sold to end consumers (full declaration). The Swiss GO supply mix represents the difference of GOs sold to end consumers minus GOs sold with dedicated electricity products based on renewable energies. Both mixes contain a share of few percents of untracked consumption (modelled with the residual mix).

scenarios. The additional electricity is expected to be produced in gas fired gas combined cycle power plants.

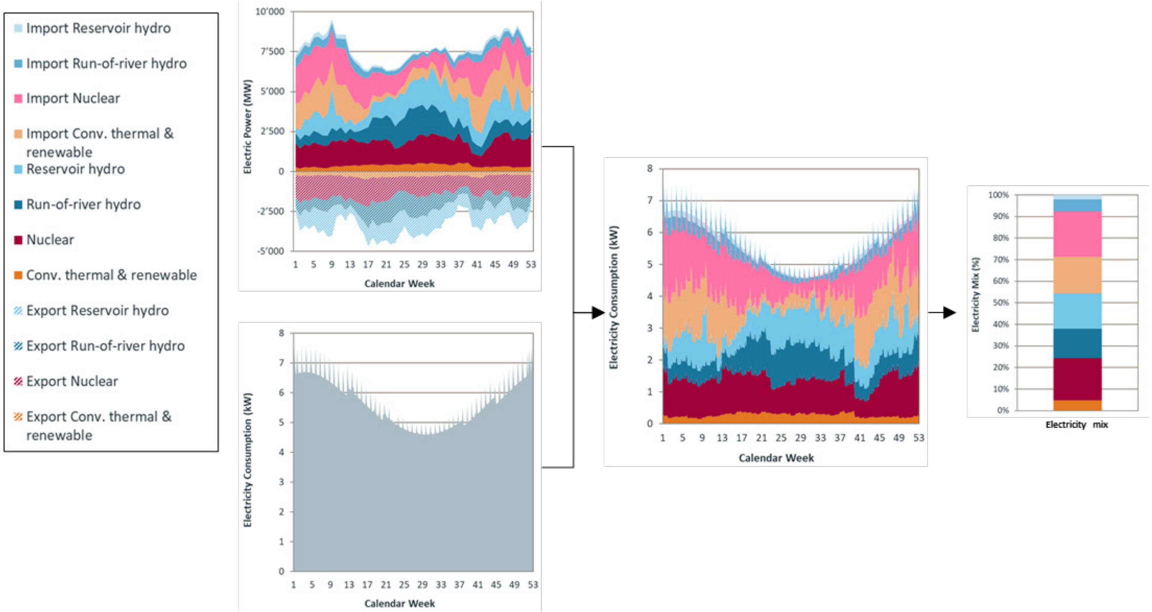

Figure 6: Derivation of the annual attributional electricity mix for buildings (and Switzerland). The electricity generation, export and import profile (top left) and the consumption profile of the building (and Switzerland, respectively; bottom left) are combined (centre) and integrated over time (right) in order to obtain the attributional electricity mix supplied to the building (and to Switzerland, respectively).

Material manufacture and construction of the buildings was modelled with the Swiss supply mix 2011 as published in the KBOB recommendation 2009/1:2016.

Results:

The results of the LCA of the residential building are described here as they are considered representative for both buildings assessed. The greenhouse gas emissions of the residential building Rautistrasse operated with the different electricity mixes vary between 9.8 and 12.4 kg CO_2-eq per m^2 and year (with 20.3 kg CO_2-eq per m^2 and year applying the longterm marginal electricity mix, see Figure 7). The variation is uniquely caused by differences in the amount of electricity supplied from the grid, the manufacturing of PV and battery systems for self generation and consumption of electricity and the greenhouse gas emission intensity of the electricity mix used in operation. The greenhouse gas emissions of material manufacture and construction (labelled “building” in Figure 7) are identical.

In most cases the share of greenhouse gas emissions caused during construction (and the corresponding end of life) is higher than the share of operational greenhouse gas emissions. More than two third of the greenhouse gas emissions caused during the life cycle of the residential building are due to construction and in particular building material manufacture.

The greenhouse gas emissions of the operation phase differ substantially, in particular when comparing for instance the environmental impacts of the attributional mixes established in this project with the mixes based on guarantees of origin, the average future electricity mix, the long term marginal mix and the ewz mix 2017.

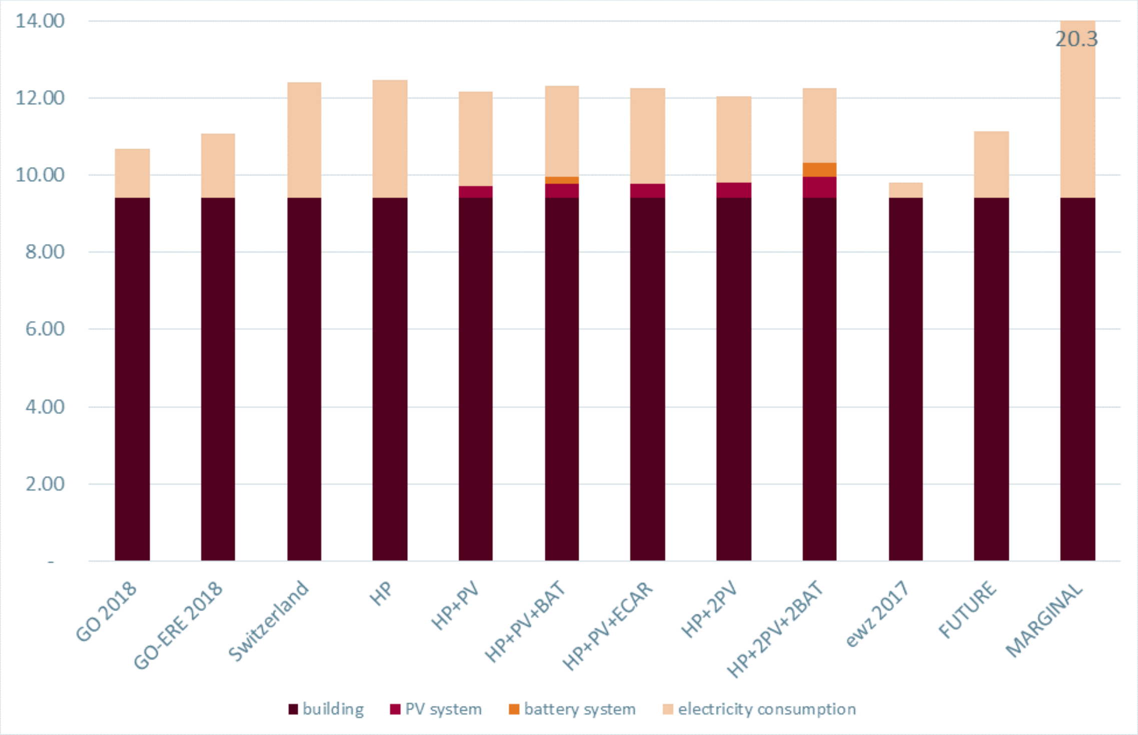

Figure 7: Greenhouse gas emissions in kg CO$_2$-eq. per m^{2}a of the residential building Rautistrasse, Zurich. Target values SIA 2040:2017: 9 and 3 kg CO$_2$-eq./m^{2}a (construction including end of life and operation, respectively).
GO 2018: Swiss consumer mix based to guarantees of origin 2018; GO-ERE 2018: Swiss supply mix based to guarantees of origin 2018, i.e. excluding deliberately purchased electricity products based on renewable energies; Switzerland: Swiss annual mix (national load profile); ewz 2017: ewz electricity mix based to guarantees of origin 2017; FUTURE: average future electricity mix Switzerland 2020-2050 according to the New Energy Policy Scenario of the Swiss energy strategy 2050; MARGINAL: long term marginal electricity mix (Switzerland and ewz).
Building specific electricity mixes matching hourly production and trade with the electricity consumption profile of the building, equipped with:
HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system;

The greenhouse gas emissions of the building specific electricity mix (“HP”) and of the national average attributional mix (“Switzerland”) are nearly identical. Self generated electricity leads to lower environmental footprints. The reduction in environmental impacts is mainly due to the lower demand of grid electricity. The environmental profile of grid electricity supplied to the building is hardly affected by the self generated and consumed PV electricity. The investment in storage facilities does not necessarily lower the greenhouse gas emissions of the building.

The results of the LCA of the office building show similar patterns: the environmental impacts of the building are very similar when applying the building specific and the Swiss average attributional electricity mix and lower when applying the Swiss and the ewz mix based on guarantees of origin.
The environmental impacts of the summer electricity mixes (building specific and Swiss average) differ substantially from those of the winter mixes. The winter mixes cause for instance between 160 and 169 g CO$_2$-eq/kWh and the summer mixes between 70 and 78 g CO$_2$-eq/kWh.

<u>Discussion and conclusions:</u>

The results of this study confirm the environmental relevance of electricity consumption of buildings and of the choice of the appropriate electricity mix model, irrespective of the environmental indicator chosen.

However, at the same time the results show that construction (manufacture of building materials, building elements and building technology) contributes between somewhat less than 50 % and more than 95 % to the life cycle based environmental impacts of buildings and therefore necessarily needs to be included in environmental analyses of buildings and the corresponding target values.[11]

The summer and winter Swiss electricity mixes show distinctly different patterns. During the summer period, more electricity is being produced with hydropower and the mix relies much less on imports of non renewable electricity from neighbouring countries. During the winter period substantial shares of fossil based electricity is being imported.

The annual and seasonal electricity mixes derived from the load profile of the two buildings and of Switzerland are close to identical. Obviously the load profile of energy efficient residential and office buildings are very similar to the load profile of the country.

The comparison of the Swiss national electricity mix 2018 established by integrating the combination of hourly technology mixes (domestic production minus commercial exports plus commercial imports) with the hourly load profile of Switzerland with the Swiss consumer mix based on guarantees of origin (GO) 2018 reveal substantial discrepancies: while Switzerland still consumes electricity with a share of 40 % nuclear power and 10 % fossil power, the GO mix shows shares of about 20 % and 4 % of nuclear and fossil power, respectively.

The average future Swiss electricity mix causes less environmental impacts than the Swiss annual attributional electricity mix. The level of environmental impacts is similar to the Swiss consumer mix based on guarantees of origin 2018. The average future mix lacks trade related technology shares and thus is hardly comparable with the other mixes which represent the current situation.

The ewz 2017 electricity mix shows the lowest specific environmental impacts due to the low share of nuclear power and the absence of fossil based electricity. This is however not a carte blanche for an excessive and inefficient use of electricity. Capacity constraints (in the case of ewz but also on country level) would call for additional power plant capacities, which, according to the national energy strategy 2050 and ewz scenarios, would likely be natural gas fired gas combined cycle power plants.

Despite the large variety in electricity mixes developed and analysed in this study, its variability can effectively be narrowed down by assigning specific electricity mixes to specific policy relevant questions and scopes.

Recommendations:
The analyses and results presented in this study lead to the following recommendations:

5. Refrain from establishing building sector specific electricity mixes and instead use Swiss national electricity mixes based on physical production and commercial trade as established in this project.
6. Reconsider the current use of the Swiss supply mix based on guarantees of origin in building LCAs and in LCAs in general. It is recommended to use the Swiss national electricity mix based on physical production and commercial trade, which reflects the economic reality of the purchase of electricity *production* (which is considered more important that the economic reality of the purchase of the *quality* of the electricity).

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[11] A recent study showed that building material manufacturers may lower the specific greenhouse gas emissions of their products by 65% on average (Alig et al. 2020), by investing in completely new technologies (hydrogen based steel) and in technical reduction measures such as carbon capture and storage (e.g. in cement production) in addition to switching to renewable energy sources.

7. Use the long term marginal electricity mix in scenario analyses of investments in new buildings and in particular in refurbishment projects with comparatively low energy efficiency. This is particularly important in situations where the electricity causes low specific environmental impacts and greenhouse gas emissions and shows the resilience of the investment towards changes in the electricity producing technologies.
8. Self generation of electricity with PV helps to reduce the environmental impacts of buildings supplied with a building specific or a national average electricity mix. The effect of on site individual storage of electricity in batteries is less distinct and thus not recommended. Centralised storage facilities on district level may show a different performance.

Given the increasing significance of the construction phase of buildings as shown in the building case studies, establish binding and steadily lowering target values on greenhouse gas emissions per m^2 and year. The SIA 2040 technical bulletin is a reality proven basis for such a regulation.

3.3.5 Sweden

The integration of a full LCA in building design or in architectural competitions is currently very limited in Sweden. If comparisons are carried out, they are usually based on the criteria from certification schemes mentioned in the previous section (Miljöbyggnad, LEED, BREEAM-SE or Nordic Swan Ecolabel). Common tools that can be used for this purpose include One Click LCA and Byggsektorns Miljöberäkningsverktyg (Building Sector Environmental Calculation Tool, a software tool with a built-in database, designed to easily calculate embodied greenhouse gas emissions in construction materials). Another method has been developed specifically for the consequential assessment of building energy solutions, called Tidstegen (Time Steps). It has been released as a free software tool[12], but has not been used in a lot of practical cases so far (Gode, Nilsson, Ottosson, & Sidvall, 2019).

3.4 Environmental Optimum between Construction/End-of-life and Operation

3.4.1 Denmark

There have been published research papers on subjects such as the environmental impact trade-offs between the heat produced to meet a building's space heating load and insulation produced to reduce its space heating load throughout the whole life-cycle of a building (Sohn et al. 2017).

3.4.2 France

At the moment, only the EQUER model[13] is linked with an optimization module (genetic algorithm[14]). Both annual average or hourly electricity mix are possible but of course the same option is used for all alternatives.

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[12] https://www.ivl.se/projektwebbar/tidstegen.html

[13] Recht T., Schalbart P., and Peuportier B., Ecodesign of a "plus energy" house using stochastic occupancy model, life cycle assessment and multi-objective optimisation, Hamza N and Underwood C. (Ed), Building Simulation & Optimization 2016, Newcastle, September 2016

[14] Genes correspond e.g. to insulation thickness, type and area of glazing etc. Individuals with highest performance are selected among a population, and their children are then selected again so that optimal solutions are identified after a certain number of generations, see details in the previous reference.

3.4.3 Hungary

In research, an optimization framework has been developed using a parametric approach and evolutionary algorithms. In this framework, currently and annual average electricity mix is applied, but the integration of hourly resolution and a future electricity mix is in progress.

3.4.4 Switzerland

As far as we know, this question has not been tackled yet in Switzerland. No specific methodology/approach is available for this question, but the technical bulleting SIA 2040 would be suited and used to address such a question.

3.4.5 Sweden

Recent LCA studies of Swedish buildings, in particular low-energy buildings, point to a rising importance of greenhouse gas emissions from construction materials compared to operational energy use (Larsson, Erlandsson, Malmqvist, & Kellner, 2016; Liljenström et al., 2015). This has lead to more focus on embodied emissions, and trade-offs between the impact of operational energy use and e.g. insulation materials are being discussed. However, there is currently no method or optimization framework to systematically find this optimum.

3.5 Synthesis

As a first step to prepare this synthesis, the modelling possibilities are summarized below with example choices in different tools and countries.

A) Electricity mix modeling possibilities

1. Generic or provider specific electricity mix
2. Regional, national or continental mix
3. Production mix or supply mix
4. Physical flows, contracts, guarantee of origin coupled with physical production, or guarantee of origin only, electricity trade with neighbouring countries
5. Mix corresponding to production + import, production – export + import (possibly according to guarantee of origin), or national electricity declaration
6. Universal electricity mix or use-specific electricity mix (heating, cooling, lighting, hot water…)
7. Present or future mix (e.g. average present-2050)
8. Average or marginal mix
9. Annual, seasonal or hourly mix
10. Allocation approach for electricity produced on site (photovoltaics, but also wind) exported to the grid

B) Synthesis table

Type of choice	Application cases			
	Regulation/ certification	Design tool	Facility assessment	Research
1_Generic vs provider-specific electricity mix	generic	generic	specific	
2_Geographic scope	national	national	national	
3_Production mix vs supply mix	supply mix	supply mix	supply mix	
4_Nature of trade flows	commercial or physical flows, explain the choice			
5_Modelling choice for the supply mix	production-export+import or production+import, explain the choice			
6_End uses dependence	universal if same temporal variation in buildings as national consumption, use-specific recommended otherwise (e.g. winter peak demand for heating)			
7_Time dimension	present, near future or long-term future mix, explain the choice			
8_LCA modelling approach	average, short-term marginal or long-term marginal, explain the choice			
9_Time granularity	annual or hourly, explain the choice			

Choices made in different existing tools

Criterion	Choices made in the different tools		
1 Generic or specific	Provider specific FR2[15]	Generic CH1, CH2, CH3, FR1, FR2, HU1, HU2, SE1, SE2	
2 Geographic scope	Continental	Regional SE2	National CH1, CH2, FR1, FR2, HU1, HU2, SE1
3 Type of mix	Production mix	Supply mix CH1,CH2, CH3, FR1, FR2, HU1, HU2, SE1, SE2	
4 Nature of trade flows	Physical flows CH2, FR1, FR2, HU1, HU2, SE1, SE2	Flows based on contracts CH3	Flows based on Guarantee of Origin (GO) CH1
5 Modelling choice for the supply mix	(1) Production + imports CH2, HU2	(2) Production – exports + imports FR1, FR2, HU1, SE1, SE2, CH3	(3) According to national electricity declaration CH1
6 End uses dependence (heating, lighting, cooling, etc.)	Universal mix CH1,CH2, CH3, FR2, HU1, HU2, SE1, SE2	Use specific mix FR1	
7 Time dimension	Present mix CH1,CH2, CH3, HU1, HU2, SE1	Near future mix FR1, FR2	Long term future mix CH3, FR2, HU2, SE1, SE2
8 LCA modelling approach	Average mix CH1,CH2, CH3, HU1, HU2, SE1	Marginal mix CH3, FR1, FR2, SE2	
9 Time granularity	Annual average mix CH1,CH2, CH3, FR1, HU1, HU2, SE1	Seasonally differentiated mix CH3, SE2	Hourly differentiated mix CH3, FR2, HU2
10 Allocation of in site PV electricity production	Impacts of self consumed part only (A2) CH2	Gross impacts minus PV impacts of fed in electricity (A1) CH1, CH3	Gross impacts minus grid mix impacts of fed in electricity (B) FR1, FR2, HU1, HU2, SE1, SE2

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[15] If the purpose of the study is to compare different electricity providers or contracts during operation

4. Suggested Solutions and Typologies

4.1 Introduction

This document was written for method and tool developers and policy makers (regulation). Users are invited to follow the recommendations provided by the developers (e.g. certification scheme, design tools).

Some of the following recommendations are case specific. We propose to distinguish the following four cases:
A. Assessments against benchmarks defined by voluntary certification schemes and regulation
B. Environmental reporting of facility management companies and assessment of private lifestyles:
C. LCA in building design tools (building optimisation independent of voluntary schemes or regulation)
D. LCA in building research

If appropriate these cases are listed in the recommendations related to 10 topics.

These recommendations address electricity related impacts. Methodological choices should be consistent across energy sources. Thus, the following recommendations should be applied on fuels as well. For instance, if a future renewable scenario is applied for electricity production, the same level of ambition should preferably be applied for gas (future supply with biogas and/or synthetic gases produced with biogenic carbon and renewable electricity) and liquid fuels.

4.2 Recommendations

1. Generic or provider specific electricity mix

Assessments against benchmarks defined by voluntary certification schemes and regulation:
A generic mix is commonly appropriate because e.g. in the design phase the occupant is generally not known and neither the electricity provider so that a specific mix cannot be identified. But if the occupant is known (e.g. in case of a household or a company developing a project for their own use) or if a long term contract exists with an energy provider, one of the Swiss methods (2000 W society) considers the specific mix of this provider but only for 50% of the total consumption in order to account for the risk that this situation may change.

Environmental reporting of facility management companies and assessment of private lifestyles:

If the goal of the LCA study is to compare various electricity providers in order to advise a facility manager or owner of an existing building, using a specific mix is more appropriate.

2. Regional, national or continental mix

Using a national mix is recommended, because the choice of some production technologies (energy transition towards renewables) is related to a national democratic process. Averaging a continental mix would lead to consider e.g. a % of nuclear or coal power plants even in countries having decided to abandon such technologies. But the national mix shall include imported electricity, see the following §4 and 5.

3. Production mix, supply mix

The supply mix should be used, as it corresponds to the electricity delivered to a country's consumers, including buildings.

4. Physical flows, contracts, guarantee of origin coupled with physical production, or guarantee of origin only, electricity trade with neighbouring countries

Using guarantees of origin (GOs) purchased independently of purchasing the electricity is not recommended because fossil or nuclear production may be artificially transformed into renewable electricity (a company could use electricity produced with coal or nuclear power but purchase GOs of renewable electricity to claim that it uses renewable power). It is likely to lead to double counting of renewable electricity (building LCAs in Switzerland and Norway both claim (partly) GOs of Norwegian hydroelectric power) because GOs are a voluntary means of communication.

Tool, certification scheme and method developers may either use "commercial flows" or "physical flows" to model electricity trade, and provide reasons for the choice.

It is recommended to consider physical domestic production (e.g. according to the data from transmission system operators) and commercial or physical trade with neighbouring countries reported on a transparency platform such as ENTSO-E in Europe (see the implication in §5).

Reasoning for commercial trade 1: Life cycle assessment is a method that complements economic information about products, services and technologies with information on their environmental impacts. That is why life cycle inventory models are supposed to describe or at least approximate economic realities. Data on commercial trade is chosen (and preferred to physical exchanges) because it better reflects the economic realities of electricity trade.

Reasoning for physical trade 2: The physical trade approach models the real exchanges and underlines an overall stability of the electricity supply at every time step which is part of the analysed service for the electricity consumption mixes. The "physical flow" approach can be used if the goal is to optimize the global energy balance of production/consumption in a country. It is also relevant to be used for analysing demand-side management strategies using hourly data to check if the consumption occurs during the best period of time in terms of GHG emissions).

The 2019 suggested update of the European Product Environmental Footprint method[16] proposes to select in priority supplier specific electricity product based on GOs, which has been discussed in §1, and otherwise a "residual grid mix" defined as characterizing the unclaimed, untracked or publicly shared electricity. As reasoned above we do not recommend methods based on GOs.

LCA in building research: compare physical and commercial trade to check whether or not differences are substantial.

5. Mix corresponding to production + import, production – export + import (possibly according to guarantee of origin), national electricity declaration

Tool, certification scheme and method developers may either use "production – export + import" or "production + import", and provide reasons for the choice.

Note: the reasoning presented below allows to inform the users of the "philosophy" behind each modeling approach even if there is no "right" and "wrong" modelling approach. The user should only select the one that better describe his context of use.

Reasoning for P-E+I: It is rare for a country to import electricity in order to export it further to another country, in particular in larger countries such as Germany, France or Poland. There are some transit contracts, which however are not part of the commercial trade data in the ENTSO-E transparency platform. Hence, it is safe to assume that all exported electricity stems from domestic production. It is also generally more precise because the % of import is related to the national consumption volume.
Reasoning for P+I: The exported electricity from the assessed country is considered equivalent to the electricity supplied to domestic customers. In addition, the P+I model is able to attribute the environmental responsibility of consuming the electricity in the assessed country not only to the direct "first level[17]" neighbouring countries but also to the "second level" countries (in a view of ensuring at every hour grid stability) even if there are no direct economical trade flows from the assessed countries and the second level countries contributing to the LCA of the consumption mix of the assessed country.

In both approaches, it is important to check that imports and exports do not include transit flows because this may lead to a bias if a large amount of imported electricity is not consumed in the country but readily re-exported. If the transit flows can be identified, they may be subtracted from both export and import.

A gross balance should be used because import and export electricity mixes are generally different so that import and export flows do not compensate (even if the physical flow is zero, see §4).

6. Universal electricity mix or use-specific electricity mix (heating, cooling, lighting, hot water…)

A universal mix is recommended if the seasonal variation of the electricity consumption in buildings is similar to the seasonal variation of national consumption. Use-specific average electricity mixes may be used otherwise (e.g. accounting for winter peak demand mix for heating).
We recommend to validate the universal and use-specific electricity mixes by comparing the LCA results to an hourly electricity mix model, for a sample of building types (residential, offices…), and their electricity demand for space heating, hot water, ventilation, lighting and auxiliaries.

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[16] Zampori, L. And Pant, R., Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN, Publications office of the European Union, Luxembourg, 2019, ISBN 978-92-76-000654-1, doi:10.2760/424643, JRC 115959

[17] For instance of a country A exports to a country B exporting to a country C, country B is first level and country A is second level for country C

7. Present or future mix (e.g. average present-2050)

The choice of the appropriate mix should be made considering the (un)certainty of the information, the appropriateness of the electricity mix in a 50 to 60 years framework of building operation and whether or not temporal variations matter or should be taken into account.

According to the goal:

Assessments against benchmarks defined by voluntary certification schemes and regulation:
We recommend using a recent past mix, near future mix (e.g. 5 years) or a realistic long-term future mix and update it e.g. every 5 years in order to account for the real progress of energy transition while reducing the risk of under- or over estimating future impacts if the actual development is not on track compared to the scenario assumed.
Electricity mix data from TSOs, utilities, ministries or administrations (e.g. energy or environment agencies) and national statistics are normally available for the past years, near future and long term future.

LCA in building design tools and research: long term future mixes may be useful, particularly in sensitivity studies. In this case, scenarios (e.g. Eurostat, the EU Roadmap 2050, national energy strategies), statistical models or economical models (e.g. TIMES) can be used.
In any case the benchmarks against which the environmental impacts of a building are compared need to be aligned with the electricity mix applied (present, near future or future).
Electricity mixes (present, near future or future) with low environmental impacts may support buildings with low efficiencies and high specific electricity consumption. Perform sensitivity analyses with additional electricity mixes, for example long-term marginal electricity mixes (see Clause 8).

8. Average or marginal mix

Tool, certification scheme and method developers may either use average (attributional LCA) or marginal (consequential LCA), and provide reasons for the choice.

Reasoning for attributional mix: Buildings are just one (admittedly important) group of electricity consumers among many. The evolution of the electricity demand of buildings is the result of a mixture of efficiency gains in existing buildings, additional demand by new buildings on greenfields, change in demand by new buildings replacing old ones. It is hard to substantiate and to determine why new and refurbished buildings should be linked to additional power production and not to the average electricity production volume. An attributional mix treats all electricity consumers equally.

Reasoning for long-term marginal mix: Future scenarios of electricity demand and production are based on assumptions about the energy efficiency of buildings, cars, industrial processes etc. Existing buildings may reduce their operational environmental impacts by switching to electric heat pumps operated with renewable energies without improving the energy efficiency. Such refurbished old buildings may contribute to a demand for electricity which exceeds the production capacity of the ambitious future senario. In such situations longterm marginal mixes, established as the difference of

the future electricity mixes in a business-as-usual and in an ambitious energy scenario, are useful to test the resilience of refurbishment measures to the electricity mix in scenario analyses.
Reasoning for short term marginal mix

Replacing gas or fuel boilers by electric heating or heat pumps is often proposed to reduce GHG emissions. But this will create a high peak demand during cold winter days. This supplementary demand requires peak production techniques which may be different from average production because such capacities will be used only a limited time of the year. High CAPEX techniques would not be economical, so that older or cheaper capacities (e.g. gas or coal thermal plants) may be used.

In such a case a short term marginal mix is appropriate. Identifying a marginal mix is based upon an assumption (e.g. 10% top of the merit order) or requires a model of the electric system in order to identify which production process is added when adding a supplementary demand corresponding to the studied building consumption or energy use. This approach can be applied to a present situation, or a future prospective scenario, e.g. using a market allocation model (e.g. TIMES), i.e. a bottom-up linear optimization model that computes a least cost pathway for a system of interest subject to the satisfaction of specified service demands and user specified constraints.

Results can be averaged according to a typical load profile corresponding to a certain use (e.g. space heating, domestic hot water...) allowing simpler annual calculation to be performed in e.g. a regulation or certification scheme (e.g. in the French E+C- method 210 g CO_2/kWh heating, 83 g CO_2/kWh domestic hot water).

Studying the environmental benefit of smart buildings is an example research topic for which a consequential approach considering both short term and long term aspects is relevant. Buildings consume a large share of the total electricity production in many countries, so that accounting for interaction between this sector and the electric system is useful towards a higher global environmental performance.

9. Annual, seasonal or hourly mix

Tool, certification scheme and method developers may either use annual or hourly, and provide reasons for the choice.

Reasoning for annual mix:
electricity products and hence the technology shares purchased are usually bought on an annual basis. The use profiles of residential and office buildings do not significantly deviate from the national use profile, which reduces the need for hourly mixes. Many design tools are not able to model operational electricity demand nor supply on an hourly basis. Long term future electricity mixes presented in official future scenarios are annual, sometimes additionally seasonal but not hourly.

Reasoning for hourly mix:
The electricity demand varies according to the hour of the day (it is lower at night), the day of the week (it is lower during week-ends) and the season (it is higher during hot days due to cooling, and during cold days if electric heating is used). Thermal mass allows storing heat which may reduce the demand during peak hours and the related environmental impacts, but impacts are produced for the fabrication of such materials. Hourly calculation allows a trade off, which is useful in a design tool and does not add complexity for users if energy calculation is also performed hourly.

Results of an hourly calculation can be averaged over a year so that a simpler annual calculation can be performed in a regulation or certification method, accounting for a typical hourly profile corresponding to specific uses like heating, cooling etc.
Developing control systems algorithms or demand side management in terms of environmental impacts, i.e. in order to use the electricity when its carbon footprint will be lower and/or minimized, is an example research question where hourly calculation is appropriate.

10. Allocation approach for electricity produced on site (photovoltaics, but also wind) exported to the grid

Three main approaches are:

"Step[18] A" approach according to ISO 52'000-1, clause 9.6.6 (identical to approach B of the draft version of the revised EN 15978 standard): A share of the environmental impacts of on-site electricity production corresponding to the proportion of self-consumed electricity is accounted for in the building LCA. The rest of the impacts, corresponding to exported electricity, is accounted for in the electricity mix of the buyer of the electricity.

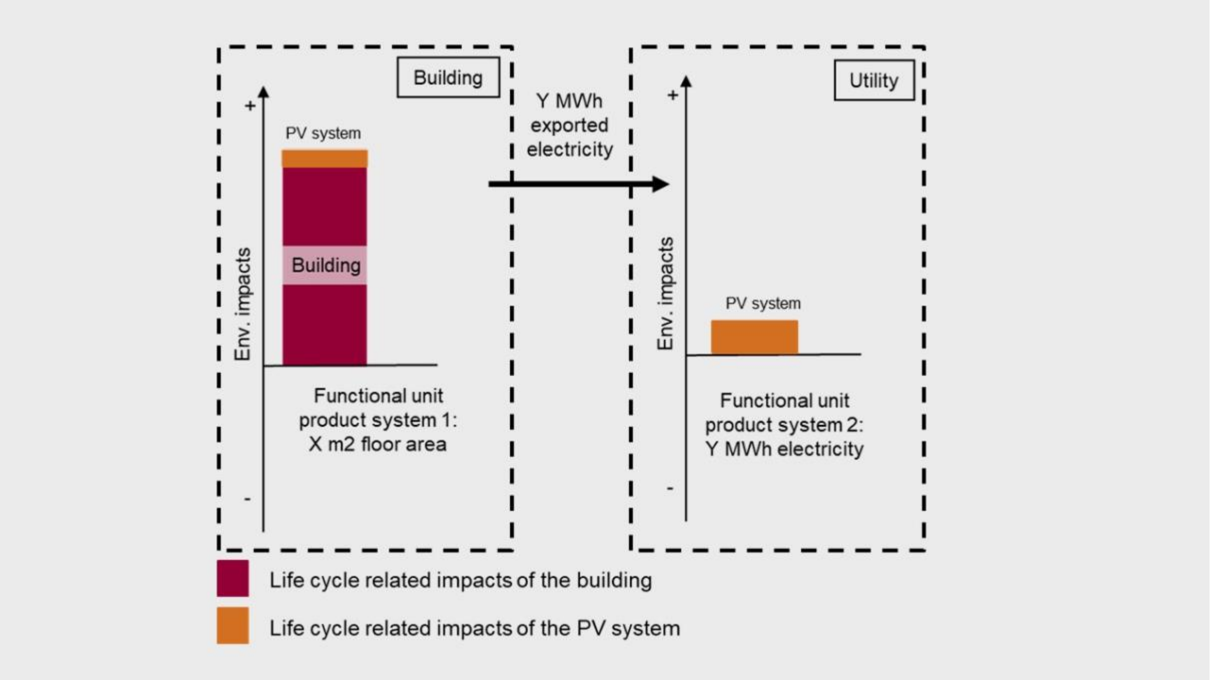

Figure 8: Step A (ISO 52000-1; and approach B of draft EN 15978): Allocation of environmental impacts caused by onsite energy production between the building and the energy ex-ported based on the share of self-consumed energy produced onsite. Note: The main elements of this approach are: (a) impacts related to the self-consumed share of PV electricity attributed to building; (b) impacts related to the ex-ported share of PV electricity attributed to exported electricity; (c) Overall sum of environmental impacts equals the observed environmental impacts.

"Step B" approach according to ISO 52'000-1, clause 9.6.6: All impacts of the PV system are allocated to the building. The building LCA also includes the potentially avoided impacts from exporting electricity to the national grid (or e.g. future European mix). In the grid mix of the one purchasing the exported

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[18] The word « step » in the standard is the label for an approach and actually corresponds to a methodological choice.

electricity, the exported electricity bears the environmental impacts of the national grid (or future European mix).

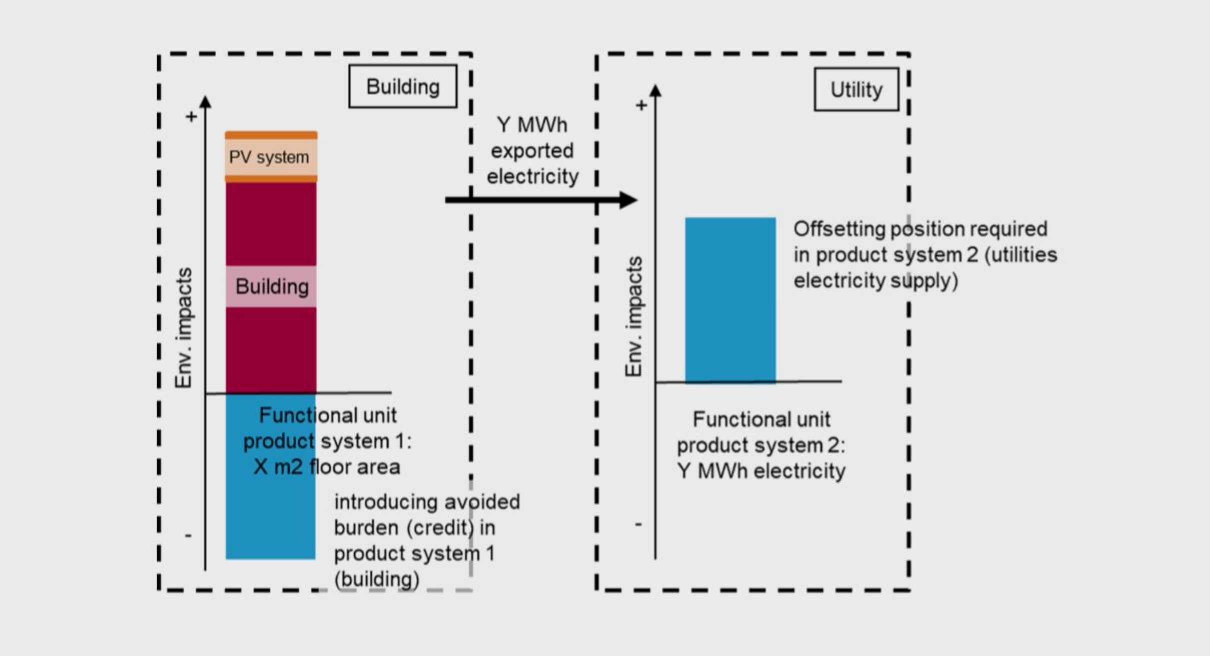

Figure 2: Step B (ISO 52000-1): Allocation of 100 % of the environmental impacts of onsite energy production and 100 % of potentially avoided emissions outside the system boundary to the building. Note: The main elements of this approach are: (a) Potentially avoided burdens (credits), determined with grid mix environmental impacts and amount of electricity exported, are accounted for in building LCA; (b) (equivalent) off-setting position in utility's LCA of electricity required to avoid dou-ble counting; (c) Overall sum of environmental impacts equals the observed environmental impacts, only if off-setting position is booked in utility's LCA.

Approach A of EN 15978 standard: All impacts of the PV system are allocated to the building, and potentially avoided impacts from electricity export are reported as additional information in module D, which is outside of the building LCA boundaries and therefore not accounted for in the building LCA result contrarily to step B of the ISO standard.

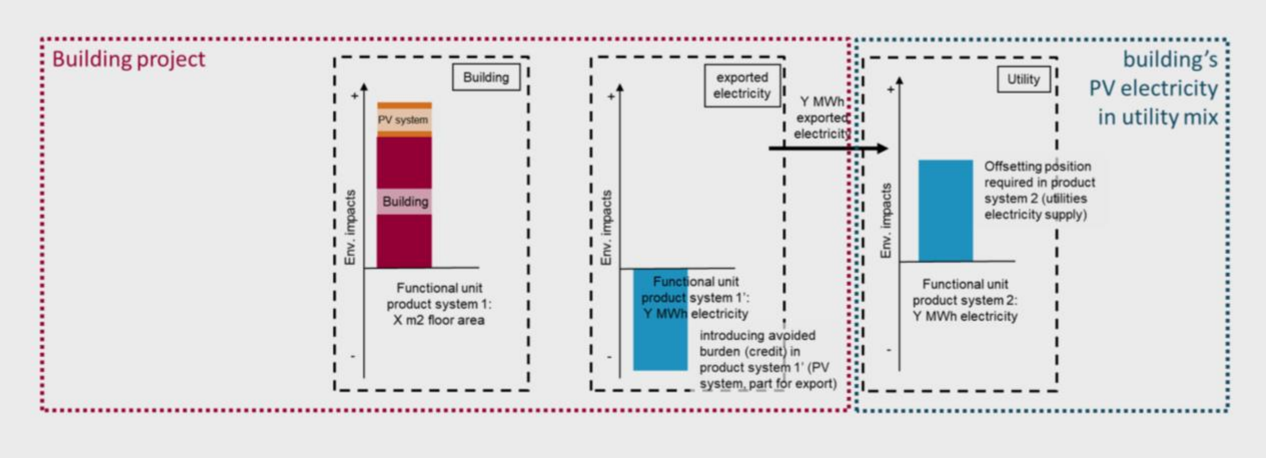

Figure 4.3: Approach A of EN 15978 standard: Allocation of 100 % of the environmental impacts of onsite energy production and 100 % of potentially avoided emissions in Module D2, outside the system boundary of the building but as part of the building project.

In step B of the ISO standard and approach A of the CEN standard, the avoided impacts have to be evaluated according to an electricity mix which can either correspond to attributional LCA (average mix) or consequential LCA (marginal mix), using hourly, seasonal or annual time step, recent past or future mix etc. (see the previous §). It is recommended to be consistent in evaluating the impacts related to the electricity consumption from the grid and potentially avoided impacts from PV export, and to report potentially avoided impacts separately as additional information.

Reasoning for the Step A approach of the ISO standard (and Approach B of the current draft of EN 15978):

Step A approach ensures that electricity produced on-site and exported to the grid shows the environmental performance of the technology used to produce it (e.g. PV, wind, combined heat and power plant). The share of environmental impacts of manufacturing, operating and dismantling the energy producing technology attributed to the building corresponds to the share of self-consumption. Building integrated PV systems may be subdivided into the parts needed for weather protection (front glass, supporting structure; attributed to the building's LCA) and the parts needed to produce electricity (panel except front glass, cabling, inverter; attributed to electricity production). The building's environmental performance depends on the share of self-consumption.

Step A may be implemented in two different ways: In option A1 100 % of the construction and manufacturing efforts of the energy technology (such as (BI)PV) are attributed to the building in Module A and the pro rata environmental impacts of exported energy are subtracted in Module B6. In option A2 the share of self-consumption is determined and only this share of construction and manufacturing efforts of the energy technology is attributed to the building in Module A. No further (negative) environmental impacts shall nor need to be accounted for in Module B6, see Table 1: Example application of step A approach.

This approach ensures that the environmental impacts of renewable energy are only accounted once: the self-consumed part is attributed to the building's LCA; the exported part is attributed to the utility or third party purchasing the renewable electricity. No potentially avoided impacts (grid mix electricity) are accounted for in the building's LCA which would imply that the exported electricity must bear the environmental impacts of the grid mix (corresponding to the avoided impacts).

How the environmental impacts of a building with and a building without (BI)PV[19] compare shall be assessed by comparing the LCA of a building with and a building without (BI)PV and not by including avoided burdens into the assessment of the building with (BI)PV.

Reasoning for the Step B approach of the ISO standard:

A building exporting locally produced renewable electricity corresponds to a system with two co-products: the building and an electricity production. Evaluating the part of impacts related to the building is an allocation problem. The environmental benefit of a renewable production compared to the standard grid (avoided impacts) can be allocated to the consumer or to the producer. Installing a PV roof requires more effort (investment, time) than just consuming renewable energy produced by others. The whole roof is part of the property, and not only the self-consumption % of the PV roof. This is why method B accounts for this benefit in the environmental value of the property. Also, this benefit is a consequence of a design decision, so that it is accounted for when comparing a building with and without PV. There is no double counting of this benefit because if the exported renewable electricity is included in the grid mix, the benefit of the local renewable production is lower. The LCA results remain consistent if the scale of the evaluation is expanded at the neighbourhood level: neighbour buildings may consume exported electricity so that the self-consumption % is larger than modelling each building separately, but the environmental impact of a building remains the same using method B. The results are also consistent regarding the environmental payback time of e.g. PV modules.

Reasoning for the approach A of the draft CEN standard:

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[19] Building Integrated PV

The reason for attributing all the impacts of the renewable energy producing unit to the building is the same as for the step B approach from ISO. Namely, that the unit is part of the building (site). It is a conscious choice of the building owner/designer to place the energy producing unit (sometimes for economic reasons), so he or she should know which impact this generates.

Reporting the potential benefits from exported energy in module D (outside of the system boundaries) is consistent with the recycled content approach at material level (prescribed by ISO 21930 and EN 15804). In both cases potential benefits occurring outside of the system boundaries are reported separately, as additional information and shall not be summed up with modules A-C results. This prevents uncertain benefits (e.g. the choice of the grid mix used to model the avoided impact from exported electricity is prone to discussion and likely to evolve over the life cycle of the building) from being credited against impacts that occur today (production of the energy producing unit) and from being accounted twice (in the building LCA and in the LCA of the grid mix of the utility purchasing the exported electricity).

Table 1: Example application of step A approach

			Module [A]	Module [B]			Module [C] assuming 5% of [A1-A5] embodied impacts for end-of-life	Module [D]		Issues/Comments
			[A1-A5] Assumptions: Building embodied impacts: 100,000 kgCO2e PV embodied impacts: 15,000 kgCO2e	**[B2]** Assumptions: 10% of [A1-A5] embodied impacts for maintenance	**[B4]** Assuming 1 replacement over the building's life cycle	**[B6]** Assumptions: Building operational energy use over life cycle: 500,000 kWh Total energy generated by the building over life cycle: 160,000 kWh Self-consumed energy: 40,000 (25% of total energy generated by the building) Exported energy: 120,000 kWh (75% of total energy generated by the building)		**[D1]** Materials reuse, recycling and recovery	**[D2]** Exported energy	
Approach B --- **Building LCA to report:** impacts from **building and self consumption PART of the energy generating equipment.** **1 additional table presenting the impacts of exported energy - NOT part of the building assessment** - as presented hereby in yellow header proposed **for ALL 22 impacts/indicators**	**Building assessment** incl. Building + PV-part related to energy consumed by the building	***Flows*** *KWh*				***460’000 kWh***			**-**	Two complete results tables showing the impacts related to the intended use of the building (white header) and to the exported energy (yellow header) separately. The assessment of exported energy follows the rules of ISO 52000-1, clause 9.6.6.2
		Impacts kgCO2e	**103’750**	**10’375**	**108’938**	**138’000 kgCO2e**	**5’188 kgCO2e**		**-**	
	Energy sub-system made available to third parties as a service PV-part related to energy exported	*Flows* *kWh*				*-120’000 kWh*			*-120’000 KWh*	
		Impacts kgCO2e	11’250 kgCO2e	1’125 kgCO2e	11’813 kgCO2e		563 kgCO2e		**-36’000 kgCO2e**	

Additional table to describe energy flows - to be further developed and finalised in line with the updated main LCA results table for consistency and avoidance of duplication

Energy reporting ***(Energy flows)***	**Additional Table 3: Operational building energy use & generation** (accompanying both versions of table 1 above)			
	[B6]			
	Building energy use	**[B.6.1]** **Regulated building-integrated systems**	*350’000 KWh*	**Total Imported energy** *Total energy use - Generated energy used in the building*
		[B.6.2] **Non regulated building-integrated systems**	*100’000 KWh*	
		[B.6.3] **Non building-integrated systems**	*50’000 KWh*	
		Total energy use *Sum of [B.6.1] + [B.6.2] + [B.6.3]*	***500’000 KWh***	***460’000 KWh***
	Building energy generation	**Used in the building**	*40’000 KWh*	
		Exported	*120’000 KWh*	
		Total energy generated *Sum of Energy used in the building + Exported*	***160’000 KWh***	

4.3 Conclusion

Even if it is sometimes difficult to express recommendations that are relevant in all situations, this document explains the choices made in different contexts. The following Table 2: Synthesis tabl an overview of the recommendations, and

Table 3 presents the choices made in different existing tools. To ensure transparency in LCA results, the assessment method of electricity related emissions must be described by indicating methodological choices listed in

Table .

Table 2: Synthesis table

Type of choice	Application cases			
	Regulation/ certification	Design tool	Facility assessment	Research
1_Generic vs provider-specific electricity mix	generic	generic	specific	
2_Geographic scope	national	national	national	
3_Production mix vs supply mix	supply mix	supply mix	supply mix	
4_Nature of trade flows	commercial or physical flows, explain the choice			
5_Modelling choice for the supply mix	production-export+import or production+import, explain the choice			
6_End uses dependence	universal if same temporal variation in buildings as national consumption, use-specific recommended otherwise (e.g. winter peak demand for heating)			
7_Time dimension	present, near future or long-term future mix, explain the choice			
8_LCA modelling approach	average, short-term marginal or long-term marginal, explain the choice			
9_Time granularity	annual or hourly, explain the choice			

Table 3: Choices made in different existing tools

Criterion	Choices made in the different tools		
1 Generic or specific	Provider specific FR2[20]	Generic CH1, CH2, CH3, FR1, FR2, HU1, HU2, SE1, SE2	
2 Geographic scope	Continental	Regional SE2	National CH1, CH2, FR1, FR2, HU1, HU2, SE1
3 Type of mix	Production mix	Supply mix CH1,CH2, CH3, FR1, FR2, HU1, HU2, SE1, SE2	
4 Nature of trade flows	Physical flows CH2, FR1, FR2, HU1, HU2, SE1, SE2	Flows based on contracts CH3	Flows based on Guarantee of Origin (GO) CH1
5 Modelling choice for the supply mix	(1) Production + imports CH2, HU2	(2) Production – exports + imports FR1, FR2, HU1, SE1, SE2, CH3	(3) According to national electricity declaration CH1
6 End uses dependence (heating, lighting, cooling, etc.)	Universal mix CH1,CH2, CH3, FR2, HU1, HU2, SE1, SE2	Use specific mix FR1	
7 Time dimension	Present mix CH1,CH2, CH3, HU1, HU2, SE1	Near future mix FR1, FR2	Long term future mix CH3, FR2, HU2, SE1, SE2
8 LCA modelling approach	Average mix CH1,CH2, CH3, HU1, HU2, SE1	Marginal mix CH3, FR1, FR2, SE2	
9 Time granularity	Annual average mix CH1,CH2, CH3, FR1, HU1, HU2, SE1	Seasonally differentiated mix CH3, SE2	Hourly differentiated mix CH3, FR2, HU2
10 Allocation of in site PV electricity production	Impacts of self consumed part only (A2) CH2	Gross impacts minus PV impacts of fed in electricity (A1) CH1, CH3	Gross impacts minus grid mix impacts of fed in electricity (B) FR1, FR2, HU1, HU2, SE1, SE2

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[20] If the purpose of the study is to compare different electricity providers or contracts during operation

Table 4: Checklist for the documentation of building LCA results

Criterion	Choice made in the LCA method regarding the assessment of electricity related impacts
1 Generic or specific	Generic ☐ Provider specific ☐ Other ☐
2 Geographic scope	Continental ☐ National ☐ Regional ☐ Other ☐
3 Type of mix	Production mix ☐ Supply mix ☐ Other ☐
4 Nature of trade flows	Physical flows ☐ Flows based on contracts ☐ Flows based on Guarantee of Origin (GO) ☐ Other ☐
5 Modelling choice for the supply mix	Production + imports ☐ Production – exports + imports ☐ According to national electricity declaration ☐ Other ☐
6 End uses dependence (heating, lighting, cooling, etc.)	Universal mix ☐ Use specific mix ☐ Other ☐
7 Time dimension	Present mix ☐ Near future mix ☐ Long term future mix ☐ Other ☐
8 LCA modelling approach	Average mix ☐ Marginal mix ☐ Other ☐
9 Time granularity	Annual average mix ☐ Seasonally differentiated mix ☐ Hourly differentiated mix ☐ Other ☐
10 Allocation of in site PV electricity production	Impacts of self-consumed part only ☐ Gross impacts minus PV impacts of fed in electricity ☐ Gross impacts minus grid mix impacts of fed in electricity ☐

Annex A: Different Electricity mix models – a description

In this Annex A the different models used to derive life cycle inventories of electricity mixes, their assumptions and data sources are described.

A.1 Introduction and scope

The modelling of electricity mix is challenging as there are many options regarding the temporal and spatial scope (Esser & Sensfuss 2016).

The electricity network is highly interconnected, which makes the modelling of electricity challenging from a geographical scope. Usually a national scale is considered, but for traded electricity different modelling approaches are available (Itten et al. 2014; Ménard et al. 1998):

- Model 1: supply mix = domestic electricity production mix. This is the production of different power plants within a geographical boundary, without electricity trading considered. This can be an acceptable simplification in countries with a low share of import/export.
- Model 2: supply mix = domestic production + imports. This model does not differentiate between electricity exported and electricity supplied to the domestic market.
- Model 3: supply mix = domestic production – exports + imports. This model assumes that the exported electricity is produced by the domestic power plants and the imported electricity is used exclusively for electricity supply within the importing country. This model does not take into account that the imported electricity can be re-exported to other countries.
- Model 4: supply mix = domestic production + net imports/exports. This model assumes that simultaneous, physically measured imports and exports is transit trade. This may deviate from the economic realities.
- Model 5: consumer mix. The electricity mix of the domestic supply is modelled according to the integration of the electricity declarations of all electric utilities in a country. The declaration includes a differentiation according to technology and whether or not the electricity is produced domestically or abroad.

Besides the national scale, in some cases a regional or continental scale may also be applied.

The following sections present the options for modelling the temporal scope of electricity mix: present mix and future scenarios, as well as intra-annual variation between seasons and hours. Finally, modelling approaches for determining the longterm marginal electricity mix for a consequential LCA are described.

A.2 Present annual average electricity mix

The most common approach applied in LCA is a static approach when an average annual national mix is used for the entire reference study period. This average mix may be an electricity mix from a specific recent year or an average of a longer period.

In LCA studies of buildings, typically the supply mix of the country is applied, but there may be differences between countries in the consideration of import and export flows (see the different models in the previous section).

A.3 Future annual average electricity mix

Data for the future annual average electricity mix is based on several expected future data points. The forecasting can both include dynamic data related to the development within the mix and to the expected technological development.

This approach has been introduced in the national LCA tools for buildings in Denmark, where the forecasting scenario is based on estimation of the expected development of the energy mix for electricity and district heating. The forecasting scenario does not include forecasting technology development of boilers etc. The first dataset was published in 2016 (COWI, 2016) and updated in 2020 (COWI, 2020). The approach includes energy composition in five data points and the corresponding expected environmental impacts. The first version included forecasting from 2015-2050, while the updated version only covers 2020-2040. Table 4 gives an example of the values for one selected impact category (greenhouse gas (GHG) emissions).

Table 4: Life cycle based greenhouse gas emissions of electricity and district heat in g CO_2-eq/kWh and MJ, respectively for the forecasting scenarios for five data points (year) (COWI 2016, COWI 2020)

	2015	2020	2025	2030	2035	2040	2050
Electricity: 2015 g CO_2-equiv./kWh	352	201	169		31		24
Electricity: 2020 g CO_2-equiv./kWh		264	135	47	41	40	
District heating: 2015 g CO_2-equiv./MJ	52	31	28		20		16
District heating: 2020 g CO_2-equiv./MJ		37	24	20	19	19	

A.4 Seasonal (summer/winter) average electricity mix

A seasonal variation can be generally observed in the composition of the electricity mix, which has been shown by several researchers. The environmental impacts are typically lower in the summer months than in the winter months (Roux et al. 2016b). This seasonal variation can be explained by the variation on the supply side on the one hand, and the variation on the demand side on the other hand.

On the supply side, the output of renewable technologies exhibits high variability depending on weather conditions. For example, photovoltaic power plants produce more solar energy in summer than in winter and there is a larger production from run-of-river power plants in spring.

On the demand side, there is also some seasonality, for example space heating induces winter peak demand in countries with a high penetration of electric heating, while space cooling may result in summer peaks. Peak demand leads to an increase of production from fossil thermal plants, which can flexibly participate in load modulation.

A seasonal electricity mix has been developed in some countries, for example in Switzerland, as an average of winter months (October-March) for winter electricity mix and an average of summer months (April-September) for summer electricity mix (Frischknecht et al. 1996).

A.5 Hourly resolution of the electricity mix

Seasonal variation of the electricity demand, and therefore of the mix, may occur due to heating and cooling loads according to climatic conditions. Moreover photovoltaic electricity production, higher in summer, may cover the electricity consumption for heating, higher in winter, on an annual basis. However, the environmental impacts related to the electricity consumed during the heating season (winter) may differ substantially from the environmental impacts of PV electricity or, in case a “potentially avoided emissions” concept is applied, from the emissions of the electricity avoided by feeding PV electricity into the grid.
The variation can also occur according to the day of the week because of a lower consumption in office buildings during week-ends. Hourly variation corresponds to human activities: for instance the demand is currently lower late during nighttime. Hourly values of electricity production using different technologies are provided by Transmission System Operators (organizations managing the grid). The data includes imported quantities from different countries. Using some assumption regarding imported electricity (e.g. yearly average production mix corresponding to the exporting country etc.), the mix corresponding to consumed electricity is therefore estimated for past years.

Electric system models can be developed (e.g. Kiss et al. 2018; Roux et al. 2017) in order to evaluate hourly mix values according to energy transition scenarios and climatic data. Energy consumption in buildings is generally estimated using "typical meteorological years" (TMY), corresponding to a statistical average of e.g. 20 real years. The electricity supply mix corresponding to such TMY can be evaluated on an hourly basis using an electric system model. Energy transition scenarios may provide installed capacities in future years, and the corresponding hourly mix can also be evaluated using the same electric system model. Effects of climate change on e.g. hydroelectric power production can be taken into account.

A.6 Marginal electricity mix (electricity mix(es) applicable in consequential LCAs)

Introduction

A new construction increases the electricity demand, while renovating a building usually aims at reducing this demand. In attributional LCA, an average electricity mix is considered when evaluating the corresponding environmental impacts. In consequential LCA, a marginal mix may be considered instead, in order to account for the consequences of the studied system (building) on the background system (including electricity production).

Marginal electricity mixes depend on the time scale and may be defined on a short term for particular time during a day (e.g. peak loads during cold and hot days, respectively), or during a season (e.g. reduced electricity consumption during the winter season caused by the replacement of direct heating systems with heat pumps) and they may be defined on a long term to capture long term changes in electricity demand due to national energy policy measures (affecting both the demand and energy efficiency in housing, industry, mobility, etc.).

Furthermore, electricity mixes usable in consequential LCA may be based on 1) economic models, 2) policy scenarios quantifying the annual average (and seasonal) production of electricity, 3) a “thinking model”.

1) Marginal electricity mix based on techno-economic models

If the electricity demand is reduced thanks to retrofit measures in a building with electric heating, the most expensive electricity production may likely be avoided which does not necessarily correspond to average impacts. For instance, in France during the winter peak electricity demand, thermal power plant production will be avoided rather than cheaper production like hydro-power. In such case, the reduced greenhouse gases emissions correspond to these thermal plant emissions and not to average emissions. Marginal processes can also be considered when evaluating additional impacts related to an increase of consumption (new building), or when evaluating potentially avoided impacts corresponding to onsite renewable electricity production exported into the grid, if applying an avoided burden approach (see Chapter XXX on exported electricity).

The marginal technology is among the technologies on the market capable of responding to changes in demand (Mathiesen et al. 2009). Long term changes (e.g. large scale change leading to change infrastructure and installed capacities) or short term changes (leading to adapt the production without changing the infrastructure) could be considered.

Existing methods regarding the use of marginal electricity production in consequential LCA have been reviewed, eg in Menten et al. (2015). The short-term marginal mix depends on installed capacities, electricity market, resources and possible downtime or maintenance activities (Lund et al. 2010). Two terms are considered in the Greenhouse Gases Protocol (WBCSD & WRI 2007): one corresponds to modified infrastructure (long term) and one to modified production (short term). A building has a limited influence on the whole electric system and infrastructure, so that only the term corresponding to a change in production is generally considered when the aim of the LCA study is to help in the design of a single building (Roux et al. 2016a). But if LCA is used on a large scale, e.g. in the frame of a regulation, the whole building sector will be influenced so that long term effects have to be considered (Roux et al 2016a).

The different production techniques are ranked using a "merit order". Technologies that cannot be adjusted according to the demand (e.g. wind or PV, that depend on the weather) are at the bottom of this ranking. Adjustable technologies with the lowest constraints and the highest cost are at the top. The Greenhouse Gases Protocol suggests as default value a marginal mix corresponding to the 10% top ranked productions.

A more conceptual/theoretical way based upon physics is to evaluate the mix with and without the studied building, using a model representing the electric system as presented in the previous paragraph.

Like in the previous paragraph, a marginal electricity mix can be defined for past years (historical mix) or for a long term period using energy transition scenarios.

2) Marginal electricity mix based on policy scenarios

Countries like Switzerland established long term energy and electricity strategies to step out of nuclear power and engage in renewable energies. Usually these strategies include different scenarios of possible developments, including a business as usual scenario and scenarios of different ambition levels (Prognos 2012). The scenarios cover both supply and demand and include assumptions on the development of consumption, technology and shares of technologies. In the energy sector the energy efficiency of buildings, the portfolio of heating systems (e.g. share and volume of electric heat pumps installed), and the development of individual mobility (e.g. number of cars, average annual distances travelled) as well as the development and the shift in technologies (e.g. fuel efficiency, share of electric and hydrogen cars) are important aspects which determine the future demand in fuels and in electricity.

Assessing the environmental impacts of electricity consuming products such as buildings or private cars which do not meet the energy efficiency assumptions assumed in the more ambitious energy scenarios call for a longterm consequential electricity mix.

Such a consequential electricity mix is defined as the difference of the absolute production volumes in a given year in the future (e.g. 2050) in the business as usual scenario and in the new energy policy scenarios (see example in Annex B Switzerland). It indicates the production volumes per power plant technology which would be needed in case the energy efficiency targets are missed. And the energy efficiency targets are most likely missed with products (for instance buildings and private cars), which do not meet the individual energy efficiency requirements of the new energy policy scenarios.

3) Marginal electricity mix based on a thinking model for Europe

This approach applies the following thinking model: The amount of electricity based on renewable energies is limited. If electricity is used economically, utilities may be able to shut down (and dismantle) power plants which run on fossil or fissile fuels, i.e. lignite, hard coal, fuel oil, natural gas and nuclear power plants. Because this opportunity is available as from today, the use of the present (for instance European) non-renewable residual electricity mix is recommended (see example in Annex B, Switzerland).

A.7 Electricity mix based on information from guarantee of origin certificates

The current electricity market distinguishes between the physical electricity and the quality of the electricity (described by guarantees of origin), which are traded separately (see Figure 9). As a consequence, the certified quality of the electricity purchased and consumed by a country or a building may significantly deviate from the physical electricity mix purchased and consumed. This deviation occurs when the electricity qualities

(GOs) are purchased independently of the physical amounts, the latter being purchased on a spot market with no information about their provenience.

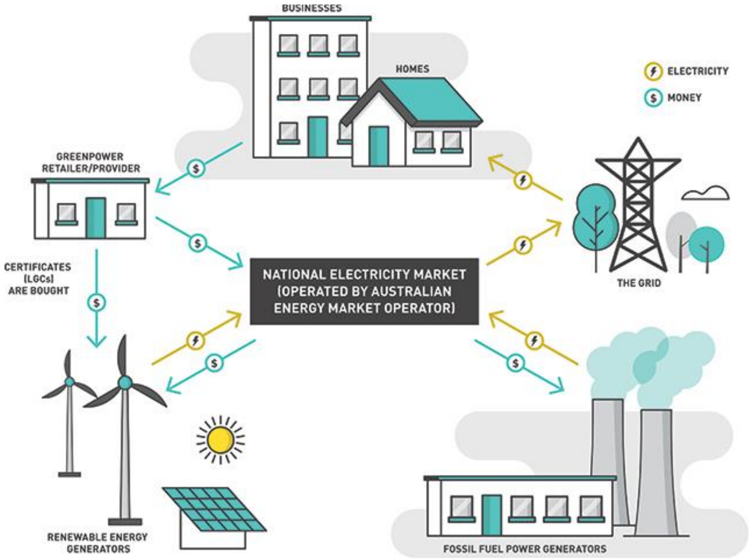

Figure 9: System of guarantees of origin and certificates explained in an Australian context; Source: https://www.choice.com.au

Electric utilities have to balance their guarantees of origin with the electricity supplied on a yearly basis. Temporal variations within days, weeks and seasons are not reported and thus disregarded in the electricity mix based on guarantees of origin. An electricity mix based on GOs is thus an attributional annual average electricity mix. In this report annual average electricity mixes based on GOs are listed and treated separately due to their particularities described above.

The Swiss supply mix used for instance in life cycle assessments of buildings according to the technical bulletin SIA 2040 SIA energy efficiency path (SIA 2017) is based on the accounting of GOs. The life cycle inventories of the Swiss supply mix in 2014 were compiled by Messmer and Frischknecht (2016) using the “Cockpit Stromkennzeichnung” published by Swissgrid (2016). This is an aggregation of the reported electricity certificates of all electric utilities in Switzerland. The Swiss supply mix contains a relevant share of non-verifiable electricity not covered by GOs.[21] The technological composition of non-verifiable electricity needs to be suitably approximated in the life cycle inventory. The European residual mixes published by the Association of Issuing Bodies (AIB 2015) account for the non-cancelled GOs in the European electricity market. This so-called European attribute mix (EAM) was used to model the share of non-verifiable electricity in the Swiss supply mix 2014 (Messmer & Frischknecht 2016).

The “Cockpit Stromkennzeichnung” does not distinguish whether or not the quality of electricity was purchased from the same source like the physical amount of electricity. Hence, the electricity mix based on the purchases of the physical amounts of electricity and its supply to Swiss consumers may differ from the one reported in the “Cockpit Stromkennzeichnung”. Several utilities, such as EKZ offer electricity products including significant shares of European hydroelectric power. It is likely that these utilities purchase power from e.g. Axpo with significant shares of nuclear power, and add GOs from Norwegian hydroelectric power plants to create electricity products which appear to be 100 % renewable.

The KBOB guidelines for life cycle assessment of building products (KBOB et al. 2015) include rules on how to deal with GOs. Companies which may choose their electricity supplier must purchase the physical amounts and the quality of electricity from the same power plants (congruency). Otherwise they shall establish the

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[21] The declaration of non-verifiable electricity on the electricity labelling is no more allowed since 1 January 2018 (UVEK 2017).

environmental profile of the mix of the physical electricity purchase and may report on the environmental benefits due to the purchase of GOs of renewable electricity as an improvement measure.

Norway is issuing Guarantees of Origin (GOs) for electricity. On average Norway is a net exporter of electricity, Norwegian power suppliers that do not purchase GOs for their sold electricity, must refer to NVEs (The Norwegian Energy Regulatory Authority) national electricity disclosure when communicating the production sources. NVEs base their calculations for the disclosure on the best practice recommendations from the European RE-DISS project (2020), and is based on European trade of GOs and the European Attribute Mix (EAM)/European residual mix for Norway, undertaken by Association of Issuing Bodies (AIB 2016, 2017, 2018 and 2019). Table 6 shows the relationship between Production, Exchange, Consumption and GOs in Norway for 2015 to 2018 (NVE 2016, 2017, 2018 and 2019).

Table 5: Disclosure of Norwegian electricety 2015 to 2018 (NVE 2016, 2017, 2018 and 2019).

Year	**Consumption (TWh)**	**Norwegian Production (TWh)**					**GO Norway (TWh)**		**EAM production (TWh)**				**Norwegian Production**	**Disclosure Norwegian Power**
		Hydro	Wind	Thermal Biofuel	Fossil Thermal	Total	GOs issued	Gos redeemed	Renewable Power	Nuclear Power	Fossil Thermal	EAM total	g CO2/kWh	g CO2/kWh
2015	130,4	139,0	2,5	0,2	3,1	145,0	134,7	19,4	3,9	34,2	59,6	97,7	17,0	509
2016	133,1	144,0	2,1	0,2	3,2	149,5	136,0	21,0	3,7	23,8	68,9	112,0	16,0	530
2017	134,1	143,0	2,1	0,2	3,2	149,3	109,0	25,0	7,6	29,4	59,2	108,7	16,4	531
2018	136,7	139,5	3,9	0,2	3,3	146,8	140,9	19,7	2,6	39,1	64,1	105,7	18,9	520

And here is the foundation for a controversy since Norwegians households pays for electricity based on the floating price on the European electricity market, and only 20% buys GOs. Due to the bottlenecks in the import/export to Norway, the Norwegian electricity prices is on average lower than the European prices. Thus, most Norwegians regard their electricity to be (mostly) hydropower with a very low carbon footprint, whereas the disclosure shows a significantly higher carbon footprint (a factor of 25!), because more than 85 % of the GOs are exported.

Annex B: National electricity mix models

B.1 Introduction and scope

This Annex is structured according to the list of mixes in Annex A and within each of the mixes according to countries/organisations. It describes the actual composition of the different mixes as applied/modelled in the different countries reporting.

B.2 Present annual average electricity mix

Denmark

The LCA data for Danish electricity supply and district heating for use in LCAbyg was developed by Cowi consulting in 2016 (COWI 2016). Table 6 shows the electricity mix for the dataset representing year 2015. Based on this data environmental impact categories are calculated.

Table 6: Electricity mix in percentages (%) in Danish electricity production for LCA dataset representing year 2015 (COWI 2016).

	Condense (steam turbine)		CHP (steam turbine)					Engine					
	Coal	Wood + Wood chips	Coal	Gas	Wood + wood chips	Straw	Waste	Biogas	Natural gas	Gas turbine	Industry + bio factories	Wind	PV
Electricity mix	12%	0%	19%	5%	3%	1%	6%	3%	1%	4%	2%	42%	2%
Electricity efficiency	43%	43%	34%	34%	34%	34%	34%	37%	37%	43%	-	-	-

France

In the E+C- label, the electricity mix is not indicated but environmental indicators are provided for various uses of electricity: heating, cooling, domestic hot water, lighting and other uses, for housing and tertiary buildings.

In the EQUER design tool, the user can input a present constant electricity mix for heating and for other uses, or choose a variable mix (see below). The annual average mix in 2018 is 71.7% nuclear plants, 12.4% hydro-electricity, 7.2% gas and coal thermal plants, 5.1% wind, 1.9% PV and 1.8% bioenergies.

Hungary

In Hungary, nuclear power, fossil fuels and import dominate the electricity mix, with shares of 34%, 26% and 34%, respectively, in 2018 in the supply mix (MAVIR 2019). Renewables account only for 4% and 2% come from other sources. The life cycle based non-renewable cumulative energy demand was 12.1 MJ-eq/kWh and GHG emissions were 486 g CO_2-eq/kWh (Kiss et al. 2019) in 2018. With these values, Hungary is slightly above the average of the UCTE countries.

As there is no standard national assessment data, LCA practitioners/ researchers generally use data available in generic databases for the electricity mix. In studies by different researchers, different electricity mix, in some cases older datasets are applied, depending on the database available to the researcher.

Table 7: Life cycle environmental impact of the Hungarian average annual electricity mix 2018, reference unit: 1 kWh electricity supplied to the low voltage customers (Kiss et al. 2019)

Indicator	Unit	Supply mix
Cumulative energy demand, non renewable	MJ-eq/ kWh	12.1
Climate change – GHG emissions (GWP 100)	g CO_2-eq/kWh	485.8
ReCiPe-Endpoint (2016), total	1000 Points/ kWh	50.5

Switzerland

The Swiss average annual electricity mixes were last updated in 2020 and cover the year 2018 (Krebs & Frischknecht 2020). In Switzerland five different annual average mixes are distinguished: the production mix (electricity produced with power plants located in Switzerland), the suppliers mix (electricity delivered to customers in Switzerland), the average electricity product based on renewable energies, the consumer mix (suppliers mix minus electricity products from renewable energies) as well as the production mix including commercial trade.

In Switzerland, electricity is mainly produced with hydroelectric power plants (56.0 %), nuclear power plants (37.6 %) and from wastes (1.9 %). The Swiss suppliers' electricity mix is distinctly different from the production mix. The share of hydroelectric power plants (56.0 %) is the same but the share of nuclear power plants (18.4 %) is distinctly lower in the suppliers mix compared to the production mix. This is due to substantial GO imports (29.3 %) from renewable (17.7 %), non-renewable (1.6 %) and non-verifiable[22] (6.7 %) power plants.

The average Swiss electricity product based on renewable energies is composed of 94.4 % hydroelectric power, 2.7 % domestic PV electricity, 1.8 % domestic and foreign wind power and electricity from further renewable sources (about 1.0 %). The Swiss average annual consumer mix contains less hydroelectric power (39.8 %), because a substantial share of Swiss hydroelectric power is sold separately with dedicated electricity products. The shares in nuclear power (26.1 %) and of imports (36.4 %) in the consumer mix are significantly higher than in the suppliers mix.

Table 8 shows the environmental impacts of the four different Swiss average annual electricity mixes 2018.

Table 8: Environmental impacts of the Swiss average annual electricity mixes 2018, reference unit: 1 kWh electricity supplied to the low voltage customers (Krebs & Frischknecht 2020)

Indicator	Unit	Production mix	Supply mix GO	Electricity product based on renewable energies	Consumer mix GO	Production plus commercial trade
Greenhouse gas emissions	g CO_2-eq/kWh	29.6	54.7	15.7	71.0	128.0
Cumulative energy demand, non renewable	kWh oil-eq/kWh	1.65	1.08	0.04	1.51	2.08
Cumulative energy demand, renewable	kWh oill-eq/kWh	0.70	0.91	1.17	0.81	0.59
Environmental impacts (ecological scarcity 2013)	UBP/kWh	208	165	48	215	324

The greenhouse gas emissions of the average Swiss electricity product based on renewable energies and the Swiss production mix amount to 15.7 g CO_2-eq/kWh and 29.6 g CO_2-eq/kWh, respectively. The greenhouse gas emissions of the average suppliers and consumer mixes based on GO are substantially higher (54.7 g CO_2-eq/kWh and 71.0 g CO_2-eq/kWh). The significant increase compared to the production mix is mainly caused by the import of electricity from non-verifiable sources and, to a minor extent from known fossil-thermal power plants. The Swiss annual electricity mix 2018 based on production plus commercial

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[22] The non-verifiable power plants are modelled with the Swiss Residual mix 2018.

trade emits 128 g CO_2-eq/kWh, thus more than double the amount emitted by the Swiss supply mix 2018 based on GO.

The cumulative energy demand, non-renewable of the production, the suppliers, and the consumer electricity mix amounts to 1.65, 1.08 und 1.51 kWh oil-eq/kWh, respectively. The cumulative energy demand, non-renewable of the Swiss annual mix 2018 based on production and commercial trade is much higher with 2.08 kWh oil-eq/kWh whereas the CED non renewable of the average Swiss electricity product based on renewable energies is much lower with 0.04 MJ oil-eq/kWh. Nuclear power and electricity imports from unknown sources are the main drivers of the cumulative energy demand of Swiss electricity.

The environmental impacts of the average Swiss electricity product based on renewable energies quantified with the Swiss eco-factors 2013 of the ecological scarcity method amount to 48 eco-points/kWh and are much lower than the environmental impacts of the other mixes. The environmental impacts of the production, the suppliers, the consumer and the annual mix based on production and commercial trade are at 208, 165, 215 and 324 eco-points /kWh, respectively. The specific environmental impacts of electricity from hydroelectric and other renewable power plants are low. Nuclear power plants and imports from non-verifiable power plants as well as the electricity grid cause the main share of environmental impacts.
Most life cycle assessment studies, including the building sector, apply the consumer mix based on GO to model the electricity demand during operation of buildings located in Switzerland and in manufacturing construction materials produced in Switzerland. In 2021 the consumer mix will be represented by the annual mix based on production and commercial trade.

Sweden

The most commonly used emission factor for the Swedish annual average electricity mix is based on the work of the EU Joint Research Center (JRC) (Moro & Lonza, 2018). This represents the Swedish production mix, subtracting exports and adding imports and including grid losses. The calculation is based on data from IEA, ENTSO-E and Eurostat (European Network of Transmission System Operators, 2020; Eurostat, 2020; International Energy Agency, 2015). As of the beginning of 2020, the commonly used value is still based on the JRC calculation mentioned above, which relies on data for the year 2013. However, an updated value for the year 2018 is used for the development of the $NollCO_2$ certification. The value for 2013 is 47 gCO_2e/kWh for the supply mix (considering production, imports, exports and losses) and 25 gCO_2e/kWh for the production mix (considering only production and losses; this value is not commonly used). The updated value for 2018 for the supply mix is 22 gCO_2e/kWh (the difference is explained primarily by the fact that Sweden imported more electricity from Norway in 2018, and the Norwegian electricity mix has a comparatively low emission factor).

It should be noted that some other Swedish studies (e.g. Erlandsson, Sandberg, Berggren, Francart, & Adolfsson, 2018), as well as the Tidstegen tool for consequential assessments of energy solutions (Gode et al., 2015), use a Nordic electricity mix rather than a Swedish mix. The Nordic scope is also used within the Fossil Free Sweden initiative to develop a method for voluntary assessments of greenhouse gas emissions within the construction and infrastructure sector (although the development of this method is at an early stage)[23]. The Nordic scope represents the supply of electricity on the common market Nordpool. However, the Swedish Energy Agency now recommends the use of a national electricity mix, in accordance with practices in other European countries.

Norway

There is no average emission factor for the electricity in Norway. But the disclosure of electricity for Norway gives two emission factors, depending on whether the consumer has purchased a GO or not. For 2019 the emission factor for electricity was 18,9 g CO2eq/kWh with GO and 529 g CO2eq/kWh without GO. In the Norwegian standard NS3720:2018 („Method for greenhouse gas calculations for buildings“) requires the use

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[23] http://fossilfritt-sverige.se/fardplaner-for-fossilfri-konkurrenskraft/fardplaner-for-fossilfri-konkurrenskraft-byggbranschen/

of the future Norwegian production mix (2050, 18 g CO_2/kWh) or a future European electricity mix (2050, 136 g CO_2/kWh).

B.3 Future electricity mixes

Denmark

The LCA data for Danish electricity supply and district heating for use in LCAbyg was developed by Cowi consulting in 2016 (COWI 2016). Table 10 shows the electricity mix for the dataset representing the forecasting scenario for year 2015-2050. Based on this data environmental impact categories are calculated. The table shows an example for GHG emissions but other environmental impact categories are calculated as well.

Data for year 2015, 2020 and 2025 are from "Denmark's Climate and Energy Projection 2014". For year 2035 and 2050, data is calculated on the basis of "Energy scenarios against 2035 and 2050" as an average between the so-called wind scenario and the so-called biomass scenario.

CHP and condensation reflect different operating patterns. During condensation operation, only electricity (with a relatively high efficiency) is produced. In cogeneration operations, both electricity and district heating are produced (where the electricity efficiency is slightly lower, while, on the other hand, one uses more of the fuel by simultaneously producing district heating).

Allocation of potential environmental impacts between electricity and district heating is included in the data submitted by the Danish Energy Agency before the initiation of the emission factors. This allocation is expressed via the efficiencies.

Generally, the inventory is based on the technologies used today. Therefore, it is assumed that a potential production expansion could be carried out with the existing production equipment or similar equipment. In addition, the efficiencies for the individual types of plants do not change over time from 2015 to 2050 according to data from the Danish Energy Agency (COWI 2016).

Table 9: Electricity mix in percentages (%) in Danish electricity production for LCA dataset representing year 2015 (COWI 2016). Greenhouse gas emissions in g $CO_{2\text{-equivalents}}$ in parenthesis.

	Condense (steam turbine)		CHP (steam turbine)					Engine					
Year (and GHG emissions)	Coal	Wood + Wood chips	Coal	Gas	Wood + wood chips	Straw	Waste	Biogas	Natural gas	Gas turbine	Industry + bio factories	Wind	PV
2015 (352)	12%	0%	19%	5%	3%	1%	6%	3%	1%	4%	2%	42%	2%
2020 (201)	9	0	6	2	11	1	5	1	5	2	2	53	3
2025 (169)	9	0	4	1	12	1	5	1	3	3	2	56	4
2035 (31)	0	9	0	0	11	0	6	6	0	0	1	65	2

2050 (24)	0	9	0	0	1	0	5	3	0	1	2	76	3

France

In the EQUER design tool, the user can input a constant future electricity mix for heating and for other uses, or choose a variable mix (see below). Scenarios for a future mix have been elaborated by various organisations, e.g. the French Transmission System Operator (RTE) and the Agency for energy management and environment (ADEME).

Hungary

In the South East Europe Electricity Roadmap (Szabó et al. 2017) project three different scenarios were established for the development of the Hungarian electricity mix until 2050. In the "No target" scenario, no long-term goal is set for carbon-dioxide emission reduction. In the "Decarbon" scenario an emission reduction target of 94% is set for 2050 compared to the 1990 emission levels in line with the goals of the European Union. In the "Delayed" scenario, policy makers react to the European goals but with less intensity in the first years and a significant increase in renewables from 2035.

The forecast for the electricity mix was developed by the interaction of the European Electricity Market Model (EEMM) of the Regional Centre for Energy Policy Research (REKK), and the Green-X model, developed by the Energy Economics Group of the Vienna University of Technology. Based on this forecast, an environmental assessment has been carried out (Kiss et al. 2019).

All scenarios achieve a reduction in the environmental impact of electricity supply, but there are significant differences between the different scenarios. Depending on the scenario, the GHG emissions are expected to decrease to 340 or 42 g/kWh in the No target and the Delayed scenario, respectively. All the three scenarios included nuclear-based generation based on the latest available information on the decommissioning and commissioning date of "Paks 1" (existing) and "Paks 2" (planned) nuclear power plants. The two power plants (or at least some of their blocks) will operate in parallel between 2030 and 2036. The nuclear share is around 35% in all long-term scenarios, except in the years of parallel operation.

Table 10: Life cycle environmental impact of 1 kWh supplied electricity, low voltage for three different future scenarios for 2050 (Kiss et al. 2019)

Indicator	Unit	No target scenario	Decarbon scenario	Delayed scenario
Cumulative energy demand, non renewable	MJ-eq/ kWh	11.1	7.7	7.5
Climate change – GHG emissions (GWP 100)	g CO_2-eq/kWh	340.8	63.7	42.1
ReCiPe-Endpoint, total (2016)	1000 Points/ kWh	34.8	8.15	6.1

Switzerland

The future average annual electricity mix of Switzerland is based on the energy strategy 2050 scenarios of the Swiss Government (Prognos 2012). The LCA of these electricity mixes is published in Wyss et al. (2013).

In 2011 the exit from nuclear power was declared. In regard for a sustainable and 'green' future, Switzerland outlined different options for prospective energy strategies and securitiy of energy supply. In this context the Swiss Federation elaborated the Energy Strategy 2050, in which three different scenarios for possible future energy situations were designed. The scenarios are 'business as usual' (WWB), 'new energy policies' (NEP)

and 'political measures' (POM). The scenarios differ in energy policies, electricity demand, production volumes and the technological mix for achieving security of energy supply.
This study analyzes environmental impacts of three electricity mixes in 2050, according to the scenarios. The analysis is conducted for the year 2050 and for Switzerland. The functional unit of this study is 1 MJ of electricity consumed in Switzerland (low voltage). The environmental impact categories greenhouse gas emissions (based on GWP 100), 'cumulative energy demand' (CED) and ecological scarcity 2006 were assessed.

The electricity production was modelled with present technologies. However the shares per production technology comply with the year 2050 (in accordance with the scenarios from the Energy Strategy 2050). Two data-sets are generated: one regards only domestic production and one includes electricity trade according to present trade volumes. Electricity import and trade is modeled based on scenario information about the European electricity mix in 2050. For the three scenarios WWB, NEP and POM dedicated and consistent European mixes were chosen. Within the scenarios NEP and POM, European coal and natural gas fired power plants are equipped with carbon capture and storage (CCS). Table 11 shows a comparison of all three scenarios and the indicators analyzed for the electricity mixes in 2050 as well as the environmental impacts of the present electricity mix in Switzerland and Europe. Figure 10 to Figure 12 show a graphical comparison of the environmental impacts of the electricity mixes with and without trade.

Table 11: Summary of the life cycle based cumulative environmental impacts of electricity mixes according to the scenarios in the Energy Strategy 2050, per MJ electricity, low voltage

Electricity mix	**Primary energy total** MJ oil-eq/MJ	**Primary energy non-renewable (fossil and nuclear)** MJ oil-eq/MJ	**Primary energy non-renewable - fossil** MJ oil-eq/MJ	**Primary energy non-renewable - nuclear** MJ oil-eq/MJ	**Primary energy renewable** MJ oil-eq/MJ	**Primary energy waste/ wasteheat** MJ oil-eq/MJ	**Carbon dioxide fossil** g CO_2-eq/MJ	**Greenhouse gas emissions** g CO_2-eq/MJ	**Ecological scarcity** eco-pt/MJ
WWB, option C	1.67	0.96	0.94	0.02	0.72	0.00	54.2	59.2	39.5
NEP, option C+E	1.38	0.28	0.26	0.02	1.09	0.00	17.0	21.2	26.6
POM, option E	1.40	0.29	0.23	0.06	1.11	0.00	12.8	16.9	26.8
WWB incl. trade, option C	2.20	1.61	1.28	0.32	0.59	0.00	86.9	93.7	76.9
NEP incl. trade, option C+E	1.58	0.41	0.39	0.02	1.18	0.00	23.4	27.5	32.7
POM, incl. trade, option E	1.92	1.06	0.69	0.38	0.86	0.00	16.8	21.8	45.1
CH-Production mix[1]	2.41	1.76	0.10 [2]	1.65 [2]	0.65 [2]	-	0.007 [2]	8.3	75.7
CH-Supply mix[1]	3.05	2.63	0.51 [2]	2.13 [2]	0.42 [2]	0.02 [2]	0.038 [2]	41.3	125
UCTE-Mix[1]	3.54	3.32	2.01 [2]	1.32 [2]	0.22 [2]	-	0.156 [2]	165.0	177

[1] data from the KBOB recommendation 2009/1, July 2012 (KBOB et al. 2012)

[2] data from Frischknecht & Itten (2011)

The electricity mix of the scenario NEP has the lowest environmental impacts regarding CED and ecological scarcity. Within the NEP scenario a strict policy for renewable energy is proclaimed. Hence the electricity mix of the NEP scenario has the highest share of renewable energy sources and only little fossil fuels. As there is no import, there is no electricity from european nuclear or coal power. The electricity mix of the POM scenario has a slightly lower share of renewable energy sources compared with the electricity mix of the NEP scenario. It contains hardly any fossil fuel based electricity. Furthermore about 9 % of the electricity is imported. European fossil fuel based power plants in the electricity mix imported are equipped with CCS-technologies. In consequence the electricity mix of the scenario POM causes slightly lower greenhouse gas emissions compared to the electricity mix of the NEP scenario.

The use of fossil fuels has a large impact on the indicators GHG emissions and CED. Hence the electricity mix of the scenario WWB, which has no particular emphasis on renewable electricity, causes higher environmental impacts (all indicators) than the electricity mix of the NEP or POM scenarios.

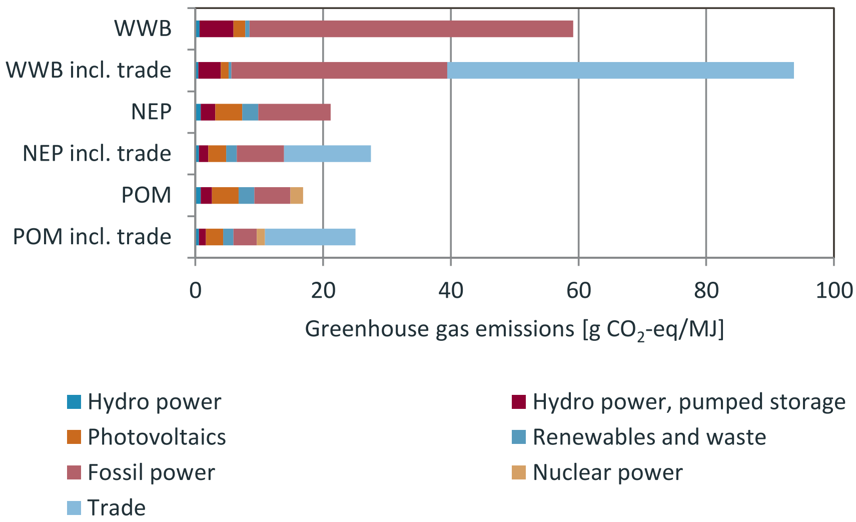


Figure 10: Greenhouse gas emissions of the electricity mixes, with and without trade

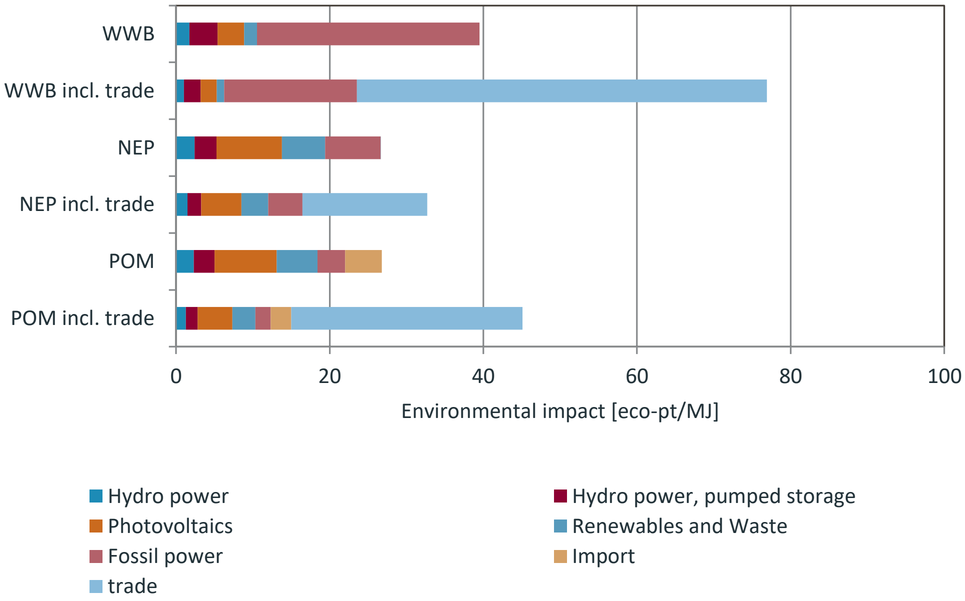


Figure 11: Environmental impacts of of the electricity mixes, with and without trade, ecological scarcity method 2006

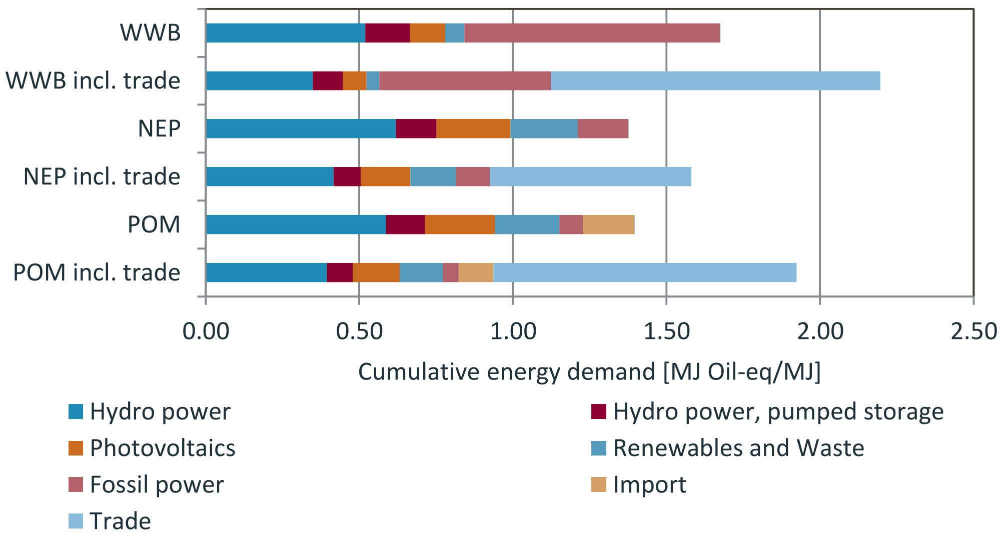


Figure 12: Cumulative energy demand of the electricity mixes, with and without trade

The environmental impacts of the aspired electricity mixes in the year 2050 are clearly lower than those in Switzerland in 2009 (production mix as well as supply mix). However the current production mix causes lower greenhouse gas emissions than any of the three future electricity mixes, due to todays share of domestic electricity production from hydroelectric and nuclear power. At the same time, nuclear power is the main reason for the high environmental impacts of the current electricity mixes. The ENTSO-E electricity mix causes the highest amount of greenhouse gas emissions and the largest environmental impacts. The share of non renewable energy sources in the year 2050 decreases about 45 to 84 % (depending on the scenario) compared to the present Swiss production mix.

The environmental impacts with electricity trade are larger than without trade. This is especially true for the electricity mix of the scenario WWB, which has a large share of fossil fueled electricity produced without CCS-technologies. It is noticeable, that POM electricity has the lower global warming potential than NEP electricity (both including trade). This results from the lower share of fossil fueled domestic electricity production and the high share of imported electricity, which includes fossil fueled electricity produced with CCS-technologies. These come with low CO_2-emissions.

Sweden

It is not yet common to include future scenarios for the energy mix in building LCAs in Sweden, but several recent initiatives are taking up this issue. First, a recent report includes a model to assess future greenhouse gas emissions from the Swedish building sector, including a future scenario for the energy supply (Erlandsson, 2019). This scenario is based on long-term forecasts from the Swedish Energy Agency (Swedish Energy Agency, 2019). It leads to an emission factor for Swedish electricity of 36 gCO_2e/kWh in 2035 and 22 gCO_2e/kWh in 2050. Second, assessments in the upcoming NollCO_2 certification system use a future emission factor based on forecasts from the European Union until 2050. Electricity production in Sweden and the rest of Europe is assumed to be carbon-neutral in 2050, in accordance with long-term strategies from Sweden and the EU. The emission factor of electricity is assumed to decrease linearly between 2020 and 2050, reaching 0 in 2050. Since these forecasts lead to decreasing emission factors for electricity, one of the consequences is that environmental benefits from exported PV power decrease over time (since NollCO2 relies on an avoided burden approach taking into account potentially avoided emissions from locally produced electricity exported to the grid). Third, the Tidstegen (time step) tool for consequential assessments of energy measures considers three future scenarios for the Nordic electricity mix, up to 2040. The scenarios differ notably regarding assumptions about the cost of carbon emissions in the future. A linear programming model is used to asses the consequences of a change in demand on different production technologies, depending on the year, the season and the time of day when this change happens. The

Tidstegen tool calculates a marginal electricity mix including both short term and long term effects, for each of these time steps (Gode et al., 2015).

A previous work had also been carried out to develop hourly average and marginal future mixes for the Nordic electricity market, based on a scenario from the International Energy Agency (Erlandsson et al., 2018; International Energy Agency, 2016). However, results from this work are usually not used in other assessments. A number of other future scenarios have been developed in Sweden, including backcasting scenarios (i.e. scenarios where a specific goal is fulfilled), e.g. Four Futures (Swedish Energy Agency, 2016) and Beyond GDP Growth (Gunnarsson-Östling et al., 2017). Such scenarios represent developments of the energy system that are possible, but not necessarily likely. Therefore, they are usually not used in LCA.

Norway

The Norwegian Standard on LCA of buildings (NS3720:2018) has two scenarios for future electricity mix;

- Scenario 1 – NO, which gives an average CO_2 emission factor for Norwegian el. production from 2015 to 2075 of 18 g CO_{2eq}/kWh.This value calculation is based on the median values from Turconi et.al (2013).
- Scenario 2 – EU28+NO, which gives an average CO_2 emission factor for European el. production from 2015 to 2075 of 136 g CO_{2eq}/kWh. This value is calculated on basis of values from Eurostat, the EU Roadmap 2050 and Turconi et.al (2013).

The EU value does correspond to the CO_2 factor used by the Research Centre on Zero-Emission Buildings (ZEB), in the LCA for the validation of the “Zero-emission”. The ZEB framework uses a CO_2-factor of 132 g CO2eq/kWh, which is a modelled average CO_2-factor from Europe production between 2010 and 2050 (Graabak et al 2014).

However, the values for the future Norwegian production mix is much lower than the disclosure of the Norwegian electricity consumption. So in order to use Scenario 1, users has to purchase a Garantie of origien for the electricety.

B.4 Seasonal (summer/winter) average electricity mix

Denmark

No dataset available.

France

Seasonal average is not used in France, but the constant mixes defined according to the use (heating, cooling etc.) in E+C- correspond to a similar concept. The average mix is evaluated according to a consumption profile of a building type (housing or tertiary) and an electricity use (heating, hot water, lighting etc.).

Hungary

Analysis of the current electricity supply shows that the seasonal variation of the supply is very small. The difference between the environmental impact of electricity in the heating and the non-heating seasons is negligible. This is explained by the fact that the share of renewables, which have a seasonal variation, is very small in the Hungarian supply mix.

Some difference can be observed between the environmental impact in different months, mostly due to a slight variation in the relative contribution of nuclear power plants and a slight increase in renewables in the summer. In the future electricity mix with more renewables, the difference between months is expected to grow (Kiss et al 2020).

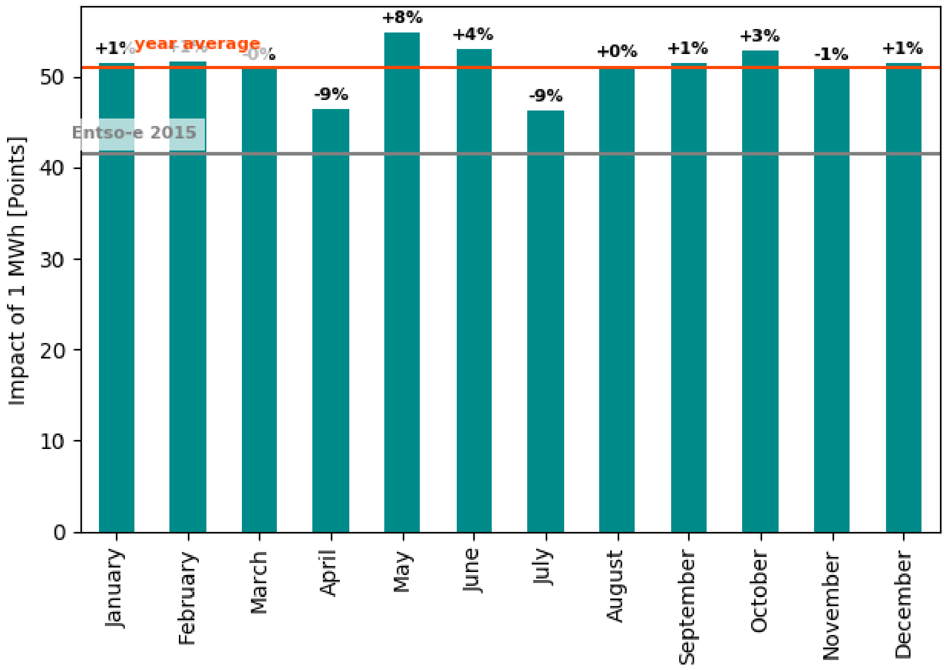


Figure 13: Average environmental impact of the electricity mix in each month for year 2018 compared to the year average, “Decarbon” scenario, ReCiPe Endpoint total indicator (Kiss et al. 2019)

Switzerland

No dataset available yet.

Sweden

The seasonal variability of the energy supply is usually not taken into account in Swedish LCAs. The Tidstegen (time step) method tackled this issue for consequential LCAs of building energy solutions (Gode et al., 2015). The Tidstegen method has not seen much application in Sweden, but has recently been published as a free software tool, which might increase its adoption (Gode, Nilsson, Ottosson, & Sidvall, 2019).

The general assumption in Tidstegen is that time resolution does not matter in the short term, i.e. a change in energy demand in a building will have the same impact in the coming 5-15 years regardless of whether it happens in winter or summer, during peaks or off-peak. The main justification for this assumption is the large share of hydropower on the Nordic grid, which can regulate seasonal and hourly changes in demand. Since the yearly output of hydropower is limited, an increase in demand will result in an overall increase in importation of electricity produced with fossil fuels in Denmark or Germany, regardless of the season or time of day when this increase in demand happens.

However, in the long term, time resolution matters, and the marginal mix depends on how supply and demand will evolve in the future. A change in electricity demand will have different short- and long-term consequences, depending on the year, season and time of day (daytime or nighttime) when it happens. Three future scenarios are used. A different marginal mix taking into account short- and long term effects (and a corresponding emission factor) is calculated for each time step and each scenario. A measure is assumed to have positive (resp. negative) environmental effects if its effects are positive (resp. negative) in most scenarios.

Seasonal aspects are even more significant when assessing the impact of heating (in Sweden, district heating is the prominent solution). Gode et al. (2015) then use dynamic emission factors for heating depending on outside temperature.

B.5 Hourly resolution of the electricity mix

Denmark

No dataset available.

France

Hourly values of electricity production using different technologies are provided by the French Transmission System Operators (RTE). The data includes imported quantities from different countries. Using some assumption regarding imported electricity (e.g. yearly average production mix corresponding to the exporting country), the mix corresponding to consumed electricity has been estimated for past years. The quantity of imported electricity was 5.5% of the consumption in 2018.

An electric system model has been developed (Roux et al. 2017) in order to evaluate hourly mix values according to energy transition scenarios and climatic data. This model has been linked to the Building LCA tool EQUER. Energy consumption in buildings is generally estimated using "typical meteorological years" (TMY), corresponding to a statistical average of e.g. 20 real years. The electricity supply mix corresponding to such TMY is evaluated on an hourly basis using the electric system model. Energy transition scenarios may provide installed capacities in future years, and the corresponding hourly mix can also be evaluated using the same electric system model. Effects of climate change on e.g. hydroelectric production can be taken into account.

This model has been complemented in order to integrate short term and long term temporal variation (Frapin et al., 2021) by connecting three models addressing: market allocation on a national scale over a long term period, short term variation (i.e. seasonal, daily and hourly) of the electricity mix also on a national scale, and building energy simulation at the scale of one building. The short term variation model has been updated using more recent data from the French TSO.

The bottom-up linear optimization model computes a least cost pathway for the electricity system subject to the satisfaction of specified service demands and user specified constraints, accounting for the interaction with the gas supply system. This allows for systemic description of gas-to-power and power-to-gas interactions. It also includes a new description of flexibility options on the demand-side which influence the penetration of renewables and the shape of the load. This optimisation process provides electricity production mix scenarios according to 4 main parameters regarding: the ambition level of the environmental policy (from 30 €/tCO_2 carbon penalty to carbon neutrality), technology acceptance (with or without carbon capture and storage, nuclear plants), acceptance of demand control technologies by end-users, and cost reduction scenario of solar and wind technologies. 50 energy transition scenarios have been developed by combining these 4 parameters.

Three LCA methods were used. The average approach, associated to attributional LCA evaluates an average electricity mix for each hour of the reference year, which is then linked to technologies life-cycle impacts per kWh. Associated to consequential LCA, two marginal approaches were compared. The first one evaluates a marginal electricity production using the electricity mix model to simulate an additional electricity demand evaluated for the studied project using the building energy simulation model. The second one uses the GHG Protocol procedure (GHG protocol, 2007) from a reference electricity production, ranking the technologies by merit-order and choosing a 10% operational margin. The first one is more accurate but also time-consuming; the second one is fast, more flexible (adaptable to electricity mix results from other models or scenarios) but less specific to a given project.

This methodology has been applied to a case study including a sample of buildings in the French context, but it can be used in other countries. Six buildings have been studied over 100 years considering the 50 energy transition scenarios mentioned above. Results show that the environmental impacts vary more depending on the scenarios than on building types. They depend on the use: for instance CO_2 emissions are higher for heating due to a larger use of thermal plants during winter peak demand periods, whereas avoided impacts considered for exported PV production mostly correspond to low demand periods in summer, during which low carbon electricity production capacities are available. Marginal mixes considered in consequential LCA are mainly composed of coal, gas, nuclear and peak technology production which explains the highest values of the different impacts compared to average mixes used in attributional LCA. The error bars correspond to upper and lower values for the 50 scenarios.

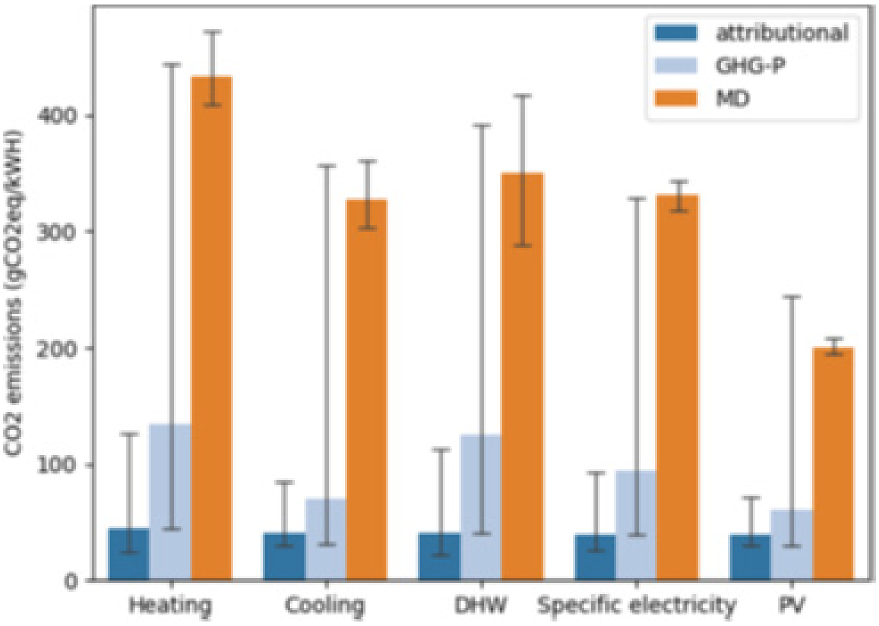


Figure 14a: Use specific CO2 emissions according to the LCA method (Frapin et al., 2021)

Impacts of universal mixes (average of all uses) obtained using the CMA market allocation model, considering a reference (C1) or reduced (C2) cost of wind and solar technologies, are compared to scenarios defined by the French environment agency (ADEME) and TSO (RTE).

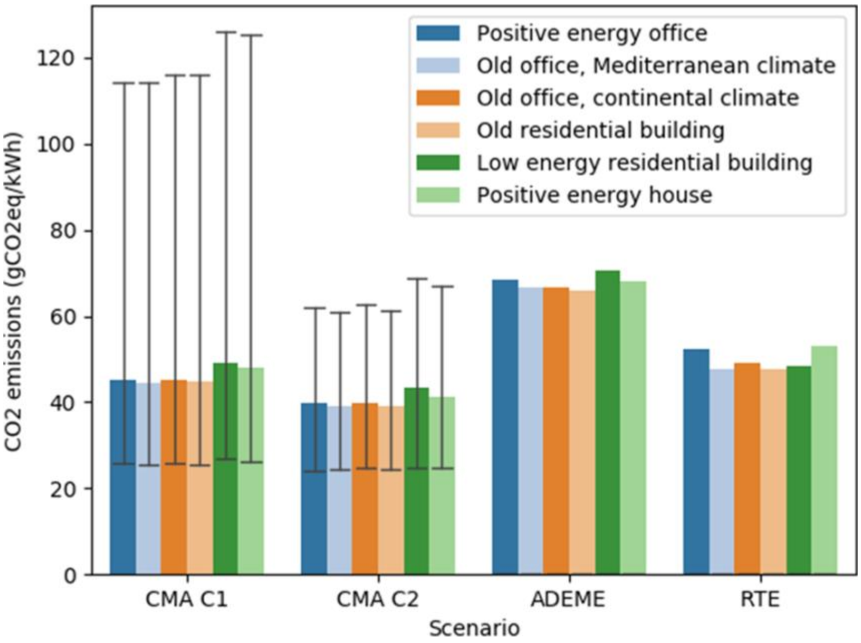


Figure 15b: Sensitivity analysis of GHG emissions to the scenario and type of building (attributional LCA) (Frapin et al., 2021)

This approach allows to address uncertainties related to electricity production over the long life span of buildings (100 years are considered in this study).

Hungary

In today's electricity mix in Hungary, the intra-annual variation of the environmental impact of electricity supply is ± 15% for CED n.r. and ± 30% for GHG emissions and ReCiPE. The coefficient of variation is 5% for CED, and 10% for GHG emissions and ReCiPe (Kiss et al. 2019).

The application of the European Electricity Market Model (EEMM) makes it possible to analyse the hourly resolution of the electricity mix also in the long term. Research shows that the coefficient of variation in the environmental impact of electricity is expected to significantly increase in the future due to decarbonization and a higher share of renewables (CV = 23% for CED n.r., 77% for GHG emissions, 59% for ReCiPe) (Kiss et al 2020). This suggest that in the future it will be even more important to consider the intra-annual variation of the electricity mix. Simplification to an annual mix may lead to under- and overestimations if electricity use is not constant during the year.

Switzerland

In hourly assessment, different examples of the physical approach can be mentioned including: the computational tool developed as part of the EcoDynbat project at HES-SO (Padey et al, 2020) and the ELCAB project led by Treeze Ltd.

EcoDynBat project, method & computational tool

The EcoDynBat research project (Dynamic LCA of buildings) funded by the Swiss Federal Office of Energy (SFOE) from 2018 to 2020 aims to assess the effect of different intra-annual time step on the environmental impacts of the Swiss building electricity demand.

To do so, a computational tool able the calculate the hourly LCA data of national electricity mixes for Switzerland and neighbouring countries was developed. It is based on empirical data provided by TSO and other sources for Switzerland and the neighbouring countries. Such hourly LCA data does not exist yet in Switzerland or at least does not exist at this level of details using a computational approach based on a matrix inversion (see below for more information) and hourly data for both domestic production means and imports from neighbouring countries. Different steps were conducted including:

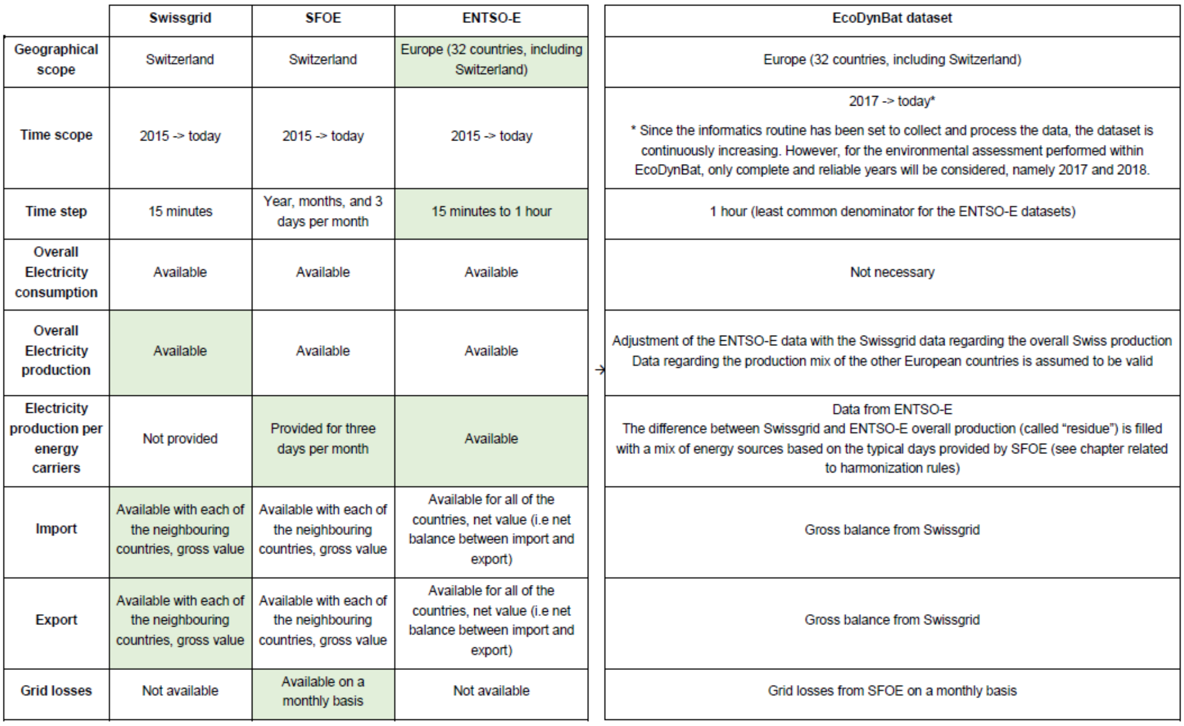
1. Data collection and adjustments
2. Matrix-based calculation based on hourly data for the electricity mixes
3. Use of the hourly electricity mix in the LCA of the energy use in Swiss buildings

<u>1) Data collection and adjustments</u>.

First, the hourly Swiss consumer mix has been defined for the years under study (e.g. 2017 and 2018). The mix is defined by considering the specific physical imports for each Swiss neighbouring countries (Germany DE, Italy IT, Austria AT and France FR) as well as Czech Republic (CZ). Indeed, a preliminary screening assessment has identified that the CZ contribution to the Swiss consumed electricity impact was significant because of the interaction of this country with Germany and Austria (cf. point 2 below for more information). The other exchanges with the neighbouring countries of AT, IT, DE, FR and CZ are also considered but the environmental impacts for these flows is assumed to be constant and to correspond to the European average electricity (from ecoinvent V3.4).

The hourly Swiss consumed electricity has been defined based on various data sources. The backbones rely on the ENTSO-E data which provides the production mixes for the different European countries as well as the physical cross boarder exchanges. Nevertheless, this data source has been found to be partially matching the EcoDynBat project objectives. First, the cross boarder exchange considered within ENTSO-E are net exchanges. Thus, the cross boarder exchanges have been modified in order to consider the gross exchanges (i.e., the import and exports at the Swiss borders) and fulfil the project scope.

The data from Swissgrid, the Swiss TSO have been use for this purpose. Then, a comparison for the production mixes with the national data sources has been performed. While the ENTSO-E data shows a correct adequacy compared to the national datasets for France, Italy, Germany and Austria, the Swiss data from ENTSO-E shows some inconsistencies compared to the national statistics from the Swiss Federal Office for Energy (SFOE). There are indeed significant differences between the ENTSO-E data and the national SFOE data for the hydroelectricity from run-of river and photovoltaic production means. The ENTSO-E data has been adjusted by correcting the production volume of these two production means with the data from the Swiss Energy statistics published by the SFOE for representative days in the year.
The next table summarizes this first important step.



	Swissgrid	**SFOE**	**ENTSO-E**	**EcoDynBat dataset**
Geographical scope	Switzerland	Switzerland	Europe (32 countries, including Switzerland)	Europe (32 countries, including Switzerland)
Time scope	2015 -> today	2015 -> today	2015 -> today	2017 -> today* * Since the informatics routine has been set to collect and process the data, the dataset is continuously increasing. However, for the environmental assessment performed within EcoDynBat, only complete and reliable years will be considered, namely 2017 and 2018.
Time step	15 minutes	Year, months, and 3 days per month	15 minutes to 1 hour	1 hour (least common denominator for the ENTSO-E datasets)
Overall Electricity consumption	Available	Available	Available	Not necessary
Overall Electricity production	Available	Available	Available	Adjustment of the ENTSO-E data with the Swissgrid data regarding the overall Swiss production Data regarding the production mix of the other European countries is assumed to be valid
Electricity production per energy carriers	Not provided	Provided for three days per month	Available	Data from ENTSO-E The difference between Swissgrid and ENTSO-E overall production (called "residue") is filled with a mix of energy sources based on the typical days provided by SFOE (see chapter related to harmonization rules)
Import	Available with each of the neighbouring countries, gross value	Available with each of the neighbouring countries, gross value	Available for all of the countries, net value (i.e net balance between import and export)	Gross balance from Swissgrid
Export	Available with each of the neighbouring countries, gross value	Available with each of the neighbouring countries, gross value	Available for all of the countries, net value (i.e net balance between import and export)	Gross balance from Swissgrid
Grid losses	Not available	Available on a monthly basis	Not available	Grid losses from SFOE on a monthly basis

Figure 16: Summary of the EcoDynBat dataset choice, in green the chosen route from the literature sources (Swissgrid, SFOE, ENTSO-E); figure taken from the final report of the EcoDynBat project

Based on these different data choices and adjustments, and including the conversion losses from high voltage to low voltage, the overall Swiss consumed electricity mix has been obtained, based on an empirical approach using, for this contribution to IEA-EBC Annex 72 project, existing data for the years 2017 and 2018[24], Figure 17.

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[24] The approach allows to regularly update the Swiss electricity hourly dataset in the future as so far only the two first years (2017 and 2018) are available in an appropriate format especially from ENTSO-E (as it is a relatively recent initiative).

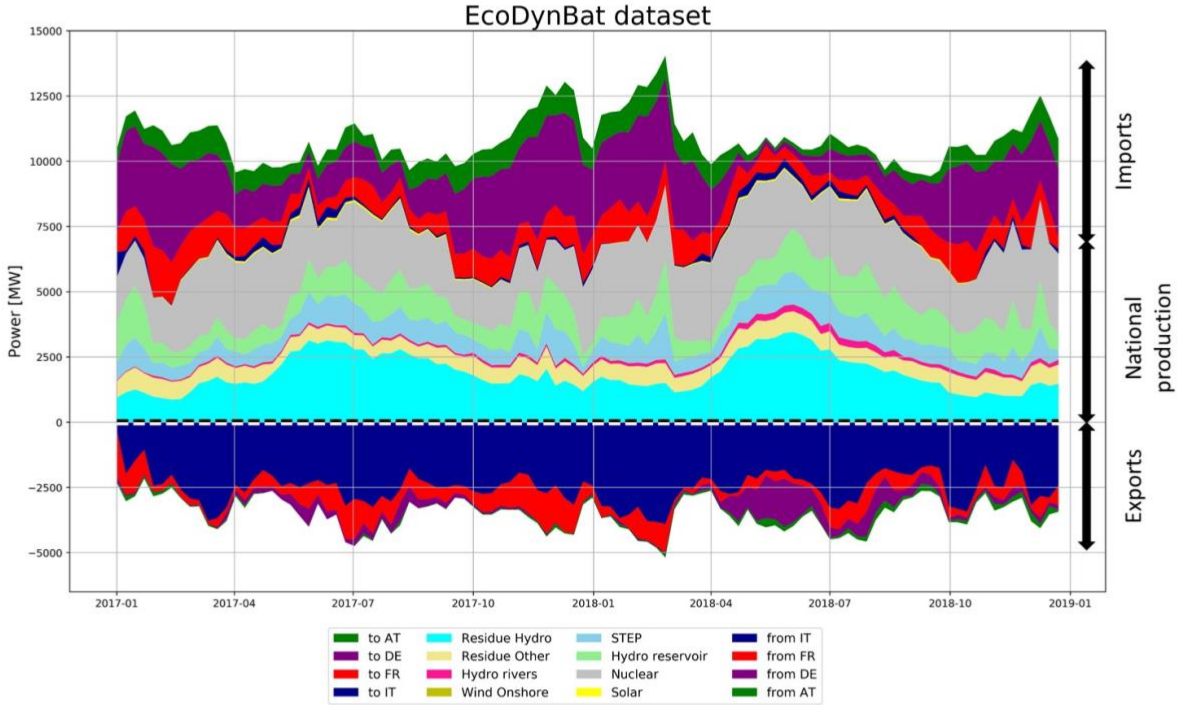


Figure 17: Swiss electricity flows; results given for the years 2017-2018

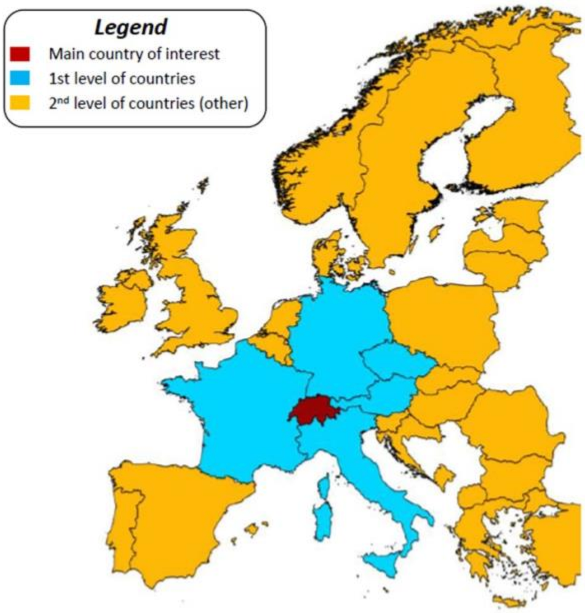
2) Matrix-based calculation to calculate the Swiss consumption mix

Then, a matrix-based approach has been used in order to calculate the contribution of each production means to the environmental impact of the Swiss consumed electricity. Generally speaking, the algorithm is able to calculate 1 kWh of consumption mix for all the European countries considered in the EcoDynBat approach. As in any matrix-based calculations, the user just needs to define the reference flow e.g., 1 kWh of consumption mix for Switzerland. Then, the matrix-based framework will perform the calculation using hourly data for all European countries.

However, in order to avoid running such a large dataset with hourly data of all European countries, a preliminary contribution analysis of impacts from countries' mixes in a standard LCA of the annual Swiss mix show that only six countries (AT, FR, DE, IT, CZ) as well as Switzerland are contributing to the total Life Cycle Impact Assessment (LCIA) indicators at 99% or above for the three commonly used indicators in the Swiss building sector: GHG emissions, Cumulative Energy Demand (CED), and the total environmental impact expressed as Ecological scarcity (UBP). All the other European countries contribute to less than 1% to the total impacts for all categories. The next table presents the obtained results:

Levels of details in the ecoinvent model of the consumers' mix	Global warming potential	Cumulative energy demand	Ecological scarcity (UBP)
Share of total impacts from CH production only	10.3%	65.0%	45.5%
Share of total impacts from CH production + imports from direct neighbors (FR, DE, IT, AT)	84.5%	95.5%	92.8%
Share of total impacts from CH production + imports from direct neighbors (FR, DE, IT, AT) + imports from AT, CH, DE, FR, IT in neighboring countries	91.4%	98.0%	96.3%
Share of total impacts from CH production + imports from direct neighbors (FR, DE, IT, AT) + imports from AT, CH, DE, FR, IT in neighboring countries + imports from CZ	98.8%	99.6%	99.5%
Share of total impacts for CH consumers' mix coming from other EU countries	1.2%	0.4%	0.5%

Finally, at each time step, a 144x144 matrix (corresponding to the production means of each considered countries, namely, DE, IT, AT, CH, CZ and FR as well as the gross cross boarder exchanges between each countries) is inversed to obtain the shares of the various production means to the Swiss consumed electricity. The next Figure presents these six countries of interest based on the initial contribution analysis including Switzerland.



Switzerland is the country of interest, the study considers:
- The variation the production mix
- The variation in the importation level

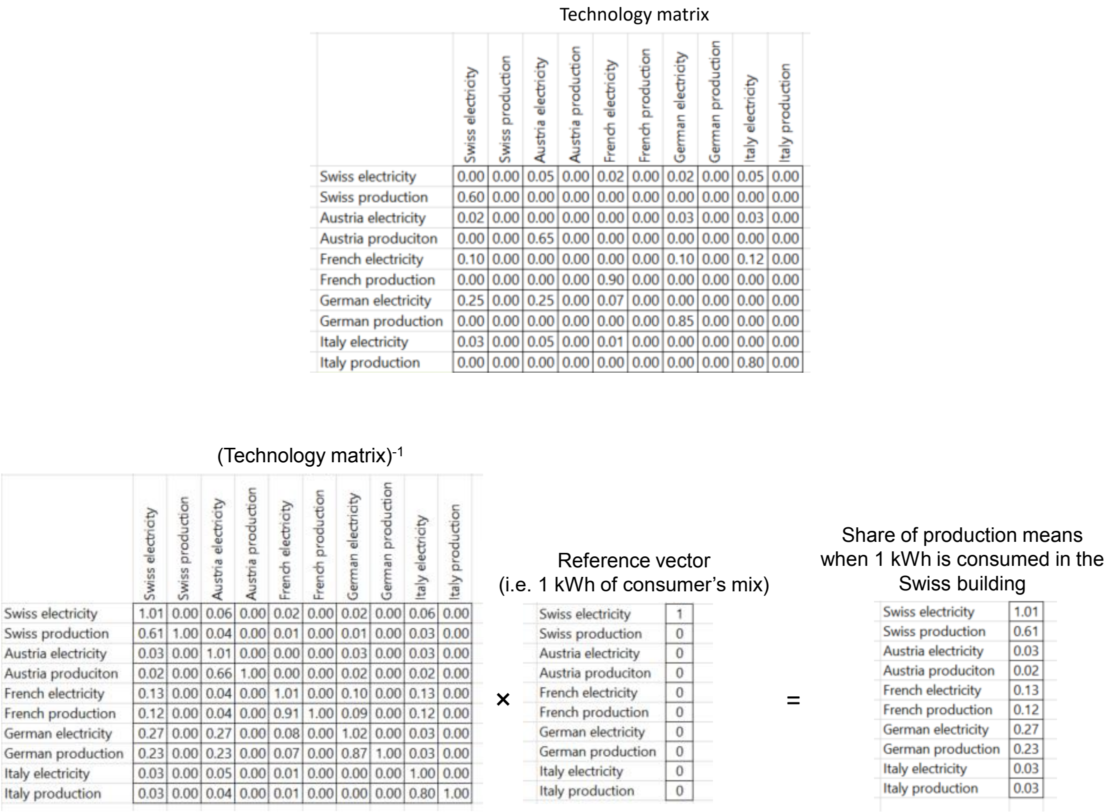
AT, FR, DE, IT, CZ = 2nd level of interest (influence the most the Swiss mix), the study considers:
- The variation the production mix
- The variation in the importation level

Other countries that have a smaller influence on the Swiss mix, the study considers:
- A constant environmental impact value
- Only the variations in the importation level

Figure 18: Graphical representation of the main country of interest and the first and second levels of countries depending on their LCIA contributions to the consumption mix of the main country of interest

Explanation of the matrix-based calculation in the Swiss EcoDynBat method in a simplified example:
The key concepts that regulate this approach are the electricity modeling approach "production + imports" and the interest to use a matrix-based structure. They are both used to consider the exchanges between the electricity mixes of the European countries. Consequently, all imports from neighbors of Switzerland will become a part of the consumer's mix, which will then be used in Swiss buildings. The imports of these neighbors will also be considered, but in a simplified manner as an average ENTSO-E mix.

A simplified example of this matrix-based calculation is provided below. The main simplifications of this example are in the aggregation of production means for a country and a limited number of considered ENTSO-E countries. Moreover, such a calculation must be done for every time step over the year (i.e. 8760 calculations for the hourly resolution). In this example, values in the technology matrix represent the input process from that row into the process from that column. For instance, 0.6 kWh of produced electricity in Switzerland is needed for the Swiss electricity mix during that period as well as 0.2 kWh from Austria, 0.1 kWh from France, 0.25 kWh from Germany and 0.03 kWh from Italy. These are only the direct needs and uncovering the full energy requirements over the entire supply chain requires the step of matrix inversion. It is only then that this inversed technology matrix is multiplied by the reference vector to obtain the life cycle energy flows for the consumption of 1 kWh of electricity in Swiss buildings at a specific time step.



Technology matrix

	Swiss electricity	Swiss production	Austria electricity	Austria production	French electricity	French production	German electricity	German production	Italy electricity	Italy production
Swiss electricity	0.00	0.00	0.05	0.00	0.02	0.00	0.02	0.00	0.05	0.00
Swiss production	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Austria electricity	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.00
Austria produciton	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00
French electricity	0.10	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.12	0.00
French production	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00
German electricity	0.25	0.00	0.25	0.00	0.07	0.00	0.00	0.00	0.00	0.00
German production	0.00	0.00	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.00
Italy electricity	0.03	0.00	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Italy production	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00

(Technology matrix)$^{-1}$

	Swiss electricity	Swiss production	Austria electricity	Austria production	French electricity	French production	German electricity	German production	Italy electricity	Italy production
Swiss electricity	1.01	0.00	0.06	0.00	0.02	0.00	0.02	0.00	0.06	0.00
Swiss production	0.61	1.00	0.04	0.00	0.01	0.00	0.01	0.00	0.03	0.00
Austria electricity	0.03	0.00	1.01	0.00	0.00	0.00	0.03	0.00	0.03	0.00
Austria produciton	0.02	0.00	0.66	1.00	0.00	0.00	0.02	0.00	0.02	0.00
French electricity	0.13	0.00	0.04	0.00	1.01	0.00	0.10	0.00	0.13	0.00
French production	0.12	0.00	0.04	0.00	0.91	1.00	0.09	0.00	0.12	0.00
German electricity	0.27	0.00	0.27	0.00	0.08	0.00	1.02	0.00	0.03	0.00
German production	0.23	0.00	0.23	0.00	0.07	0.00	0.87	1.00	0.03	0.00
Italy electricity	0.03	0.00	0.05	0.00	0.01	0.00	0.00	0.00	1.00	0.00
Italy production	0.03	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.80	1.00

×

Reference vector
(i.e. 1 kWh of consumer's mix)

Swiss electricity	1
Swiss production	0
Austria electricity	0
Austria produciton	0
French electricity	0
French production	0
German electricity	0
German production	0
Italy electricity	0
Italy production	0

=

Share of production means
when 1 kWh is consumed in the
Swiss building

Swiss electricity	1.01
Swiss production	0.61
Austria electricity	0.03
Austria produciton	0.02
French electricity	0.13
French production	0.12
German electricity	0.27
German production	0.23
Italy electricity	0.03
Italy production	0.03

Figure 19: Simplified example of the matrix-based calculation to account all production means (taken from the final EcoDynBat SFOE final report)

The other details of the modelling characteristics of the EcoDynBat electricity mix is provided in Section 1.8 **Error! Reference source not found.**. It is an hourly mix calculated by adding the production mix plus imports. The results are then aggregated for the various time steps considered in the EcoDynBat project, i.e, Hourly, Daily, Monthly and Yearly time steps. The contribution to the Swiss consumed electricity mix per countries and per production means (renewable including hydropower (and named as "EnR" in the figure below), nuclear, pumping storage (STEP), fossil and "other non-identified") is given in the Figure 20.

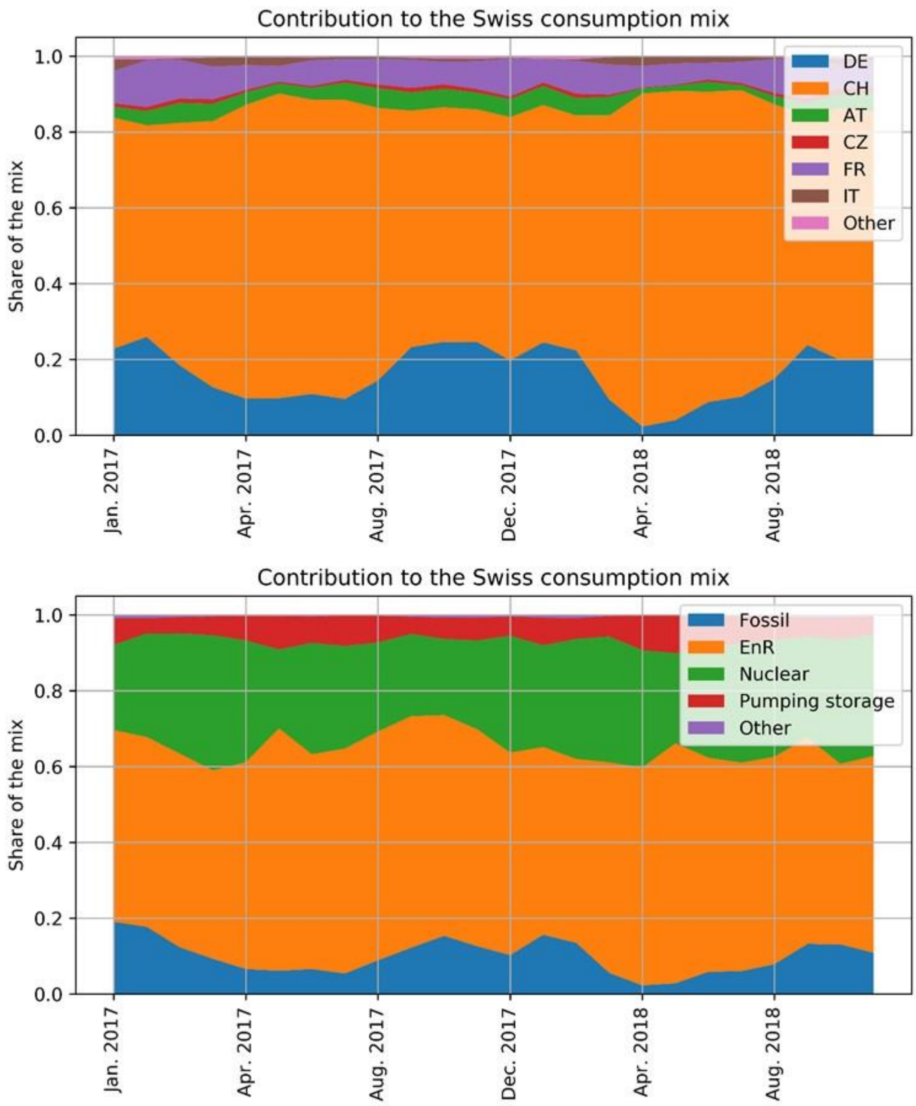


Figure 20: Contribution to the Swiss consumed electricity mix

The obtained shares of production means from each country to offer electricity to Swiss consumers has then to be multiplied by their respective environmental impacts. The impacts for all production means is calculated, with Simapro v7.4, based on ecoinvent V3.4 database. For calculating the hourly Swiss electricity supply mix, the pumping storage (STEP) is modelled using the environmental impact of the ecoinvent v3.4 dataset for the electricity produced by a pumping storage unit[25].

Nevertheless, the main source of data for electricity production at different time steps (i.e. ENTSO-E) and the chosen sources of data for the environmental assessment (i.e. ecoinvent) do not describe the energy production means with the same level of details. For example, ENTSO-E only mention "nuclear electricity" while ecoinvent will have both pressurized and boiling water reactor technologies (PWR, BWR). This discrepancy in the description of the model's components brings an issue since impacts of energy sources must fit with the description of energy production means. A mapping file was thus built to connect these two sources of information for every relevant country, energy sources and technologies. Thus, for example, an aggregated value between the PWR and BWR is developed to have the "nuclear electricity" production mean as considered in ENTSO-E.

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[25] The used approach is a simplified one for modelling the pumping storage (STEP) flows. Indeed, it could also be possible to apply different impacts when the STEP is charged and conversely when it is discharged. But this modelling approach was not within the scope of the EcoDynBat project.

The necessity of using ENTSO-E data in the EcoDynBat project requires to aggregate data from ecoinvent. It is thus essential to find a ratio of each technology in ecoinvent to describe the energy sector in ENTSO-E. This information was found in the ecoinvent database since the shares of each technology are provided for the average annual electricity production datasets in 2014. Using these values is a simplification because market shares of different technologies have changed, but such changes are expected to have very small effects on the impacts of a sector.

Based on the environmental impacts per production means for each considered countries and the shares of production means at each time step, the hourly environmental impact of the Swiss consumed electricity can then be obtained for the years 2017 and 2018. The results presented in the Figure 21 illustrate the output of the developed EcoDynBat project for the GHG emissions and the Climate change impact category.

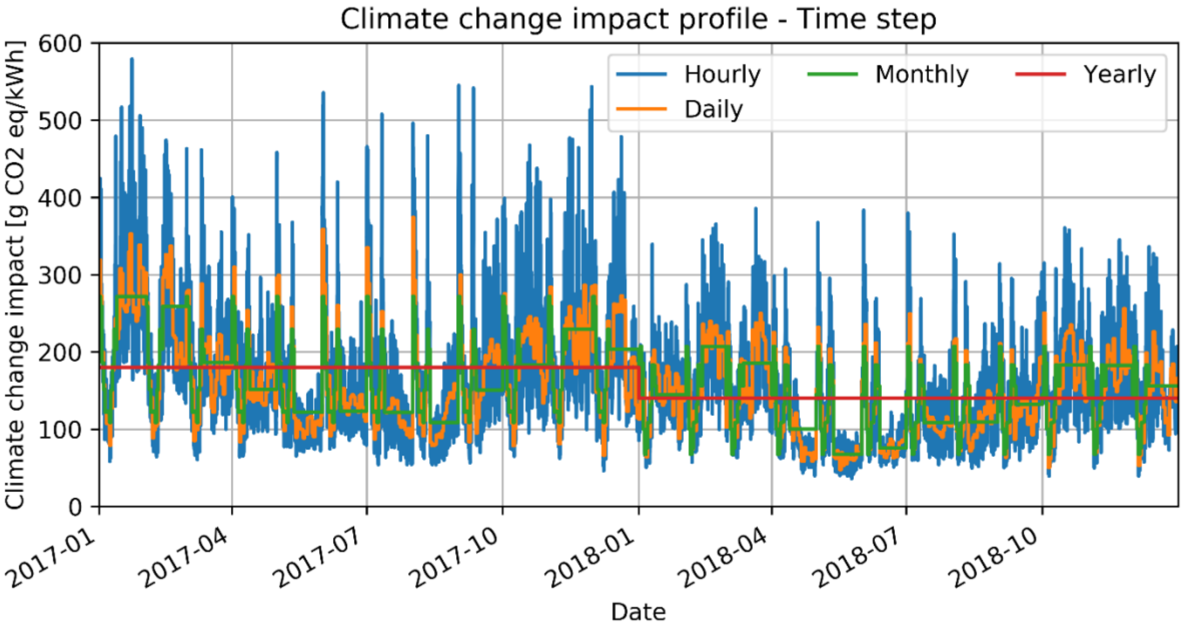

Figure 21: Climate change impact profile for the Swiss consumed electricity, according to various intra-annual time steps

Remark:
It is worth to mention that in the Swiss EcoDyynBat project, the ENTSO-E data have been collected for all the European countries and the developed method, based on a matrix-based computational approach can easily be applied to calculate the hourly electricty mix for other European countries using a physical approach for the cross-border exchanges.

Concerning the national electricity mix, challenges still remain to use a time-differentiated mix. In the EcoDynBat approach, empirical data from the past years (2017 and 2018) are used to derive the supply mix for different time series. It is a limitation, as from one year to another, fluctuations can happen due to the severity of the climate in winter, the decision to turn on or off production means in a country.

3) Use of the different LCA data (different time step from hourly to annual) in LCA of the energy use in Swiss buildings

The current supply mix is already usable to assess whether the time step influence the LCA of the building electricty demand and if yes for which use(s) and for which typology (office, residential...). First answers to these questions are provided in section 1.3.3 Switzerland part, application 2 with the LCA results of a building case study with different scenarios of energy systems.

The EcoDynbat datasets can also support the anaysis of load shiting and demand side management case studies using hourly GHG emissions as a decision criterion. However, such case studies are not reported in this report.

ELCAB project

The ELCAB research project (**E**lectricity in **L**ife **C**ycle **A**ssessments of **B**uildings) funded by the Swiss Federal Office of Energy (SFOE) from 2018 to 2020 assessed the effect of different electricity mixes, including an hourly mix on the environmental impacts of the electricity consumed by residential and office buildings. The approach chosen is described in Section **Error! Reference source not found.**. The main differences in modelling compared to the EcoDynBat project are the following:

- ELCAB uses commercial trade not physical trade data published by the ENTSO-E transparency platform.
- Commercial exports from Switzerland to neighbouring country are modelled with the Swiss production mix and subtracted from the total production before adding commercial imports.
- Imports to neighbouring countries are disregarded in ELCAB because it is assumed that electricity is hardly purchased from far distant power plants.

The following mixes were modelled:

1. Annual and seasonal attributional electricity mixes of Switzerland in 2018 and of a residential and a commercial building.
2. The Swiss consumer mix based on guarantees of origin 2018, the Swiss supply mix based on guarantees of origin 2018 and the ewz electricity mix based on guarantees of origin 2017.
3. The average future electricity mix of Switzerland
4. The long term marginal electricity mix of Switzerland and of ewz, the utility of the City of Zürich

The electricity mixes for these different load profiles are shown in Figure 22, Figure 23 and Figure 24. The electricity mixes derived from hourly production profiles and (economic) trade are rather similar and do not differ substantially from the annual national mix derived from hourly production profiles and (economic) trade. Their shares of nuclear electricity is about 40 %, hydro power contributes about 35 %, new renewables up to 10 % and fossil based electricity about 10 %.

The load profile of the office building leads to an annual electricity mix with slightly higher shares of hydroelectric power and PV electricity mainly at the expense of nuclear power.

The Swiss electricity mixes based on guarantees of origin show substantially higher shares of hydroelectric power and substantially lower shares of nuclear and fossil power. About one fourth of the electricity supplied to Swiss consumers is based on non renewable energies. If the electricity products based on renewable energies sold separately are excluded from the consumer mix, the share of electricity based on non renewable energies is about one third. More than 90 % of the ewz supply mix is produced with renewable energies, mainly in hydroelectric power plants.

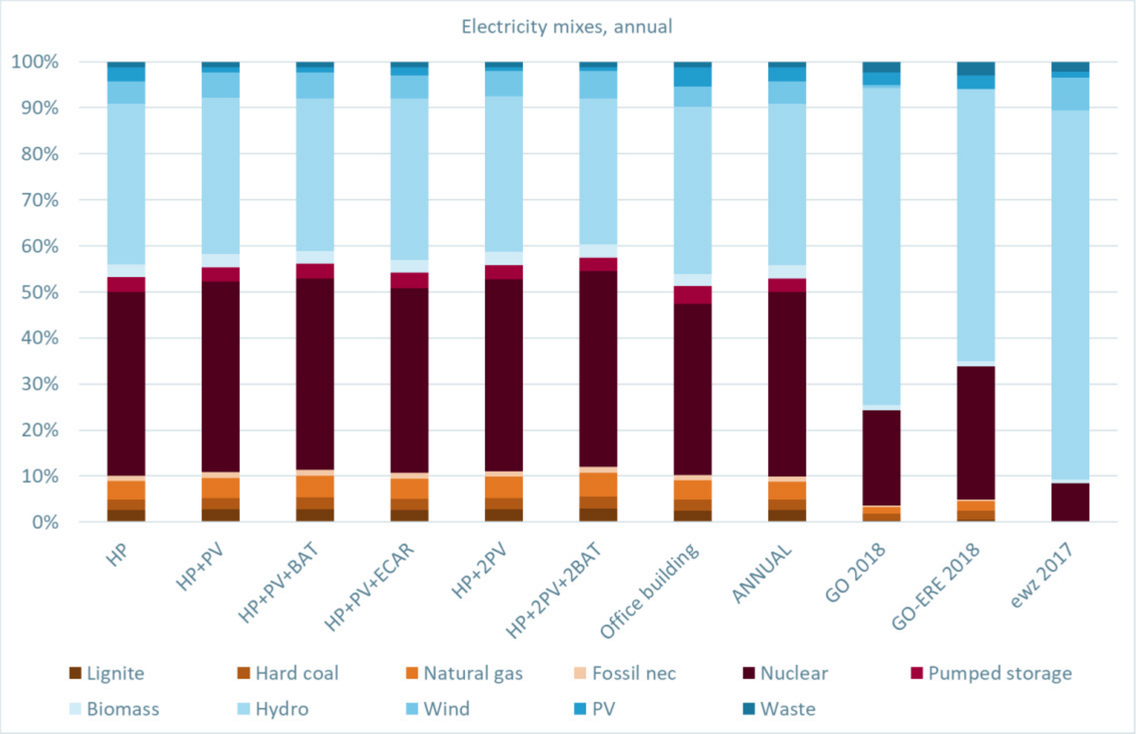

Figure 22: Technology shares of the annual Swiss electricity mixes for the different load profiles of the residential building Rautistrasse, the load profile of the ARE office building, the annual Swiss electricity mix (national load profile) and the Swiss consumer electricity mix 2018 according to guarantees of origin;
ANNUAL: Swiss annual mix (national load profile); GO 2018: Swiss consumer mix 2018 based on guarantees of origin; GO-ERE 2018: Swiss supply mix 2018 (excluding electricity products based on renewable energy sold separately); ewz 2017: supply mix of the utility of the city of Zürich.
Building specific electricity mixes matching hourly production and trade with the electricity consumption profile of the building, equipped with:
HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system;

The Swiss seasonal mixes exhibit moderate differences compared to the annual mixes. The Swiss winter mixes derived from the load profiles of residential and office buildings exhibit somewhat higher shares of nuclear and fossil based electricity (predominantly from Germany). Their profiles are all very similar. Thus there is only little variation. The Swiss summer mixes consists of less nuclear and less fossil based power plants. They show a somewhat higher dependency on the load profiles of the buildings. It is particularly interesting to note that the installation of on site PV systems leads to electricity mixes with a zero share of PV in the electricity mixes delivered from the grid.

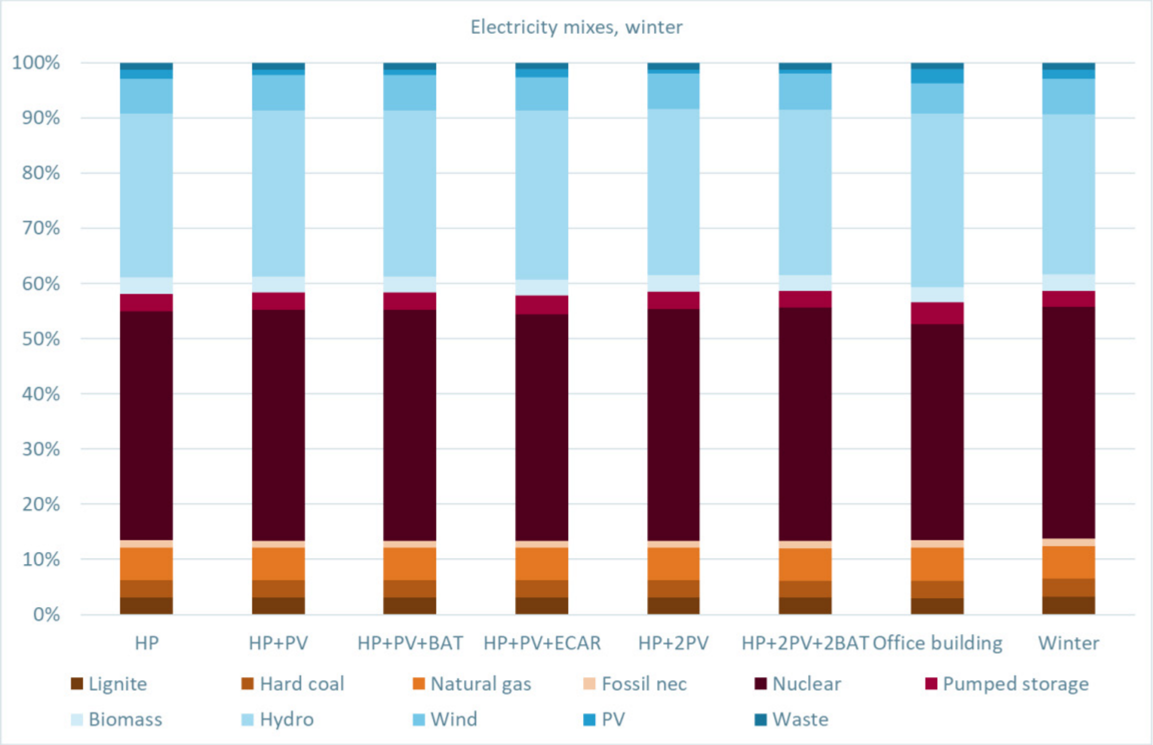

Figure 23: Technology shares of the winter Swiss electricity mixes for the load profiles of the residential building Rautistrasse, the ARE office building and the plain winter Swiss electricity mix (national load profile); Residential building equipped with: HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system; Winter: Swiss winter mix (national load profile).

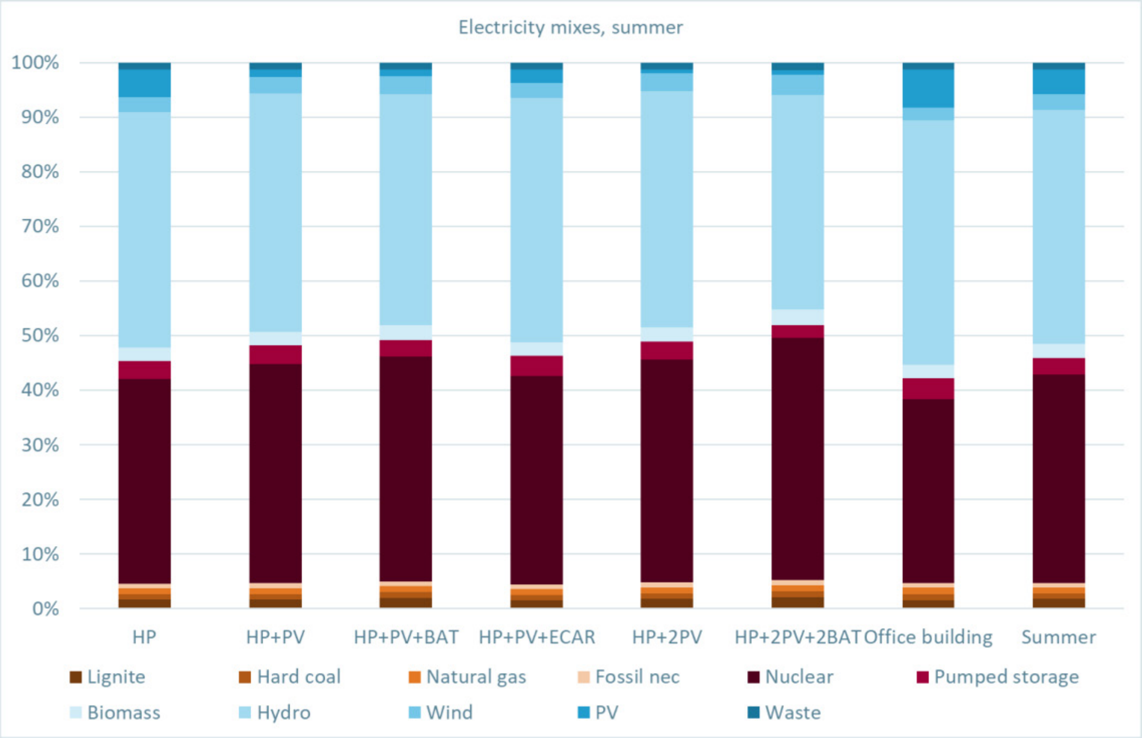

Figure 24: Technology shares of the summer Swiss electricity mixes for the load profiles of the residential building Rautistrasse, the ARE office building and the plain summer Swiss electricity mix (national load profile); Residential building equipped with: HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system; Summer: Swiss summer mix (national load profile).

The annual future Swiss electricity mix according to the Scenario “New Energy Policy”, Variant C&E will shift from nuclear power to substantially more power from renewable sources (see Figure 25). One part of the reduction in production volumes from nuclear power plants will be compensated by natural gas fired power plants. They reach a share of up to 16 % in 2035 and then drop to about 6 % in 2050. PV production will increase from a share of below 1 % to 15 % in 2050. Geothermal power reaches 6 % in 2050, wind power slightly less.

The 2020 future electricity mix generally shows more similarities to the annual electricity mix derived from annual production and (economic) trade data. The shares of new renewable energies and fossil based power in the 2018 electricity mix are higher and the share of pumped storage is smaller than in the Prognos electricity mix 2020. These seven electricity mixes are used to establish an average electricity mix for 2020 to 2050, i.e. the first half of the 60 years amortisation period of buildings. The average future electricity mix includes nearly 50 % hydroelectric power, 15 % nuclear power, 8 % produced with natural gas and 7 % PV electricity.

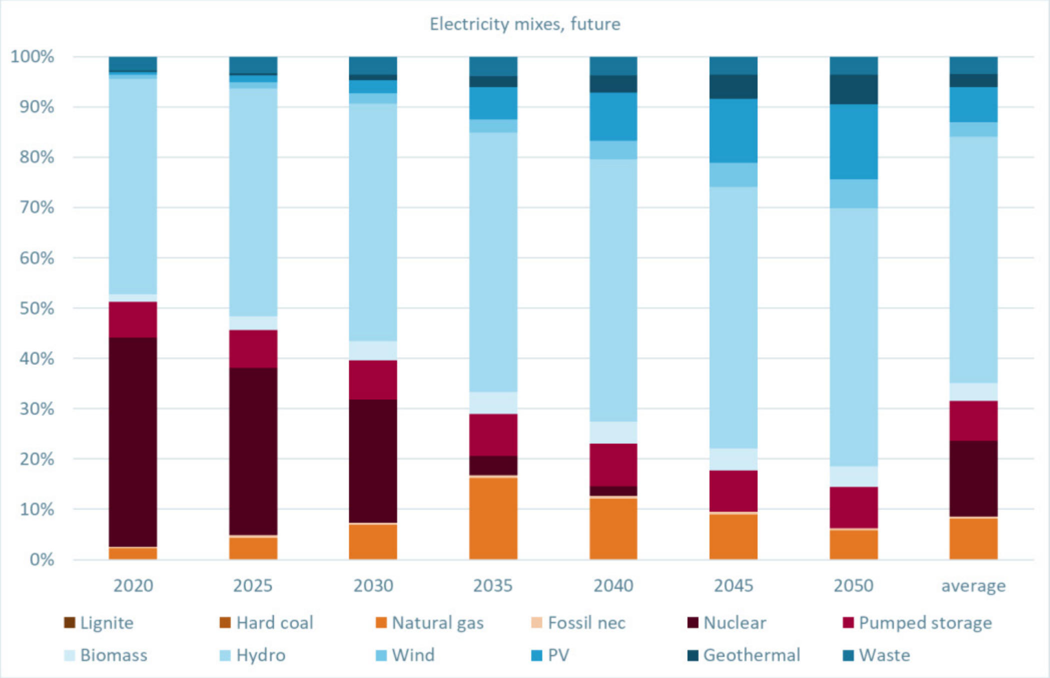

Figure 25: Technology shares of annual future Swiss electricity mixes from 2020 to 2050 according to Prognos (2012) and for the average electricity mix 2020 to 2050

The specific greenhouse gas emissions of the Swiss national electricity mix 2018 vary between 55 g CO_2-eq/kWh (Swiss consumer mix), 70 g CO_2-eq/kWh (Swiss supply mix) and nearly 130 g CO_2-eq/kWh (physical production and commercial trade covering the national load profile 2018, see Figure 26). Imports of electricity generated with fossil fuels (lignite, hard coal and natural gas) contribute up to three quarters of the total emissions.

The ewz 2017 electricity mix causes less than 20 g CO_2-eq/kWh which is mainly due to the fossil free electricity mix. The long term marginal electricity mix (100 % natural gas fired gas combined cycle) emits more than 450 g CO_2-eq/kWh.

The greenhouse gas emissions of the annual Swiss electricity mix, modelled according to the New Energy Policy (NEP) scenario of the Swiss energy strategy 2050 (see Subchapter **Error! Reference source not found.**), increase from less than 40 g CO_2-eq/kWh in 2020 to nearly 120 g CO_2-eq/kWh 2035. After that, they drop again to about 60 g CO_2-eq/kWh. On average 73 g CO_2-eq/kWh are emitted from 2020 to 2050. The emissions in 2020 are distinctly lower than those of the electricity mix 2018 based physical production plus commercial trade, because the future electricity mixes disregards trade.

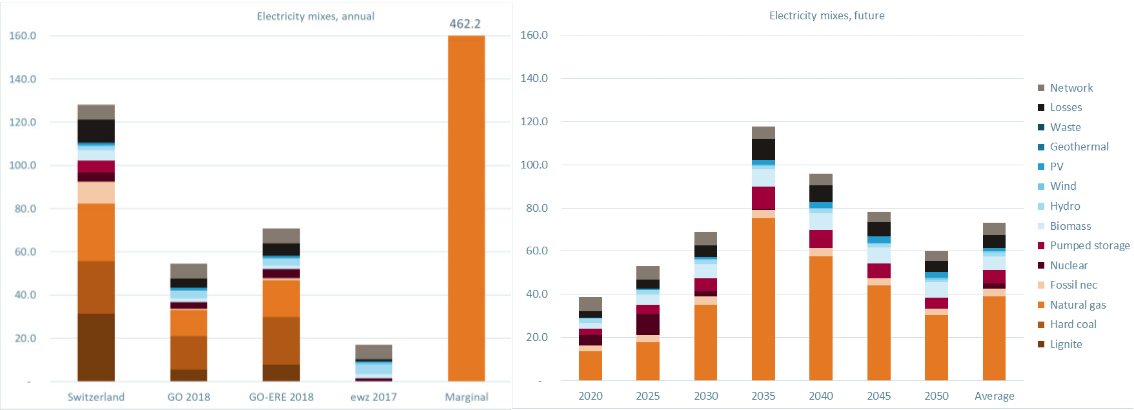

Figure 26: Greenhouse gas emissions in g CO_2-eq/kWh low voltage of the annual Swiss electricity mix (national load profile, Switzerland), the Swiss consumer mix (GO 2018), the Swiss supply mix (GO-ERE 2018, excluding electricity products based on renewable energy sold separately), the ewz electricity mix 2017 based on guarantees of origins, the long term marginal electricity (Switzerland and ewz), and the average future electricity mix Switzerland 2020-2050 (based on the New Energy Policy (NEP) scenario).

The specific greenhouse gas emissions of electricity supplied to the residential building “Rautistrasse” amount to between nearly 130 g CO_2-eq/kWh and nearly 150 g CO_2-eq/kWh (see Figure 27). Imports of fossil based electricity are the main cause.

The specific greenhouse gas emissions of the base case (HP), i.e. excluding any self generated electricity nor on site storage, are nearly identical to the specific greenhouse gas emissions of the Swiss electricity mix (physical production and commercial trade matching the national load profile). This is not surprising because the electricity mixes are very similar too (see Figure 22).

Self generation of electricity with PV and storage of this electricity in stationary batteries leads to higher specific greenhouse gas emissions of the remaining electricity supplied from the grid. For instance, PV electricity from the building displaces PV electricity in the mix supplied to the building (compare the colums “HP” and “HP+PV”).

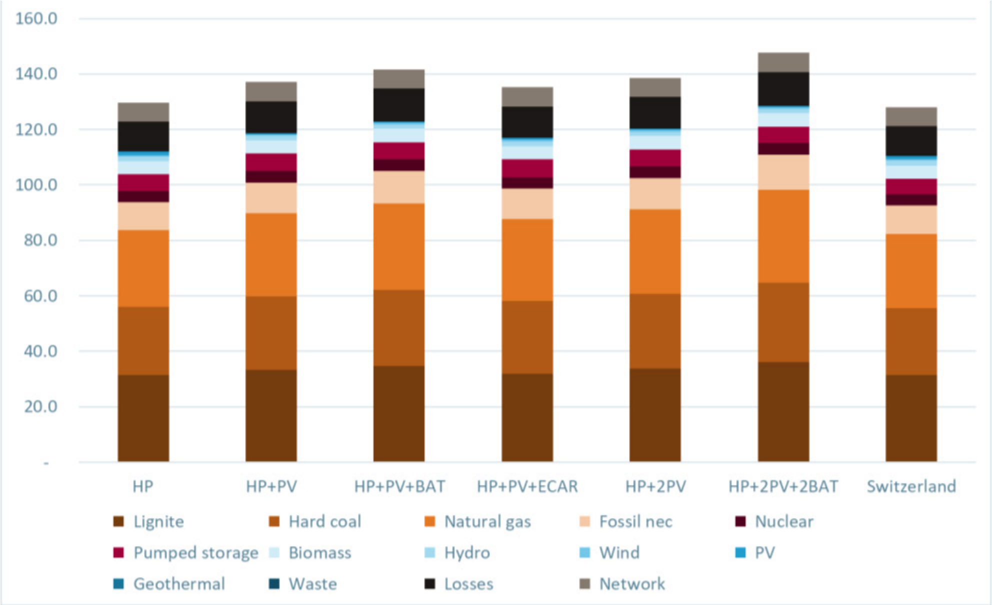

Figure 27: Greenhouse gas emissions in g CO_2-eq/kWh low voltage of the annual electricity mixes of the load profiles of the residential building and of Switzerland;
Residential building equipped with: HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system; Switzerland: Swiss annual mix (national load profile).

The specific greenhouse gas emissions of the seasonal (summer and winter, respectively) electricity mixes of the residential building and of the Swiss electricity mix based on physical production and commercial trade differ considerably: in summer (April to September) the greenhouse gas emissions vary between 70 and 78 g CO_2-eq/kWh whereas in winter (October to March) they amount to between 164 and 169 g CO_2-eq/kWh (see Figure 28). One kWh consumed in the winter period causes more greenhouse gas emissions than 2 kWh consumed during the summer period. The influence of self generation and storage of electricity on the specific greenhouse gas emissions of the remaining electricity supplied to the building is more pronounced during the summer than the winter period.

The specific greenhouse gas emissions of the remaining electricity supplied to the building decrease both in the summer and winter period. This seems to be contradictory to the effect of self generation and storage on the specific greenhouse gas emissions of the remaining electricity supplied the building on an annual basis. However, the share of winter period electricity (with higher specific greenhouse gas emissions) is higher in cases with self production and storage, which leads to the observed increase in specific greenhouse gas emissions of the electricity mix supplied to the building on an annual basis.

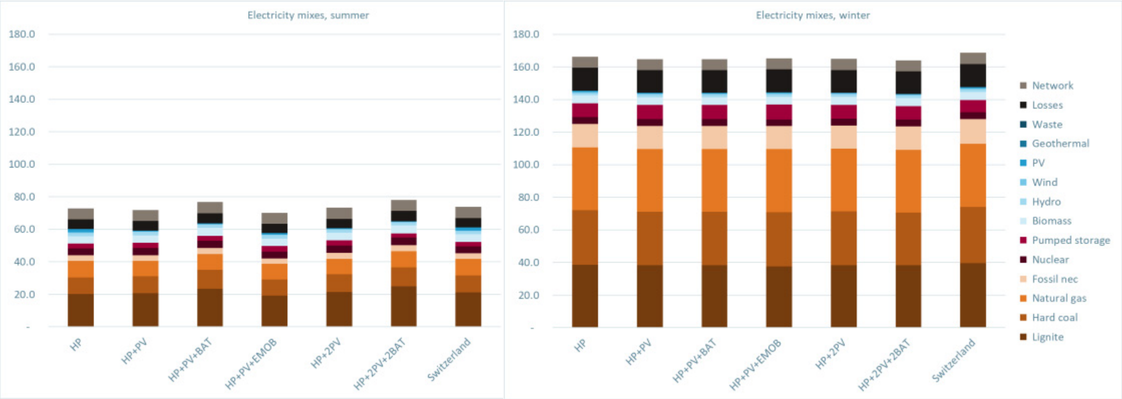

Figure 28: Greenhouse gas emissions in g CO_2-eq/kWh low voltage of the seasonal electricity mixes of the load profiles of the residential building and of Switzerland;
Residential building equipped with: HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system; Switzerland: Swiss seasonal mix (national load profile).

Sweden

Hourly data on production, imports and exports in Sweden is available from ENTSO-E and Svenska Kraftnät (European Network of Transmission System Operators, 2020; Svenska kraftnät, 2020). Previous projects have investigated the time resolution of the electricity mix on the Nordic electricity market. In developing the Tidstegen method, Gode et al. (2015) concluded that this aspect does not matter in the short term in consequential LCA, but that it might matter in the long term, depending on how electricity demand and supply evolve. Therefore, they base their long-term assessments on a breakdown of electricity demand depending on the year, season and time of day (daytime or nighttime).

Erlandsson et al. (2018) concluded that time resolution of the electricity mix did not significantly influence the results when using an average mix for the LCA of a case study building. However, they concluded that time resolution can matter when using a marginal electricity mix, depending on the method used to select the electricity mix. For instance, when selecting the top 10% of the merit order as the marginal mix, and when considering a scenario for the Nordic mix in 2050, the marginal emission factor showed a high hourly variability. This could prove important e.g. when carrying out a consequential LCA related to the choice of heating solution (e.g. electric heating or district heating).

Apilot version of the NollCO2 certification system also required an assessment of the impact of energy demand based on hourly values for supply and demand. However, the more recent pilot version uses yearly electricity emission factors instead.

Norway

Hourly data on production, consumption and exchange in Norway is available from ENTSO-E and Nordpool (2020). Norway has several physical links to the European electricity grid. But these links are bottlenecked, so that the maximum import/export capacity is approx. 6,000 MW (and growing as new connection lines are added). In comparison, the total production capacity of Norway is about 31 000 MW. Figure 29 , shows the hourly Production, Exchange and Consumption in Norway from 2013 to 2019.

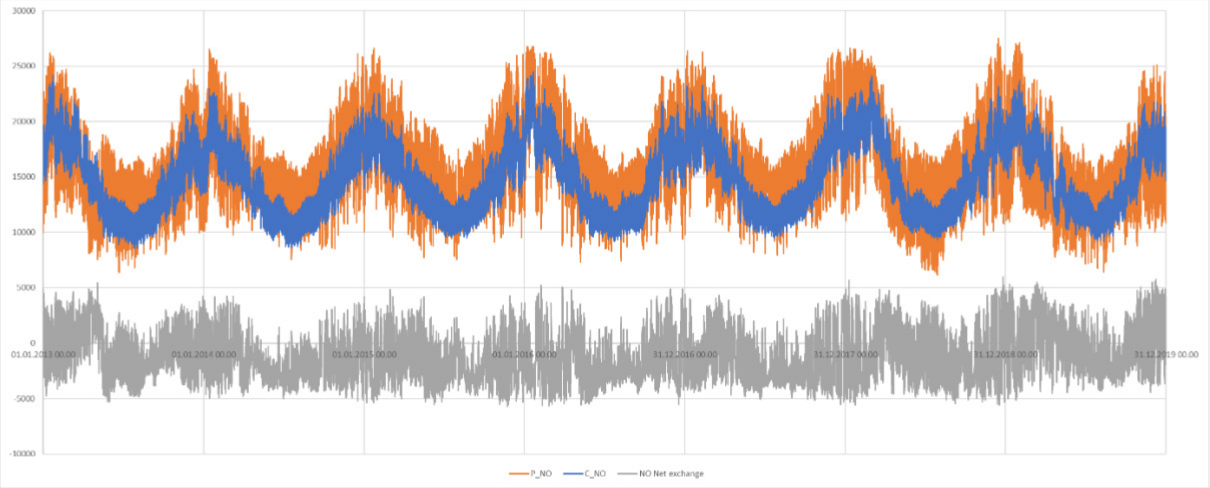

Figure 29: Electricety Production, Exchange and Consumptionn in Norway 2013 to 2919 (MWh/h)

As the figures shows, Norway is importing during winter and early spring, and are exporting late spring, summer, and autumn. The figure also shows that Norway on average is a net exporter of electricity.
The hourly mix of the Norwegian production is totally dominated by hydropower (>95%), with small contribution from wind (~2,5 %) and thermal (~2,5 %).

B.6 Marginal electricity mix (electricity mix(es) applicable in consequential LCAs)

Denmark

No dataset available.

France

In order to identify the short term marginal mix, the different production techniques are ranked using a "merit order". Technologies that cannot be adjusted according to the demand (e.g. wind or PV, that depend on the weather) are at the bottom of this ranking. Adjustable technologies with the lowest constraints and the highest cost are at the top. Two methods have been implemented in the EQUER tool:

- the Greenhouse Gas Protocol method (WBCSD & WRI 2007), considering a marginal mix corresponding to the 10% top ranked productions.
- a more physical 2 steps model, evaluating the mix with and without the studied building, using a model representing the electric system as presented in § 1.6.5 (Roux et al. 2016a). The marginal electricity mix can be defined for past years (historical mix) or for a long term period using energy transition scenarios, leading to a long term marginal approach.

Hungary

In Hungary, the marginal mix consist of natural gas power plants. No detailed assessment has been carried out.

Switzerland

There is no official, national model of a consequential LCA of electricity.

Two different concepts of establishing a consequential electricity mix are proposed (see also Frischknecht 2016). The consequential annual national electricity mix of Switzerland is derived from 1) energy policy scenarios and 2) based on a thinking model.

Ad 1: The consequential (long term marginal) electricity mix is established as the difference in technology specific power production in the future (e.g. in 2050) according to two (distinctly) different scenarios (e.g. business as usual and new energy policy according to the national energy scenarios, Prognos 2012). The procedure is illustrated using the Swiss case (see Table 12). The difference in electricity production and consumption in Switzerland in 2050 is about 8 TWh per year, strongly depending on which of the energy scenarios is likely to happen or be implemented. The additional electricity consumption of the Business As Usual scenario BAU compared to the most ambitious New Energy Policy scenario NEP will be covered with electricity from fossil power plants, mainly natural gas fired power plants. Natural gas will also be used to step in for the new renewables which are assumed to produce much less in the BAU compared to the NEP scenario. Hence, the long term marginal electricity mix of Switzerland is likely to be composed of 100 % natural gas fired gas combined cycle power plants, similar to the situation in Hungary.

Table 12: Power plant technologies in Switzerland in 2009, in 2050 according to three different policy scenarios as well as the difference in production in the BAU and NEP scenario; (Prognos 2012); specific greenhouse gas emissions and non renewable primary energy demand

Technology	**Production mix 2009 [TWh]**	**Business As Usual BAU 2050 [TWh]**	**New Energy Policy NEP 2050 [TWh]**	**Political Measures POM 2050 [TWh]**	**longterm marginal mix: BAU minus NEP [TWh]**
Hydroelectric power	37.14	41.58	44.15	44.15	-2.57
New renewables	0.91	8.96	22.59	22.59	-13.63
Nuclear power	26.12	0.00	0.00	0.00	0
Fossil Power plants	0.36	29.51	4.67	2.12	24.84
Waste	1.97	2.28	2.96	2.96	-0.68
Imports	0.00	0.00	0.00	7.2	0
Total	66.49	82.33	74.37	79.02	7.96
Climate change impact [g CO_2-eq/kWh]	**30**	**213**	**76**	**61**	**466**
primary energy demand, non renewable [kWh oil-eq/kWh]	**2.7**	**0.96**	**0.28**	**0.29**	**8.0**

Ad 2: The following thinking model is applied to derive a consequential electricity mix: Each kWh electricity (produced with renewable energies, mainly with hydroelectric power plants) which is not consumed in Switzerland, is exported to Europe and is an offer to the European utilities to shut down (and dismantle) power plants which run on fossil or fissile fuels, i.e. lignite, hard coal, fuel oil, natural gas and nuclear power plants. In a project for IEA PVPS, different European non-renewable power mixes were established (Frischknecht et al. 2015, see Table 13). It shows that the European non-renewable power mix is likely to change in future depending on the policy scenario. Because decisions on building alternatives are taken as from today, we recommend to use the present (2009) European non-renewable electricity mix.

Table 13: European non renewable electricity mix today (2009) and in 2050 (three scenarios, based on NEEDS 2008, NEEDS 2009); specific greenhouse gas emissions and non renewable primary energy demand;
nd: not determined

Technology	2009	BAU 2050	REAL 2050	OPT 2050
Hard coal	21.4%	34.2%	8.1%	14.9%
Lignite	26.4%	12.5%	0.0%	0.0%
Heavy fuel oil	1.6%	0.8%	0.3%	0.0%
Natural gas	14.9%	24.0%	57.7%	85.0%
Nuclear power	34.1%	28.5%	33.9%	0.0%
Total	100.0%	100.0%	100.0%	100.0%
Climate change impact [g CO_2-eq/kWh]	**763**	**nd**	**nd**	**nd**
primary energy demand, non renewable [kWh oil-eq/kWh]	**3.81**	**nd**	**nd**	**nd**

Sweden

Two notable reports have investigated the use of marginal electricity mixes in building LCA in the past few years, but neither method is commonly used in practical LCAs.

Gode et al. (2015) developed marginal mixes for electricity and heating for the Tidstegen method, addressing both what they called dynamics (i.e. long-term changes in the energy mix) and time resolution (i.e. differences between different seasons or times of day). For electricity, the marginal mix in the coming 5-15 years is assumed to be fully composed of fossil fuel-based electricity imported primarily from Denmark and Germany. The justification is that hydropower is used to regulate seasonal and hourly changes in electricity demand, but the amount of hydropower used in a year is limited by weather conditions. In other words, all hydropower capacity will always be used within a year; an increase in demand thus cannot be met by an increase in hydropower production and has to be met with imported electricity produced in thermal power plants.

In the long term, the marginal mix in the Tidstegen method depends on the choice of future scenario. Three future scenarios are proposed (reference, low greenhouse gas emissions and high greenhouse gas emissions). In each scenario, different technologies are used to meet a marginal increase in electricity demand depending on when this additional demand happens (season, time of day). When assessing a measure that would change the building's energy demand, this change in demand is broken down into different marginal mixes depending on when the change in demand happens. Each marginal mix takes into account short-term effects from this change in demand (e.g. changes in how plants are operated) as well as long-term effects (e.g. changes in investments and installed capacity for various technologies on the grid). For instance, a measure reducing energy demand from appliances during the night will use the nighttime emission factors, whereas the installation of on-site PV panels will mostly use the daytime emission factor for summer, and to some extent spring and autumn, but will barely use the emission factor for winter. Each measure is assessed in each of the three future scenarios, and a measure is said to have positive (resp. negative) effects if its effects are positive (resp. negative) in most scenarios.

Another report developed present and future marginal emission factors for the Nordic electricity market, with a hourly time resolution (Erlandsson et al., 2018). The hourly data was based on the ENTSO-E database (European Network of Transmission System Operators, 2020). The future scenario was based on the "Nordic Energy Technology Perspectives" report (International Energy Agency, 2016). The influence of different ways of choosing the marginal emission factor was investigated. Three short term marginal emission factors were developed for each hour of a reference year (present) and a future year (2050):

- A factor where the marginal mix is defined as the top 10% technologies in the merit order, including imports, according to the Greenhouse Gas Protocol method (WBCSD & WRI 2007).
- A factor where the marginal mix is defined as all load-following technologies including imports, i.e. all technologies that can be used to meet a short-term change in demand.
- A factor considering substitution effects. Imports are considered as above. Exports are assumed to displace a similar technology in another country, and have "negative emission factors".

This report was an initial attempt at exploring different methodological choices and their implications when applied to the assessment of a case study building. It has not been developed into a method that is commonly used in LCA.

Finally, the draft version of the NollCO$_2$ certification system uses a marginal approach to determine benefits from locally produced electricity exported to the grid. The approach is based on the GHG Protocol guidelines (WBCSD & WRI 2007). Long-term marginal effects are neglected, because each installation for on-site power production is assumed to be too small to significantly affect installed capacity for other production technologies on the grid. Regarding short-term marginal effects, on-site electricity exported to the grid is assumed to always lead to a reduction in electricity production in coal power plants. This assumption is based on two observations: First, the price of operating coal power plants is high, and it is not profitable to operate coal power plants when renewable electricity is available. Second, regardless of the time of year, there are always coal power plants being operated in neighboring countries (whose production could therefore be reduced if additional renewable power was added to the grid). This approach is only applied to calculate benefits from on-site electricity produced in excess of the building's needs. Greenhouse gas emissions from electricity used in the building are calculated using an emission factor for the average supply mix.

Annex C: Example modelling choices made in different tools

In this annex, the modelling possibilities are summarized below. Example choices in different tools and countries are pesented.

A) Electricity mix modeling possibilities

1. Generic or provider specific electricity mix
2. General mix: Regional, national or continental scale
3. Production mix, supply mix
4. Physical flows, contracts, guarantee of origin combined with physical production, or guarantee of origin only
5. Mix corresponding to production + import, production – export + import (possibly according to guarantee of origin), national electricity declaration
6. Gross or net trade balance
7. mix based upon empirical data from Transmission System Operator (TSO), data derived from/determined with a model (e.g., statistical model…) or other data
8. Universal electricity mix or use-specific electricity mix (heating, cooling, lighting, hot water…)
9. Historical, present or future mix (e.g. average present-2050)
10. Average or marginal mix
11. Annual, seasonal or hourly mix
12. Allocation approach for electricity produced on site (photovoltaics, but also wind) exported to the grid

   i. product and construction stage (“module A”): only self-consumed part of environmental impacts of the entire PV plant is accounted for, and attributed to the self-consumed part,

   ii. product and construction stage: environmental impacts of the entire PV plant is accounted for; use stage: environmental impacts of PV electricity is accounted for the electricity exported and subtracted from the use stage environmental impacts (Swiss method, according to SIA 2040), no environmental impacts on self consumed PV electricity (already accounted for in product and construction stage of the building); same result like approach i) above);

   iii. product and construction stage: environmental impacts of the entire PV plant is accounted for; use stage: exported electricity gives rise for avoided impacts according to the amount of electricity exported and the technology (mix) assumed to be replaced (French methods EQUER and E+C-).

B) Example choices

Each tool is presented in a table explaining the choices and intentions. Then a table is given in order to prepare a synthesis including all participating countries (see next table).

Template to be used by Annex 72 partners						
	Criterion	**Insert your country:……………………….** Type of approach (e.g., commonly used approach (labelling systems), research assessment/study)				
1	**Generic or specific**	provider specific	generic			
2	**Geographic scope**	continental	regional	national		
	Electricity mix model					

3	**Type of mix**	(1) Production mix	(2) Supply mix			
4	**Nature of trade flows**	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO) purchase together with physical production	Flows based on Guarantee of Origin (GO)	
5	**Modelling choice for the supply mix**	(1) Production + imports	(2) Production – exports + imports	(3) Production – Δ exports + Δ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
6	**Balance of import/export at each border with the studied country and each neighbouring country**	Gross balance	Net balance	Not applicable		
7	**Data types for the energy carrier flows**	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
8	**End uses dependence** 1) (heating, lighting, cooling, etc.)	universal mix	use specific mix			
9	**Time dimension**	historical mix	present mix	future mix		
10	**LCA modelling approach**	average mix	marginal mix			
11	**Time granularity**	annual average mix	seasonally differentiated mix	hourly differentiated mix		
12	**Allocation of in site PV electricity production**	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

[1]): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

C.1 Example for France

a) Mainstream assessment (E+C-, building regulation studied for 2020)

Choice	**Explanation / Intention**
Generic mix	The regulation is about the intrinsic quality of the building, not the choice of an electricity provider by the users
National mix	It is a national regulation the % of imported/exported electricity is low and is taken into account using a gross balance (production – exports + imports)
Consumer mix = supply mix (physical trade flows on a national level)	It corresponds to the impacts generated by buildings because of the strong interconnection among the grid.
Use-specific mix	Electric heating induces a peak load and higher CO2 emissions in winter, whereas e.g. domestic hot water is produced in the night and stored in tanks. Different CO2 emissions per kWh are therefore considered according to each use, but this is not really science based. It is rather the result of a negociation between e.g. gas and electricity lobbies.
Present or future mix ?	In the first version E+C-, the present mix is considered, empirical data from TSO are used. But the electricity lobby insists towards using a future mix, which would be more favourable to electric heating. This would increase the electricity consumption, making more difficult to progress towards energy transition. The French law imposes an objective of reducing the nuclear % and increasing the renewables, but a new law is voted every 5 years postponing the date for this objective. Environmentalists advise therefore to keep the present mix by precaution because it is not sure if energy transition and impact reduction will be effective.
Average or marginal mix ?	It is not precisely defined in the use-specific mix (see above)
Annual mix	It has to be simple, and temporal variation is accounted for in the use-specificity
Allocation for exported PV	1/3 of avoided impacts : the renewable lobby wanted 100%, the electricity lobby 0% and the ministry in charge of dwellings has decided 33%.

b) Design or research assessment (Equer method)

Choice	**Explanation / Intention**
Provider specific mix if the purpose is to help in facility management, generic mix with a sensitivity study for 100% renewable in other cases	It is often useful to show the importance of users choices in the environmental performance of buildings, and the choice of an electricity provider has a large influence on environmental impacts. A cooperative gathering renewable electricity producers proposes 100% renewable electricity to clients, and it is therefore interesting to perform a sensitivity study comparing the generic and 100% renewable mixes.
National mix	The % of imported/exported electricity is low and is taken into account using a gross balance (production – exports + imports)
Consumer mix = supply mix (physical flow)	It corresponds to the impacts generated by buildings
Universal or Use-specific mix	Specific to all uses of the studied building, being tested in a hourly marginal mix method in a research project

Choice	**Explanation / Intention**
Present or Future mix	The present mix is considered at the moment (precautionary principle). Different scenarios are compared in the research project, due to the vague long term energy transition policy in France. Empirical data from TSO are used for the present mix, data derived from a model is used for future mixes
Average or marginal mix ?	The user can choose between both options but short term and long term marginal is advised in order to show consequences of choices. Two options are being compared in the research program : GHG Protocol (10% of merit order), or supplementary consumption of the studied building.
Hourly mix	It is more precise, and simple for the user because the calculation is automatic.
Allocation for exported PV	100% of avoided impacts because the exported electricity is really consumed, there is no overproduction at the moment. The method remains valid even if 0% self-consumption (case of a PV power plant).

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FRANCE					
Criterion	**Insert your country: French method EQUER** Design and research tool				
Generic or specific	provider specific	generic			
Geographic scope	continental	regional	national		
Electricity mix model					
Type of mix	(1) Production mix	(2) Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – Δ exports + Δ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus*	(4) According to national electricity declaration *NB: This model only works for countries*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology)

			balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account	*such as EU and EFTA countries where electricity disclosure is mandatory*	*NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		
Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
End uses dependence [1]) (heating, lighting, cooling, etc.)	universal mix	use specific mix			
Time dimension	historical mix	present mix	future mix		
LCA modelling approach	average mix	marginal mix			
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix		
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

[1]): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

C.2 Example for Switzerland (a) and b) prepared by treeze Ltd., c) prepared by HES-SO)

a) Mainstream assessment (technical bulleting SIA 2040 « SIA energy efficiency path », SIA 2017)

Choice	**Explanation / Intention**
Generic mix	The technical bulletin is about assessing buildings in view of their compatibility with the intermediate goals of the 2000-Watt-society (EnergieSchweiz für Gemeinden et al. 2014b); Specific long-term contracts for renewable electricity supply may be accounted for (for max. 50 % of the electricity consumed by the building)
National mix	It is a national technical bulletin, imported/exported electricity is taken into account according to the guarantees of origin sold to Swiss consumers (Pronovo 2019).

Choice	**Explanation / Intention**
Consumer mix	See above
Generic mix	No differentiation between different use types (such as heating, cooling, ventilation, hot water etc.) ; electricity consumption of all uses are modelled with the same mix.
Present or future mix ?	The average present (recent past) electricity mix is applied.
Average or marginal mix ?	It is an average electricity mix, although in some communities/cities which rely on 100 renewable electricity, scenarios using marginal mixes have been evaluated (Frischknecht 2016).
Annual mix	The annual mix is being used to keep it simple and because no seasonal Swiss electricity mixes are available as of now but see EcoSynBat and ELCAB project descriptions.
Allocation for exported PV	Exported PV electricity has the environmental profile of PV mounted/integrated in the building under assessment. If 100 % of PV electricity is exported, the environmental impacts of PV power plant manufacture attributed to the building is zero.

SWITZERLAND					
Criterion	**Swiss case (SIA 2040:2017):** National approach used for building LCAs in the context of national labelling systems				
Generic or specific	provider specific	[✓ generic]			
Geographic scope	continental	regional	[✓ national]		
Electricity mix model					
Type of mix	(1) Production mix	[✓ (2) Supply mix]			
Nature of trade flows	Physical flows	Flows based on contracts	[✓ Flows based on Guarantee of Origin (GO)]		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – ∆ exports + ∆ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	[✓ (4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*]	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	[✓ Gross balance]	Net balance	Not applicable		

Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)
End uses dependence ^{1}) (heating, lighting, cooling, etc.)	universal mix	use specific mix	
Time dimension	historical mix	present mix	future mix
LCA modelling approach	average mix	marginal mix	
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity

^{1}): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

b) Research assessment (project « ELCAB : **E**lectricity mixes in **L**ife **C**ycle **A**ssessments of **B**uildings: Methodology and application on residential and office buildings »,

Type of mixes	**Explanation / Intention**
General information : Goal of this project is to assess different approaches of modelling the electricity mix used in the phase of operation of buildings and to offer electricity mix LCI datasets for the different approaches and applications. The mixes are established on the basis of 15/60 minutes intervals, matched with generic electricity load profiles of residential and office buildings, and integrated to months, seasons and the year. Additionally, average mixes are applied. The differences in assessment when relying on data of different time granularity of electricity mix data (hourly, monthly, seasonal, annual), when following a consequential as compared to an attributional approach, and when applying present or future mixes will be identified. The table below describes all alternatives quantified and assessed. Results about the environmental performance of the different electricity mixes, final results including environmental assessments of the buildings according to SIA 2040 (see above) by mid 2020) Remark : All alternatives are applied on the country mix and selected ones additionally on the mix of the electricity supplier of the city of Zürich, ewz	
Today	
Annual average mixes	Three different mixes : descriptive, decision oriented and based on guarantees of origin Mixes include traded electricity according to economic/contractual information (commercial trade). The descriptive mixes are established using hourly and annual mix data and archetypical load profiles of residential and office buildings and of Switzerland.
Daily mixes	not addressed
Seasonal mixes	Summer and winter mixes descriptive only. Same as with annual average mixes
Future	

Type of mixes	**Explanation / Intention**
Annual average mixes 2035 and 2050	Descriptive mixes only. Mix based on scenario information provided in official documents, modelled in steps of five years
Option 1 : building integrated PV	Use profile adjusted according to production profile of PV plant, 2 different sizes of PV plant
Option 2 : building integrated PV plus battery	Use profile adjusted according to production profile of PV plant and battery usage ; adjustment of share of self consumption, 2 different sizes of battery.
Option 3 : building integrated PV plus electric car(s)	Use profile adjusted according to production profile of PV plant and electric car charging; adjustment of share of PV self consumption.
Allocation for exported PV	Exported PV electricity has the environmental profile of PV mounted/integrated in the building under assessment. If 100 % of PV electricity is exported, the environmental impacts of PV power plant manufacture attributed to the building is zero.

Criterion	**Swiss case (ELCAB):** Research assessment of different types of mixes depending on time horizon (present, future) LCA modelling approach and time granularity				
Generic or specific	provider specific	generic			
Geographic scope	continental	regional	national		
Electricity mix model					
Type of mix	(1) Production mix	(2) Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – ∆ exports + ∆ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		

Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)
End uses dependence [1]**)** (heating, lighting, cooling, etc.)	universal mix	use specific mix	
Time dimension	historical mix	present mix	future mix
LCA modelling approach	average mix	marginal mix	
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix
Allocation of in site PV electricity production	Impacts of self-consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity

[1]): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

c) Research assessment (project « ECODYNBAT : Dynamic Life Cycle Assessment of Buildings »,

Choices	**Explanation / Intention**
General information	The EcoDynBat project assesses the environmental impacts of the electricity demand of Swiss buildings with a dynamic perspective. The project identifies the influence of increased temporal precision on the environmental impact calculations for the electricity demand of Swiss buildings. It will propose different time steps to be chosen by the user of the EcoDynBat method & tool for the calculations, which offers a balance between modelling efforts and the representativeness of results. The environmental impacts of electricity consumed at the building level is modelled by considering: - the variability of the Swiss production mix (sources varying) - the variability of the Swiss imports in quantity and source; the imports mixes of the European neighboring countries and others are varying (cf. § 1.7.5, Switzerland, EcoDynBat approach for the explanation of the matrix-based calculations and the different levels of interest for the neighboring countries + also below in Geographical scope) From the building side, the following sources of variability are considered: - Electricity consumption profile - Presence and production profile of a decentralized electricity production system (photovoltaic in particular)
Generic mix	Generic mix (on an hourly basis) at the national level,

Choices	Explanation / Intention
Geographical scope	National but considers hourly interactions with the neighboring countries. Imports are varying in quantity but also in source (i.e. the neighboring countries mixes are varying over the time) Considered countries (cf. § 1.7.5, Switzerland, EcoDynBat approach for the justification of the choice of these six countries): - Switzerland, Austria, Italy, Germany, France, Czech Republic (variation over the time of their production mixes + imports) - Other countries are considered with constant environmental impacts for their production means and only the imports amounts are varying over the time
Type of mix	Consumer mix (production mix + imports + grid losses)
Imports / Exports modelling choice	Gross physical flows, Economic contracts not considered
Allocation method for the imports/exports	Based on the idea that national generation of electricity is combined with imported electricity mixes to offer the electricity to customers. The resulting electricity mix is consumed in the investigated supply area AND exported to neighboring countries on the other. This means that the electricity mix model is equivalent for both consumption and export mixes.
Use pattern dependence	Universal hourly mix, no distinctions per usage
Time dimension	Present mix (from January 2017 until December 2018) Use of most recent data and regular updates from TSOs and other data sources useful for feeding the EcoDynBat tool.
Modelling approach	Average mix, attributional
Time granularity	From hourly to annually (daily, monthly, seasonally)
Allocation for exported PV	Only the self-consumed part of the PV is allocated to the building, the rest is deemed to be part of the national mix. The share of PV electricity sent to the grid is calculated according to the building demand profile and the PV system production profile. The impact of PV electricity is function of its technology and its production (varying from one site to another).

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Criterion	Swiss case (EcoDynBat): Research assessment & computational tool of different types of mixes (modelling options) and time granularity		
Generic or specific	provider specific	generic	

Geographic scope	Continental[1]	regional	National[1]		
Electricity mix model					
Type of mix	(1) Production mix	(2) Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – Δ exports + Δ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		
Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
End uses dependence [2]) (heating, lighting, cooling, etc.)	universal mix	use specific mix			
Time dimension	historical mix	present mix	future mix		
LCA modelling approach	average mix	marginal mix			
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix		
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

[1]): The EcoDynBat computational tool is able to calculate national hourly electricity mix for Switzerland as well as for other European countries incl e.g., Germany, Spain, Portugal, Benelux,

Denmark etc. In that context, it has a continental perspective in the way that it is able to handle hourly import/export between Switzerland and the surrounding European countries (neighbouring ones and some others). ^{2}): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

C.3 Example for Hungary

a) Mainstream assessment

Choice	Explanation / Intention
Generic mix	A generic mix is applied from a generic database (ecoinvent).
National mix	National mix is applied, with imports and exports according to data availability in generic databases.
Supply mix	National mix is applied, with imports and exports according to data availability in generic databases.
Generic mix	No differentiation between different use types (such as heating, cooling, ventilation, hot water etc.) ; electricity consumption of all uses are modelled with the same mix.
Present or future mix ?	The average present (recent past) electricity mix is applied.
Average or marginal mix ?	Average electricity mix.
Annual mix	An annual mix is applied.
Allocation for exported PV	100% of avoided impacts, assuming a potential replacement of the Hungarian electricity mix.

b) Research assessment, linking life cycle assessment and the European Electricity Market Model (EEMM) of the Regional Centre for Energy Policy Research (REKK), and the Green-X model, developed by the Energy Economics Group of the Vienna University of Technology.

Choice	Explanation / Intention
General information	The assessment of the environmental impact of the Hungarian electricity mix was carried out in a research project. The objective was to link life cycle assessment with an economic electricity market model to study the temporal variation in the environmental impact of the current and future electriticy mix. EEMM is a partial equilibrium microeconomic (supply-demand) model. It assumes a fully liberalised electricity market and perfect competition in all modelled countries. In every country, the model calculates the merit-order curve, assuming all production units offer their electricity on a marginal-cost basis. Supply includes imports as well, taking into account capacity constraints. EEMM includes 3400 power plant units in a total of 41 markets, including the EU, Western Balkans and other EU neighbouring countries. Each country is a single node in the model, with 104 interconnectors between them.
Generic mix	Generic mix for Hungary
National mix	National mix but interactions with neighbouring countries are considered. Imports are modelled as the production mix of the neighbouring countries (excluding their imports). The model assumes that the composition of the electricity that is exported is the same as the electricity supplied to the grid.
Supply mix	Production mix + imports
Universal or Use-specific mix	Universal mix, but the possibility of developing use-specific mix will be studied
Present or Future mix ?	Present mix and future mix. Future mix is based on three policy scenarios, based on the economic electricity market model.
Average or marginal mix ?	Average mix
Annual and hourly mix	Besides the annual mix, also a mix with an hourly resolution is modelled for the present and for the future scenarios.

Choice	Explanation / Intention
Allocation for exported PV	100% of avoided impacts assuming a potential replacement of the Hungarian electricity mix.

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HUNGARY

Criterion	**HUNGARY** Mainstream assessment				
Generic or specific	provider specific	generic			
Geographic scope	continental	regional	national		
Electricity mix model					
Type of mix	(1) Production mix	(2) Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – ∆ exports + ∆ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		

Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
End uses dependence [1]) (heating, lighting, cooling, etc.)	universal mix	use specific mix			
Time dimension	historical mix	present mix	future mix		
LCA modelling approach	average mix	marginal mix			
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix		
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

[1]): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

HUNGARY					
Criterion	**HUNGARY, REKK EEMM + LCA** Research assessment				
Generic or specific	provider specific	generic			
Geographic scope	continental	regional	national		
Electricity mix model					
Type of mix	(1) Production mix	(2) Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – Δ exports + Δ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where*

			hourly or 15 min basis) are taken into account	*electricity disclosure is mandatory*	*electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		
Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
End uses dependence [1]) (heating, lighting, cooling, etc.)	universal mix	use specific mix			
Time dimension	historical mix	present mix	future mix		
LCA modelling approach	average mix	marginal mix			
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix		
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

[1]): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

C.4 Example for Sweden

a) Modelling of the electricity mix following the EU Joint Research Center method (Erlandsson, 2019; Moro & Lonza, 2018), used e.g. in the NollCO$_2$ certification scheme

Choice	**Explanation / Intention**
Generic mix	The method is meant to provide a value appropriate to assess all buildings in Sweden, regardless of the energy provider. However, producer-specific emission factors may also be used in the NollCO$_2$ certification, if they have been calculated in a preexisting EPD or if they have received the "Bra Miljöval" certification.

Choice	**Explanation / Intention**
National mix	The Swedish Energy Agency now recommends using a national mix, primarily for the sake of harmonization and consistency with practices in other European countries.
Supply mix, considering Swedish production plus imports minus exports and transmission losses.	This method calculates the life cycle based emission factor for electricity consumed in a country. One objective is to consider electricity trading between European countries, hence the inclusion of both imports and exports. The original JRC method ignored upstream emissions for renewable energy, but the value calculated for the NollCO$_2$ certification includes the embodied impact of renewable power plants.
Universal mix	The aim is to obtain an average factor for attributional LCAs that can be used regardless of the context or system studied.
Data on physical flows from transmission system operators.	The method is based on data from the ENTSO-E transparency platform, IEA and Eurostat.
Present / future mix	The original work from the EU Joint Research Center only provides an emission factor for the year 2013. The NollCO$_2$ certification scheme updates this value every two years, and also includes a future scenario. Following long term strategies from Sweden and the EU, electricity is assumed to be carbon neutral in 2050. Emission factors between 2020 and 2050 are estimated through linear interpolation. Another report by Erlandsson (2019) also develops a method to assess future greenhouse gas emissions from the building sector, based on forecasts from the Swedish Energy Agency.
Average mix	This emission factor is meant to be used for accounting and certification purposes. However, it should be noted that “negative emissions” from on-site electricity exported to the grid are estimated using a marginal approach.
Annual average mix	Temporal variation is not accounted for, for the sake of simplicity. Previous works suggest that there is little difference between using yearly averages and hourly values when considering an average mix for attributional LCAs (Erlandsson et al., 2018).
Allocation for exported electricity	In NollCO$_2$, electricity exported to the grid results in negative greenhouse gas emissions by offsetting electricity produced in coal power plants (i.e. it receives a “negative emission factor” corresponding to the emission factor of coal power). This only applies to electricity that would be produced in excess of the building’s needs. In other words, on-site electricity is first assumed to reduce the building’s electricity demand, and the production that exceeds the building’s demand is assumed to displace coal power.

SWEDEN				
Criterion	**JRC Method as used in NollCO$_2$**			
Generic or specific	Provider specific	Generic		
Geographic scope	Continental	Regional	National	

Electricity mix model					
Type of mix	Production mix	Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – ∆ exports + ∆ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		
Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
End uses dependence $^{1)}$ (heating, lighting, cooling, etc.)	universal mix	use specific mix			
Time dimension	historical mix	present mix	future mix		
LCA modelling approach	average mix	marginal mix *(only for electricity exported to the grid)*			
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix		
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

b) Tidstegen tool for consequential assessments of energy-related measures (Gode et al, 2015)[26]

Choice	**Explanation / Intention**
Generic mix	The method assesses the consequences of a change in demand on the Nordic electricity grid, regardless of the producer.
Regional mix	The assessment is based on a Nordic electricity mix, due to the fact that Nordic countries share a common market (Nordpool).
Supply mix, considering Nordic production, imports and exports.	The Tidstegen method calculates the consequences of a change of electricity demand, depending on the season and time of day when it happens. Possible consequences are changes in how plants are operated, changes in investments in various production technologies, and changes in imports and exports.
Universal mix	The aim is to obtain an emission factor for consequential LCAs that can be used to assess any energy-related measure at the building level.
Data derived from a model.	A linear programming cost optimization model is used to determine the consequences of a change in demand on the operation of power plants and investments in new power plants, depending on when this change in demand happens.
Future mix	The Tidstegen tool focuses on consequences up to the year 2040. The method is based on three future scenarios, that differ primarily in terms of carbon costs.
Marginal mix (short- and long-term margin)	This method is meant to assess the consequences of a change in electricity demand on the operation of power plants, imports, exports and long-term investments in production technologies.
Seasonal mix	A separate marginal mix is calculated for each year until 2040. For each year, a separate mix is calculated for summer, spring/autumn, and winter. For each season, a separate mix is calculated for daytime and nighttime.
Allocation for exported electricity	On-site electricity exported to the grid is treated as a reduction in electricity demand on the grid.

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SWEDEN			
Criterion		**Tidstegen method**	
Generic or specific	Provider specific	Generic	

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[26] https://www.ivl.se/sidor/vara-omraden/miljodata/verktyget-tidstegen-for-klimatbedomning-av-energiatgarder.html

Geographic scope	Continental	Regional	National		
Electricity mix model					
Type of mix	Production mix	Supply mix			
Nature of trade flows	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO)		
Modelling choice for the supply mix	(1) Production + imports	(2) Production – exports + imports	(3) Production – Δ exports + Δ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
Balance of import/export at each border with the studied country and each neighbouring country	Gross balance	Net balance	Not applicable		
Data types for the energy carrier flows	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
End uses dependence $^{1)}$ (heating, lighting, cooling, etc.)	universal mix	use specific mix			
Time dimension	historical mix	present mix	future mix		
LCA modelling approach	average mix	marginal mix			
Time granularity	annual average mix	seasonally differentiated mix	hourly differentiated mix		
Allocation of in site PV electricity production	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity		

C.5 Example for Denmark

	Criterion	**Insert your country:………………………** Type of approach (e.g., commonly used approach (labelling systems), research assessment/study)				
1	**Generic or specific**	provider specific	generic			
2	**Geographic scope**	continental	regional	national		
	Electricity mix model					
3	**Type of mix**	(1) Production mix	(2) Supply mix			
4	**Nature of trade flows**	Physical flows	Flows based on contracts	Flows based on Guarantee of Origin (GO) purchase together with physical production	Flows based on Guarantee of Origin (GO)	
5	**Modelling choice for the supply mix**	(1) Production + imports	(2) Production – exports + imports	(3) Production – Δ exports + Δ imports *NB: contemporaneous physical imports and exports are considered transit trade and thus balanced. Only net import and net export volumes (determined on an hourly or 15 min basis) are taken into account*	(4) According to national electricity declaration *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*	(5) Production minus Exports (Production volume – domestic GO supply volume, per technology) plus Imports (foreign GO supply volume, per technology) *NB: This model only works for countries such as EU and EFTA countries where electricity disclosure is mandatory*
6	**Balance of import/export at each border with the studied country and each neighbouring country**	Gross balance	Net balance	Not applicable		
7	**Data types for the energy carrier flows**	Direct use of empirical data from Transmission System Operator (TSO)	Data derived from/determined with a model (e.g., statistical models…)	Other data (e.g., use of national statistics different from TSO data, literature data)		
8	**End uses dependence** [1]) (heating, lighting, cooling, etc.)	universal mix	use specific mix			

9	**Time dimension**	historical mix	present mix	future mix
10	**LCA modelling approach**	average mix	marginal mix	
11	**Time granularity**	annual average mix	seasonally differentiated mix	hourly differentiated mix
12	**Allocation of in site PV electricity production**	Impacts of self consumed part only	Gross impacts minus PV impacts of fed in electricity	Gross impacts minus grid mix impacts of fed in electricity

[1]): The mix (universal or use specific) may be defined on the level of annual, seasonal, daily, hourly or 15 minutes' averages. Combining hourly (or 15 minutes) universal mixes with the use profiles of heating, lighting, cooling or ventilation) and integrating them to annual values will result in annual use specific mixes.

Annex D: Electricity mix considered in the case of PV production on the building

Local PV production can be self-consumed or exported. The self-consumed part may reduce the use of grid electricity. How should in situ produced electricity which is exported (fed into the grid) be modelled in the LCA of a building? Which production mix should be considered if following an avoided burden approach? This annex presents the situation and modeling choices in the different countries.

D.1 France

The electricity consumption has been approximately constant these last 12 years. Small variations are mainly related to winter temperature variations because of the use of electric heating. If the grid mix still includes a share of fossil or nuclear, it would not be logical to reduce the wind or hydro-electricity production when a PV roof reduces the consumption in a building.

During these 12 years, the electricity mix has varied: the share of nuclear production decreased from 78% to 72% and coal power plants from 5% to 1% whereas the share of renewables (wind, PV and biomass) increased from 1% to 9%, hydroelectricity varying a little according to rainfalls. The new renewable production is therefore replacing nuclear and coal production. The French energy transition policy planned to reduce the share of nuclear production to 50% in 2025, but this has recently been delayed until 2035. If only 6% has been replaced in 12 years, it would need 56 years to reach a 50% share considering the present speed of the transition. The last coal power plants are used for the winter peak demand. Local PV production is higher during the other seasons. It is therefore probable that a PV system with a life span of 30 years will replace a nuclear production. An electricity mix model allows to evaluate this in a more precise way.

Accounting for the benefit of exporting electricity allows a correct evaluation of the environmental pay back time of renewable energy systems. For instance the actual energy pay back time of a PV module is a few years (depending on the climate).

Using the avoided impacts approach, the environmental balance does not depend on the self-consumption ratio. In an example case study, this ratio is around 50% at the scale of a building but at the scale of the neighbourhood, because some other buildings consume the produced electricity, the self-consumption ratio is 100%. The avoided impacts approach leads to equal energy pay back times, which is physical. The avoided impacts method provide consistent results which are scalable: the environmental pay back time is the same at the scale of the product, the building, the neighbourhood and the city.

D.2 Switzerland

Switzerland decided to step out of nuclear power. It is not allowed to commission new nuclear power plants and the existing ones may operate as long as they fulfill the safety requirements. Currently 4 nuclear power plants (located at three sites) are still running. The fifth one stopped production at the end of 2019. The energy directive includes goals for the electricity production with new renewable energies (11’400 GWh per year in 2035 compared to 3’670 GWh in 2018) and with hydroelectric power plants (37’400 GWh per year in 2035 compared to the average expected annual production of 35’210 GWh).

The technical bulletin SIA 2040 specifies how to model electricity produced in situ and exported to the electricity grid. Firstly, the environmental impacts of in situ electricity production (e.g. photovoltaic system, combined heat and power plant) are quantified and attributed to the total amount of kWh produced, i.e. the electricity exported and the electricity self-consumed. The environmental impacts of the self-consumed electricity are attributed to the building, whereas the environmental impacts of the exported electricity are attributed to the organisation (e.g. electric utility, private households) purchasing it. It is not allowed to attribute any kind of negative environmental burdens to the building’s LCA due to exported electricity.

D.3 Sweden

Electricity production in Sweden is based primarily on hydropower and nuclear power (about 40% of the production mix each), followed by windpower and combined heat and power plants (about 10% of the production mix each). Sweden is a net exporter of electricity.

There is currently no standardized method to account for the benefits of on-site PV electricity exported to the grid. Different assessments might use different methods. This situation is likely to evolve in the coming years, as there are ongoing efforts towards more harmonization.

Both the current version of the NollCO$_2$ certification method (Sweden Green Building Council, 2020), and the Tidstegen method (Gode et al., 2015), assume that the short term marginal consequences of exporting on-site electricity to the grid are a reduction of electricity production in coal power plants. Therefore, in both cases, a negative emission factor would be used, equal to the emission factor of electricity produced in coal power plants.

The two methods differ regarding the way they assess exported on-site electricity in the long term. NollCO$_2$ considers that electricity production in Europe will be climate neutral by 2050, following the objectives of Sweden and the EU. The emission factor of electricity (both for electricity used in the building, and for on-site electricity exported to the grid) is assumed to decrease linearly between 2020 and 2050. Tidstegen considers three different scenarios after 2020. In the long term, it is assumed that the marginal emission factor for electricity will depend on the time: the marginal mix is not assumed to be coal in the long term, but varies depending on the season and whether it is day or night. In Tidstegen, any energy-related measure at the building level would have to be assessed in each of these three long term scenarios. The model requires inputing hourly data for electricity demand, but the calculations only consider the total daytime (respectively nighttime) electricity demand for each season and each year.

NollCO$_2$ specifies that this marginal assessment only concerns on-site electricity produced in excess of the building's needs. On-site electricity would first be used to meet the building's electricity demand. Additionally, the embodied greenhouse gas emissions of the PV installation itself are taken into account in the emission factor of PV electricity. In other words, they are included in module B6 using values in gCO$_2$/kWh, rather than being included in module A.

D.4 Norway

There is no official electyricity mix to be considered for electricety mix regarding electricety produced by PV when exported to the grid.

However, the the Research Centre on Zero-Emission Buildings (ZEB), in the LCA for the validation of the "Zero-emission" uses a CO$_2$-factor of 132 g CO2eq/kWh, which is a modelled average CO$_2$-factor from Europe production between 2010 and 2050 (Graabak et al 2014). This value corresponds well with the Norwegian Standard on LCA of buildings (NS3720:2018) Scenario 2 (EU28+NO) for future electricity mix from 2015 to 2075 of 136 g CO$_{2eq}$/kWh.

The rationale behind the use of european future electricity mix is that the Norwagian grid is supposed to be fully integrated (withouth botlenecks) with the european grid, motivated by the tenmporal benefits of hydropower versus thermal powerproduction in buffering new-renewable electricity production in the grid.

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Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

Buildings' expected service life usually spans over at least several decades of even centuries and produce further emissions not only when they are being constructed, but also in the operational phase (including repair and replacement) and at the end of life. The problem of emissions discounting is the problem of present and future importance of GHG emissions released into atmosphere or captured for a certain period over time. The current LCA practice does not consider such temporal aspects. With the typical approach, emissions occurring at different times are aggregated, but in reality, the total emission is not present in the environment at one time, but it is spread over time.

This report summarises the most relevant approaches and their implications regarding the time-related aspects of emissions. It deals with time horizons, physical discounting, carbon budget approach, discounting, economic discounting and monetization of environmental impacts.

If temporal differentiation is considered in LCA, the following recommendations are provided:

Time in life cycle inventory
A prerequisite for considering time in impact assessment and weighting is that life cycle inventory data should be temporally differentiated. It is recommended to indicate the time when emissions occur in the inventory to make it possible that temporal issues are later considered.

Physical discounting
Physical discounting is based on the modelling the actual behaviour of emissions in the environment. While this is an important issue, it is not recommended to apply this approach to future emissions.

Carbon budget approach
The carbon budget approach is recommended. In this approach it is irrelevant whether the emission occurs now or in the future. This makes physical temporal differentiation unnecessary, but scarcity considerations might be applied.

Physical discounting based on increasing scarcity considerations
There is a (residual) budget of emissions determined using scientific methods that may still be emitted if the goal of limiting global warming is met. The amount of emissions that are still permitted to be released is therefore smaller and scarcer. Increasing scarcity can be expressed by increasing the weighting factor (e.g. ecological scarcity method).

Monetization of environmental impacts and discounting
Although physical discounting of future impacts is not recommended, in some approaches, monetization of environmental impacts is used. Once the environmental impacts are monetized, it is possible to apply discounting on the environmental external cost. However, a discount rate of zero or near zero shall be applied considering the perspective/interest of future generations. It is recommended to perform a sensitivity analysis to check how sensitive the results are to the discount rate.

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Abbreviations

Abbreviations	Meaning
EOL	End of life
EU ETS	The European Union Emissions Trading System
GHG	Greenhouse gas emission
GWP	Global warming potential
IAM	Integrated assessment model
ISO	International Organization for Standardization
IPCC	The Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
MCA	Marginal cost approach
MMG	Milieugerelateerde Materiaalprestatie van Gebouwelementen: Environmental Material Performance of Building Elements
OECD	The Organisation for Economic Co-operation and Development
OVAM	Public Waste Agency of Flanders
SCC	Social cost of carbon
TH	Time horizon
UN	The United Nations

1. General Context and Scope

1.1 General

Emissions over the life cycle of a construction product occur at different points in time and significance of their impact may vary. A typical example is waste incineration where immediate emissions to the air have to be weighed against future emissions of slag landfills (Hellweg, Hofstetter, & Hungerbiihler, 2003). In the built environment the service life may span over decades or even hundreds of years, therefore the consideration of temporal issues may become relevant. However, in general no temporal differentiation of impacts is considered in LCA. There have been attempts to adopt the approach of economic discounting where future cash flows are weighted differently than today's cash flows to account for the time value of money. The possibility of applying "physical discounting" based on the modelling the actual behaviour of emissions in the environment has also been discussed. Currently, there is no consensus on whether discounting should be applied in LCA or not. It can and must therefore be discussed whether and to what extent it is possible and sensible to transfer the discounting approach to life cycle assessment.

1.2 Context: Relation to LCA

Climate change is one of our largest challenges today. As buildings are responsible for nearly 40 % of carbon emissions and have high potential for savings, the society shall consider greenhouse gas (GHG) and other emissions in all life cycle phases of construction projects. It is especially important in buildings, as their expected service life usually spans over at least several decades of even centuries and produce further emissions not only when they are being constructed, but also in the operational phase (including repair and replacement) and at the end of life.

If there is a case, that the importance of GHG and other emissions changes over time, such fact shall definitely be considered in optimization approaches and assessment methods, because the change shall impact the optimization result.
The problem of emissions discounting is the problem of present and future importance of carbon emissions released into atmosphere or captured for a certain period over time. The current LCA practice is not to consider such temporal aspects. With the typical approach, emissions occurring at different times are aggregated, but in reality, the total emission is not present in the environment at one time, but it is spread over time.

The question arises whether the temporal aspect should be incorporated into the LCA of buildings and whether today's emissions should be evaluated differently from future emissions. Depending on the chosen approach, this may have a significant influence on the assessment results and thus influence the decision-making process in construction.

2. Status of the Discussion

Temporal issues appear at all stages of an LCA (Stefan Lueddeckens, Saling, & Guenther, 2020):

- Goal and scope definition: the temporal system boundary (time horizon) is defined and the regarded life cycle stages
- Inventory: the inventory data may have a temporal resolution
- Impact characterisation: time dependent characterisation mechanisms
- Normalisation: time dependent normalisation factors
- Weighting: temporal weighting (discounting)

In current LCA practice, the life cycle inventory is usually an aggregated total value of emissions over the service life of the product. Some time-related information is included in some databases. For example, the ecoinvent database (Wernet et al., 2016) distinguishes very long-term emissions for disposal processes. Further disaggregation in time is usually not applied.

Characterization factors of impact assessment are usually generic (average values) without temporal differences (Hellweg & Frischknecht, 2004), (C. Yuan, Wang, Zhai, & Yang, 2015). For example, no difference is considered whether an emission contributes to global warming potential today or in 150 years.

Temporal differentiation could be especially relevant for long-term emissions (slowly released over a long period of time) where the impact of long-term emissions could be very large if the same impact factors are used as for short-term emissions. This problem occurs, for example, in waste treatment processes in landfills (Hellweg & Frischknecht, 2004). Also, there is ongoing debate on carbon capture and storage technologies, that would take exhaust waste carbon emissions from industrial processes or energy production and store them for shorter or longer period of time (Marshall & Kelly, 2010). While weighting of impact categories is well established in LCA, there is a lack of consensus on temporal weighting or discounting. In this report, the most relevant approaches are summarised.

2.1 Time Horizons: Temporal System Boundary

In current LCIA practice, generally there is no explicit differentiation between emissions occurring at different points in time, but some form of implicit discounting is common practice, for example the use of temporal system boundaries or time horizons (TH). Time horizons can be applied for the whole assessment, for the life cycle inventory and for the impact characterization (S. Lueddeckens, Saling, & Guenther, 2021).

Are discounting and time horizons equivalent?

In the early 1990s there has been a discussion on discounting for global warming assessment, but the IPCC instead adopted the concept of time horizons because of its presumed simplicity (Fearnside, 2002) In the literature, setting a time horizon (temporal cut-off) for the assessment is generally regarded as equivalent to the application of discounting (Almeida, Degerickx, Achten, & Muys, 2015; Boucher, 2012; Fearnside, Lashof, & Moura-Costa, 2000; HU, 2018; Stefan Lueddeckens et al., 2020; Mallapragada & Mignone, 2017). (Hellweg et al., 2003) states that time horizon is a special discounting case with a zero rate during the considered time horizon and an infinite rate after the time horizon. On the other hand, in the opinion of (S. Lueddeckens et al., 2021) discounting and time horizons are not equivalent, as in case of time horizons some kind of standardization is possible while discounting is highly individual and fully dependent on a decision maker’s utility at different points in time (S. Lueddeckens et al., 2021).

Length of time horizon (TH)

The choice of the time horizon in LCA will significantly influence the results. For example, (Finnveden, 2000) showed how results change depending on the time horizon when assessing long-term heavy metal emissions of municipal waste sites.

The choice of TH is regarded by many as an ethical question about the rights of future generations. Very short THs are against the principle of intergenerational equality, while very long ones marginalize short-term actions and thereby reduce incentives to act (Herzog, Caldeira, & Reilly, 2003; Stefan Lueddeckens et al., 2020). For example, with an infinite TH no benefit of any sequestration measure could be shown (Brandão et al., 2013) but this would avoid problem shifting to the future (Lebailly, Levasseur, Samson, & Deschênes, 2014).

According to (S. Lueddeckens et al., 2021) an LCA can be action-oriented and measurement-oriented. Action-oriented LCA would have a short time horizon to show the consequences of actions and the responsibility of people living today. However, their opinion is that LCA should be measurement-oriented and therefore have a long TH. They recommend the use of discounting to express time preference instead of setting a short TH.

In impact assessment, pre-defined time horizons can be selected in the fate model for temporal system boundaries (e.g. GWP 20, 100, 500). There is a debate whether these time horizons are realistic, as 20 years are too short, while 500 years too long, meaning most LCA studies choose the 100-year TH (Fearnside, 2002).

The Eco-indicator 99 and ReCiPe methods also consider time according to the cultural theory (Hofstetter, Baumgartner, & Scholz, 2000). The archetypes in society are fatalist, individualist, hierarchist and egalitarian with fatalist having the shortest TH and egalitarian the longest. For example, in climate change calculations, the individualist has a 20-year perspective, the hierachist 100-year and the egalitarian an infinite TH. Most assessments apply the hierarchist perspective.

An option is to use strict time horizons. This would mean that if the impact of CO_2 emitted today is determined for a time horizon of 100 years, then the impact of CO_2 emitted in 20 years should be determined based in a time horizon of 80 years (suggested by Ollivier Jolliet in (Hellweg & Frischknecht, 2004)). Such an approach is possible by using a dynamic LCA (Pehnt, 2006).

2.2 Physical Discounting

Hellweg, Hofstetter and Hungerbiihler (2003) introduced the idea that changes in the environment can be expressed with discounting, similarly to economics where price level changes (inflation or deflation) are included in the nominal discount rate. The background concentration of pollutants values or the sensitivity of the ecosystem may change and impacts depend on doses or threshold. For example, soil has a certain buffer for acidic substances until exhaustion occurs (S. Lueddeckens et al., 2021) or the accumulation of heavy metals may trigger a change in the damage produced by an additional unit of emission (Hellweg et al., 2003).

Yuan *et al.* (2015) proposed a theoretical framework for temporal discounting in LCA. Their conclusion was that the inventory analysis stage is advantageous for addressing temporal homogeneity issue. They recommend a methodology following five steps and in their paper they summarize the possible solutions and challenges encountered in each step:

1. Calculating the temporal scale of LCA: the length of each activity when emissions are released must be determined (e.g. product production time, usage time, EOL time + time lags in between). This usually follows a stochastic pattern due to variability, so the result of this step is an expected minimum and maximum time duration of each activity (possible methods to use: fuzzy logic method, Critical Path Method, scenario analysis, statistical analysis, stochastic modelling, predictive models, degradation analysis)
2. Compiling temporally differentiated life cycle emissions: the inventory data must be temporally differentiated, which requires an activity-based modelling.
3. Modelling the actual behaviour of emissions in the environment: released emissions have an initial concentration in the environment, but through various routes and pathways their concentration is dynamically changing (e.g. transported by the fluid flow, chemical reaction, degradation by itself, interaction with other medium for interphase transport and change, absorption in the environmental sinks, precursors). The changes in the amount can be mathematically determined through appropriate fate and transport models, but this involves complex modelling.
4. Discounting emissions to a selected reference time point: the reference point can be any time, e.g. starting or ending point of the life cycle.
5. Aggregating discounted emissions at the reference time point: calculating the equivalent amount.

According to the authors, the difference between the discounted total amount and the directly aggregated amount can be significant. For example, the total discounted amount of CO_2 emissions was 19.78% lower than the total amount of CO_2 emissions in the conventional life cycle inventory in the case of a Volkswagen Golf A4 car (Yuan et al. 2015).

The concept of physical discounting was, however, rejected by (O’Hare et al., 2009) who stated “the discounting model applies to costs and benefits, not to physical phenomena that generate them, unless their economic value is otherwise stable over time”. (S. Lueddeckens et al., 2021) agrees that only utility and not physical things can be discounted. According to their opinion, changing background concentration should be modelled with dynamic characterization and normalization and the use of the term “discounting” is not appropriate for this issue.

2.3 Carbon Budget Approach

Carbon budget can be utilized for setting of national or regional benchmarks for the amount of CO_2 emissions produced by buildings over their life cycles. An emissions budget, carbon budget, emissions quota, or allowable emissions, is an upper limit of total carbon dioxide (CO_2) emissions associated with remaining below a specific global average temperature (Meinshausen et al., 2009; UN Environment, 2018).

Governments of some countries already use carbon budgets on daily bases. In the UK, for instance, “under the Climate Change Act (2008) the Government is committed to legally binding carbon budgets. These are five-year period targets for the UK’s GHG emissions set fifteen years ahead. The first four Carbon Budget periods have been legislated for: 2008-12; 2013-17; 2018-22 and 2023-2027.” (Department for Business, 2018)

The development of remaining carbon budget is monitored by UN and the results are continuously reported in the Emission Gap Reports. The latest report (UN Environment, 2018) concludes, that although most of the nations provided their Nationally Determined Contributions to the Paris Agreement, the actual commitments are not sufficient for bridging the emissions gap in 2030. Moreover, the global GHG emissions showed no signs of peaking in 2017.

The problematics of allocation of the carbon budget from the global level to national buildings-related activities is available in (Habert et al., 2020).

In the carbon budget approach, it is irrelevant whether the emission occurs now or in the future. They are considered equal. This makes physical temporal differentiation unnecessary, but scarcity considerations might be applied.

Physical discounting can be based on increasing scarcity considerations. There is a (residual) budget of emissions determined using scientific methods that may still be emitted if the goal of limiting global warming is met. This remaining budget is getting smaller and smaller as a result of continued release of emissions, and the amount of emissions that are still permitted is therefore smaller and scarcer. In some impact assessment methods, such as the ecological scarcity method, increasing scarcity is expressed by increasing the weighting factor.

2.4 Economic Discounting

Discounting in economics is common practice. A key publication that introduced the concept of discounting in LCA was the publication of Hellweg et al in 2003 (Hellweg et al., 2003), which was followed by some other papers. Discounting is still seldom applied in LCA studies and there is no consensus in the literature on its application.

2.4.1 Discounting Approaches in Economics

In economics, temporal variability is addressed with a temporal discounting approach. The motivation for discounting can be time preference, productivity of capital (related to economic growth/decline) and uncertainty/ risk perception (Hellweg et al., 2003). The basic idea behind is that money available today is worth more than the same amount in the future, because money is already there, certain and can earn interest.

In economics, cash flows occurring over time are discounted to a common metric – present values or future values. A discount rate is applied to describe the change of the value of the money during an interval. Cash flows at different points in time are projected to the reference time and then aggregated to the total value. The reference time is usually the present, but sometimes the future. The general formula for calculating the present value is:

$$PV = CFV/\ (1+r)^n$$

where

PV	is present value
CFV	is future cash flow value
N	is number of years between present time and occurrence time
r	is discount rate

2.4.2 Reasons for the application of discounting in LCA

Due to time preference: There is a general agreement that discounting because of pure time preference should not be applied in LCA as it is against fundamental ethical values (Hellweg et al., 2003) (S. Lueddeckens et al., 2021). Time preference would mean that environmental damage may be regarded worth less in the future than today. From a moral aspect, all people including those not yet born should be treated equally. However, in real life decision makers often apply an implicit discounting and most people have a short planning horizon. Ethical issues do not mean that all kinds of temporal weighting should be rejected. Weighting of damages at different times can be regarded similarly to weighting of different damage types (Hellweg et al., 2003).

Due to uncertainty: Discounting is sometimes used to reflect uncertainty. For example, some environmental damages may become less important in the future if technological breakthroughs help to reverse the damage but could become more important if they affect more people (S. Lueddeckens et al., 2021). There is a general agreement, however, that discounting is not the right method for considering uncertainty in LCA, which should rather be handled with scenario and sensitivity analysis.

Supporting decisions: According to Lueddeckens, Saling and Guenther (2021), discounting is a tool for intertemporal decision making. It is only useful if alternatives need to be compared to support decision making. They do not recommend discounting in informative assessments, e.g. in single-product LCA or labels. However, in comparative LCA, discounting may help to answer temporal decision problems, for example, a question on whether to use resources now or later. Lueddeckens, Saling and Guenther (2021) provides an example that natural gas reserves can be used now or later. Today there is plenty of solar power available which could be used to produce electricity or heat. In a worst case scenario, after a major volcanic eruption in the future, the available solar energy may be limited and without any fossile reserves energy supply would be hindered. They suggest applying the discounted utility theory for developing a discounting framework, which means that any utility can be discounted and not just money. Discounting can be regarded as a decision instrument that gives information on the difference from opportunities. The discounting function depends on the evaluated utility and personal criteria (S. Lueddeckens et al., 2021).

2.4.3 Discount rate

In most applications of discounting in environmental science, a standard exponential discount function is applied like in financial mathematics, for example in (Hellweg et al., 2003) and (C. Y. Yuan, Simon, Mady, & Dornfeld, 2009).

The discount rate will influence the weighting between present and future and it is a question to which impacts to give a higher weight. The higher the discount rate, the lower the present value of the future cash flows. Similarly, a high positive discount rate would reduce the present value of future environmental impacts. For example, regarding the use of energy source, on the one hand, the scarcity of fossil fuels and the prospect of their complete depletion in the near future say that future energy is more valuable. On the other hand, the marginal cost of extracting energy increases over time. Hence, present saving of energy should be preferred in order that today's relatively easily extractable energy is available as long as possible and other energy fields requiring more complex and more expensive exploration techniques do not have to be used. Using the discounting method makes it possible to take into account emissions concentrated over a shorter period starting in the present, such as manufacturing of materials. Due to improving technologies future energy production is expected to correspond to lower emission levels (Zöld & Szalay, 2007).

The determination of the appropriate discount rate is a challenge. In economics it could be the average bank interest rate, bond rate during the time interval, or the social discount rate used in computing the value of funds spent on social projects (Harrison, 2010). In the standard theory, the discount rate is the sum of time preference and opportunity costs or utility of economic growth (Gowdy, Rosser, & Roy, 2013).

With regards to environmental damages, the application of the social discount rate is proposed, as these damages harm all of society (Richards, 1997; J. Wang, Zhang, & Wang, 2018). This rate is typically lower than the private discount rate as society has a longer time horizon and less time preference than individuals (S. Lueddeckens et al., 2021).

According to ISO 14008:2019 (ISO, 2019), the discount rate:

$$r = d + g \cdot \mu$$

where

d is the pure rate of time preference

g is the growth rate of per capita consumption

μ is the elasticity of social marginal utility of consumption.

The ISO 14008:2019 suggests that for inter-generational (i.e. long-term) considerations from a societal perspective, the pure rate of time preference should be set to zero.

Many authors propose a small discount rate near 0% as the rate has a very large influence on the results (Bakas, Hauschild, Astrup, & Rosenbaum, 2015) In the Cultural Theory, a hierarchist would apply a discount rate of close or equal to 0%, while an individualist would choose the private discount rate and an egalitarian would prefer zero or even negative discount rate (Hellweg et al., 2003). In the opinion of (C. Y. Yuan et al., 2009), underestimation of impacts would be more critical than overestimation, hence discounting should be handled very conservatively. On the other hand, according to (S. Lueddeckens et al., 2021), the choice of the discount rate is not arbitrary and depends on the opportunity cost of the exact case. The discounting function depends on the use case and must be developed individually.

Lueddeckens, Saling and Guenther (2021) raises the possibility of using declining discount function (hyperbolic discounting) instead of the usual exponential function in certain cases, for example for long time horizons and taking into account *"individual rights to utilize parts of the natural capital (as equity) and emission rights "borrowed" from others, especially from future generations (debt)".*

It is recommended to check the sensitivity of the results to different discount rates. For example, in Germany, a discount rate of 3 percent can be expected for short-term periods (up to approx. 20 years). For claims that extend further into the future, the discount rate applied by default is 1.5 percent. Furthermore, a sensitivity calculation with a discount rate of 0 percent must be carried out for cross-generational considerations. The discount rates are to be applied for the entire period (constant discount rates). The values selected for the method convention are within the ranges that are scientifically common (Bünger & Matthey, 2018; Matthey & Bünger, 2019; Umwelt Bundesamt, 2021).

2.5 Monetization of Environmental Impacts

In economics, one reason for discounting is capital productivity, as capital can be invested so that it grows in the future. This does not apply directly to environmental issues as they cannot be stored in a fund. However, if we accept that there is a relationship between monetary values and environmental impacts, discounting could also be applied to environmental impacts (Hellweg et al., 2003; O'Hare et al., 2009; J. Wang et al., 2018).

Monetization of impacts can be based for example on the prevention or abatement costs. Arguments against monetization are that monetization of human lives or natural assets is often perceived as unethical, as future generations are left with no option to decide whether they accept compensation payment for a natural asset. Global, irreversible, critical damages are difficult to monetize (Temel, Jones, Jones, & Balint, 2018). Also, it cannot be guaranteed that the payment will be passed on by the intermediate generations (Hellweg et al., 2003).

Hellweg reached the conclusion that discounting due to capital productivity leads to an overall discount rate of close to 0%, as both compensation and discount rate relate to economic growth. The discount rate may even be negative if natural assets become scarce and a very high compensation is required.
According to Lueddeckens, Saling and Guenther (2021), discounting of monetized impacts is a valid approach but monetization is not a prerequisite for discounting. In their opinion, "discounting is independent from monetary values. Every kind of utility can be discounted. Avoided negative impact is always a utility, and negative impact is always disutility.

In the following section, a summary is provided on the available monetization approaches, with a special focus on the social cost of carbon.

2.5.1 Monetization approaches

A brief summary of monetization of environmental impacts was provided by Le Pochat (Le Pochat, 2013). The short paper also provides a general classification of methods used for the monetization of environmental impacts: a) economic valuation of biodiversity and/or ecosystem services; b) monetization of environmental impacts; and c) environmental accounting. For GHG calculation, typical approach for doing so is to calculate so called social cost of GHG emissions, sometimes shortly referred to the social cost of carbon, or SCC (class b – monetization of environmental impacts). The recommended approaches are provided in the international standard ISO 14008:2019 Monetary valuation of environmental impacts and related environmental aspects (ISO 14008:2019). ISO 14008:2019 provides an overview of procedures and requirements for monetary valuation. The list of available procedures comprises market price proxies (market proxies of traded goods and labour; cost-of-illness method); revealed preference methods (individual and public averting cost methods; hedonic pricing method; travel cost method; and evaluation based on data derived from public referendums); stated preference methods (contingent valuation; choice experiment); and value transfer (spatial value transfer; temporal value transfer).

Another approach that can be traced in the field of economy is not to use the GWP indicator with monetizing GHG emissions, but to have use other indicators such as Global Cost Potential or Cost-Effective Temperature Potential (Johansson, 2012).

2.5.2 Cost of GHG emissions arising from emission trading schemes

The minimum cost of carbon for the industry sectors covered by emission trading is given by the prices in the emission trading markets. An overview of the emission trading schemes worldwide is provided in the report of ICAP (ICAP, 2018). The report states that in 2018 15 % of global GHG emissions were covered by the emission trading schemes and provide overview of covered sectors per region and scheme. The report does not present any figures for the cost of emissions traded, but it provides an overview of various emissions trading schemes in operation or with planned launch. It covers the emissions trading schemes in force by 2018 at various levels:

- supranational level: European Union Emissions Trading System (EU ETS);
- country level: China, Kazakhstan, Korea, New Zealand, Switzerland;
- provinces and states levels: Western Climate Initiative (including California, Québec, Manitoba, Ontario, British Columbia), Regional Greenhouse Gas Initiative (including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, Vermont) and Saitama;
- city level: Tokyo.

The report also mentions different schemes in preparation (by 2018).

2.5.3 Social cost of carbon

The external climate cost (also called ‘social cost of carbon’ in literature) is increasing over time and this can be discounted.

There are various methods to evaluate the social cost of carbon (SCC).
The SCC can be set as a result of Cost-Benefit Approach by seeking for socially optimum levels of emissions through time. The shadow price of emissions is then defined as the pollution tax required to keep emissions at the optimal level (Clarkson & Deyes 2002).

Another method is the Marginal Cost Approach (MCA) represents an attempt to calculate directly the difference in future damage levels caused by a marginal change in baseline emissions (Clarkson & Deyes

2002). It is the monetized damage from emitting one additional unit of CO_2 or its equivalent to the atmosphere, often obtained from various computational Integrated Assessment Models (IAMs) (Marshall & Kelly, 2010) or the cost of actions needed to recovery the damage. There are claims that monetization of damages is essential for the determination of optimal climate policies (Nordhaus, 2017; van den Bijgaart, Gerlagh, & Liski, 2016). The MCA is used also with the abatement costs, i.e. cost of reducing emissions (Ackerman & Stanton, 2012).

There is a considerable body of literature that discuses SCC. Two main groups of sources are briefly discussed in this chapter: scientific papers that present various background calculations of SCC; and documents of public domain that proposes, prescribe or use some levels of SCC for the policy and decision-making in the public sector.

Range of SCC presented in scientific papers

Various studies propose different levels of SCC. Literature research made in this project considered research papers and reports published in the past five years, i.e. in 2014 and later. The research was made during January and February 2019 using research databases (mainly Web of Science and Elsevier) supplemented by inputs provided by the Annex 72 members. Since the topic of the cost of carbon develops rapidly, in June 2021 more sources and new updates were added. Details of all the aspects of estimations of SCC are beyond the limited scope of this text, so the review was not focusing on single studies, but rather on papers presenting outcomes of broader reviews of papers and reports in order to provide basic idea on ranges of SCC and provide links to sources of further references for deeper study.
The IPCC WGIIAR5 report (IPCC, 2014) includes chapter 10.9.3. *Social cost of carbon* which discusses the estimates published in research studies published before and after IPCC AR4, discusses the figures, used discount rates and presents statistic charts of SCC for various pure rates of time preferences. Average cost in all set of considered studies ranged between $40 for 3 % discount rates and $655 for 0 % discount rates (page 690, Table 10-9, prices in dollar per tonne of carbon).

A paper by Nordhaus (Nordhaus 2017) proposes SCC per tonne of CO_2 of $\$31.2_{2010}$ for baseline scenario and $\$184.4_{2010}$ for scenario of 2.5 degree maximum (for year 2015). The paper provides more figures for 2015, 2020, 2025, 2030 and 2050 for various scenarios. For scenario of 2.5 degree maximum proposes $351.0 for emissions in 2030, and 1,006.2 for emissions in 2050.

The team of Chinese authors (P. Wang, Deng, Zhou, & Yu, 2019) made a review of the current research on the SCC and discussed model choice of models for its calculation. They made a meta-analysis above data from 58 studies. In the conclusions they state that "*in all collected data, the estimated SCC ranged from –50 to 8752$/tC (–13.36e-2386.91$/tCO₂), with a mean value of 200.57$/tC (54.70$/tCO₂). Specifically, it equaled to 112.86$/tC (30.78$/tCO₂) with a PRTP at 3% in peer-reviewed studies*".

The authors of another paper (Yang et al., 2018) discuss the role of socioeconomic assumptions in the estimations of future SCC. They use DICE model and results of the China Climate Change integrated assessment model to update SCC in five Shared Socioeconomic Pathways. For 2020, the average SCC estimations under SSP1, SSP2, SSP4 and SSP5 were 10 $/tCO₂, 19 $/tCO₂, 18 $/tCO₂ and 12 $/tCO₂, respectively. The SSP3, which represents high mitigation and adaptation challenges, has the highest SCC early in this century, reaching 45 $/tCO₂ in 2020 and increasing to 108 $/tCO₂ by 2050. The paper also provides a wide variety for SCC in 2100 for different scenarios.

The authors of a working paper (Havranek, Irsova, Janda, & Zilberman, 2015) examine potential selective reporting in the literature on the social cost of carbon (SCC) by conducting a meta-analysis of 809 estimates of the SCC reported in 101 studies. Their results indicated that estimates for which the 95% confidence interval includes zero were less likely to be reported than estimates excluding negative values of the SCC, which might create an upward bias in the literature. Their estimates of the mean reported SCC corrected for the selective reporting bias are imprecise and range between USD 0 and 130 per ton of carbon at 2010 prices for emission year 2015.

Another paper (van den Bergh & Botzen, 2015) presents a critical review of the reported SCC estimates by examining some neglected consequences of climate change, uncertain and extreme scenarios of climate change, the discounting of future climate change effects, the treatment of individual risk aversion, and assumptions about social welfare. The text does not provide its own levels of SCC, but provide a long list of references to other studies.

Examples of use of SCC by public authorities

The examples of public authorities use the comprise USA, UK, Germany and Belgium. These documents are relevant for construction GHG as well, as they shall apply also to new legislation (incl. construction) and to public investments.

In the USA, the Interagency Working Group on Social Cost of Greenhouse Gases (or IWG) of the United States Government has a task to ensure that the social cost of carbon estimates provided to the U.S. government reflect the best available science and methodologies, so that these estimates can be used in cost-benefit analyses of regulatory actions. In its report (Interagency Working Group on Social Cost of Greenhouse Gases, 2016) IWG calculated SCC ranging from \$31 (USD_{2007}) for 2010, through \$42 for 2020 upward to \$69 for 3 percent discount rate. The report also provides ranges for 2.5 and 5 percent discount rate and for lower-probability, higher-impact outcomes and 3 percent discount range. The SCC in the report ranges between \$10 (for 5% in 2010) and \$212 (for 3%, high impact). The U.S. EPA on its website (US EPA, 2017) and in its factsheet (US EPA, 2016) on SCC referred to the levels from IWG report as well. In the new 2021 report (Interagency Working Group on Social Cost of Greenhouse Gases, 2021) IWG presents for the period 2020-2050 costs between \$14 and \$260 per metric ton of CO_2 in 2020 dollars.

In the UK, the central government uses for appraisal and evaluation in decision-making The Green Book (HM Tresaury, 2018). The document describes the principles and procedures used for public appraisal and evaluation in various segments and in *Chapter 6 Valuation of Costs and Benefits* in it specifically lists GHG emissions and energy efficiency and provides guidelines for valuing effects on the natural environment. A supplementary document (Department for Business, 2018) provides a specific guidance for valuation of energy use and GHG and makes link to the toolkit that the British government provides for valuing changes in GHG emissions. The document also provides practical guide with examples that shows how to value GHG under traded price (for the valuation of GHG under trading scheme it prescribes to calculate with traded price from EU ETS system) and under non-traded price. For the non-traded price, the example uses value 66 £/tCO_{2e} (in $£_{2017}$), the authors currently working on valuing shall use actual numbers from the provided toolkit.

In Germany, the German Environment Agency (Umwelt Bundesamt) provides Methodological Convention 3.0 for the Assessment of Environmental Costs (Matthey & Bünger, 2019). In its Table 1 on page 8, the report presents a table of SCC (in $€_{2016}$) for 1% pure rate of time preference of €180 for 2016, €205 for 2030 and €240 for 2050. It also shows figures for 0% pure rate of time preference of €640 for 2016, €670 for 2030 and €730 for 2050. For the years not indicated, the figures shall be interpolated. The recommended value of $€180_{2016}$/t $CO_{2eq.}$ is close to value determined in the 5th Assessment IPCC report of 173.5 $€_{2016}$ /tCO_2[1]. In the 12/2020 update (Matthey & Bünger, 2020) the costs range between 195 and 765 $€180_{2020}$/t CO_{2eq}.

In Belgium, Public Waste Agency of Flanders (OVAM) published a series of reports on MMG method (Milieugerelateerde Materiaalprestatie van Gebouwelementen: Environmental Material Performance of Building Elements) which is based on a first 2012 report (Debacker et al., 2012). The latest MMG report (De Nocker, L., Debacker, 2018) describes the updates in methods and presents monetary values of several

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[1] IPCC (2014), p. 691, Average of all available studies with a 1% pure time preference rate and different assumptions regarding Equity Weighting, compounded for 2016, currency conversion via purchasing parities of the World Bank.

environmental indicators based of combination of damage costs and prevention/abatement costs methods. For GWP it provides cost of 1 kg of $CO_{2eqv.}$ in three levels for Western Europe: low €0.025, central €0.050 and high €0.100, whilst the central is recommended as most representative. The central cost was estimated from prevention costs, because damage costs were highly uncertain and prevention cost information was good. The value of future impacts was discounted using a social discount rate 3 %. In chapter 4.1.1 the study cites two tables from VITO 2014 (details on the original source is not mentioned in the report references) which provide also different costs for construction phase, use phase, and end of life phase and make difference in SCC depending on the purpose of calculation – a monetary indicator for global warming for studies focusing on the comparison of impacts from different building materials or building lines; and monetary indicator for global warming, for assessment of external costs of buildings in cost-benefit analysis (e.g. for comparison with costs of emission reduction measures).

Example of use of SCC policy papers

An example of use of the SCC in policy papers is the OECD document Effective Carbon Rates 2018 (OECD, 2018a) and accompanying brochure (OECD, 2018b). The documents represent detailed and comprehensive account of how 42 OECD and G20 countries, which are responsible for 80 % of the global carbon emissions, price carbon emissions from energy use. The reports describe so-called carbon pricing gap, which measures the difference between price of emissions (combining price of emission permits, carbon taxes and specific taxes on energy use) produced in each country with two reference levels: EUR 30/t CO_{2e} and EUR 60/t CO_{2e} and describes that the carbon gap for the EUR 30 level in 2018 was 76.5%. That means that 76.5 % of emissions in the countries responsible for 80 % of global GHG emissions are valued bellow 30 EUR/t CO_{2e}.

The documents also present outcomes of an analysis, which claim, that the negative economic motivation works – those countries with a low carbon pricing gap tend to have less carbon intensive economies.

3. Recommendations

If temporal differentiation is considered in LCA, the following recommendations are provided:

Time in life cycle inventory
A prerequisite for considering time in impact assessment and weighting is that life cycle inventory data should be temporally differentiated. In building LCA, production of materials and construction happen is a relatively short time period, which is followed by a long period of operation. It is recommended to indicate the time when emissions occur in the inventory to make it possible that temporal issues are later considered.

Physical discounting
Physical discounting is based on the modelling the actual behaviour of emissions in the environment. While this is an important issue, it is not recommended to apply this approach to future emissions. These effects do hardly apply to CO_2 because of its chemical stability and thus long-term presence in the atmosphere.

Carbon budget approach
The carbon budget approach is recommended. In this approach it is irrelevant whether the emission occurs now or in the future. They are considered equal. This makes physical temporal differentiation unnecessary, but scarcity considerations might be applied.

Physical discounting based on increasing scarcity considerations
There is a (residual) budget of emissions determined using scientific methods that may still be emitted if the goal of limiting global warming is met. This remaining budget is getting smaller and smaller as a result of continued release of emissions, and the amount of emissions that are still permitted is therefore smaller and scarcer. Increasing scarcity can be expressed by increasing the weighting factor (e.g. ecological scarcity method).

Monetization of environmental impacts and discounting
Although physical discounting of future impacts is not recommended, in some approaches, monetization of environmental impacts is used (i.e. when there is need for a single indicator integrating various interests). Once the environmental impacts are monetized, it is possible to apply discounting on the environmental external cost. However, a discount rate must be chosen that considers the perspective/interest of future generations, in line with IPCC's recommendations. Hence, a zero or near zero (1% or less) discount rate is recommended. It is also recommended to perform a sensitivity analysis to check how sensitive the results are to the discount rate.

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Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA

A Contribution to IEA EBC Annex 72

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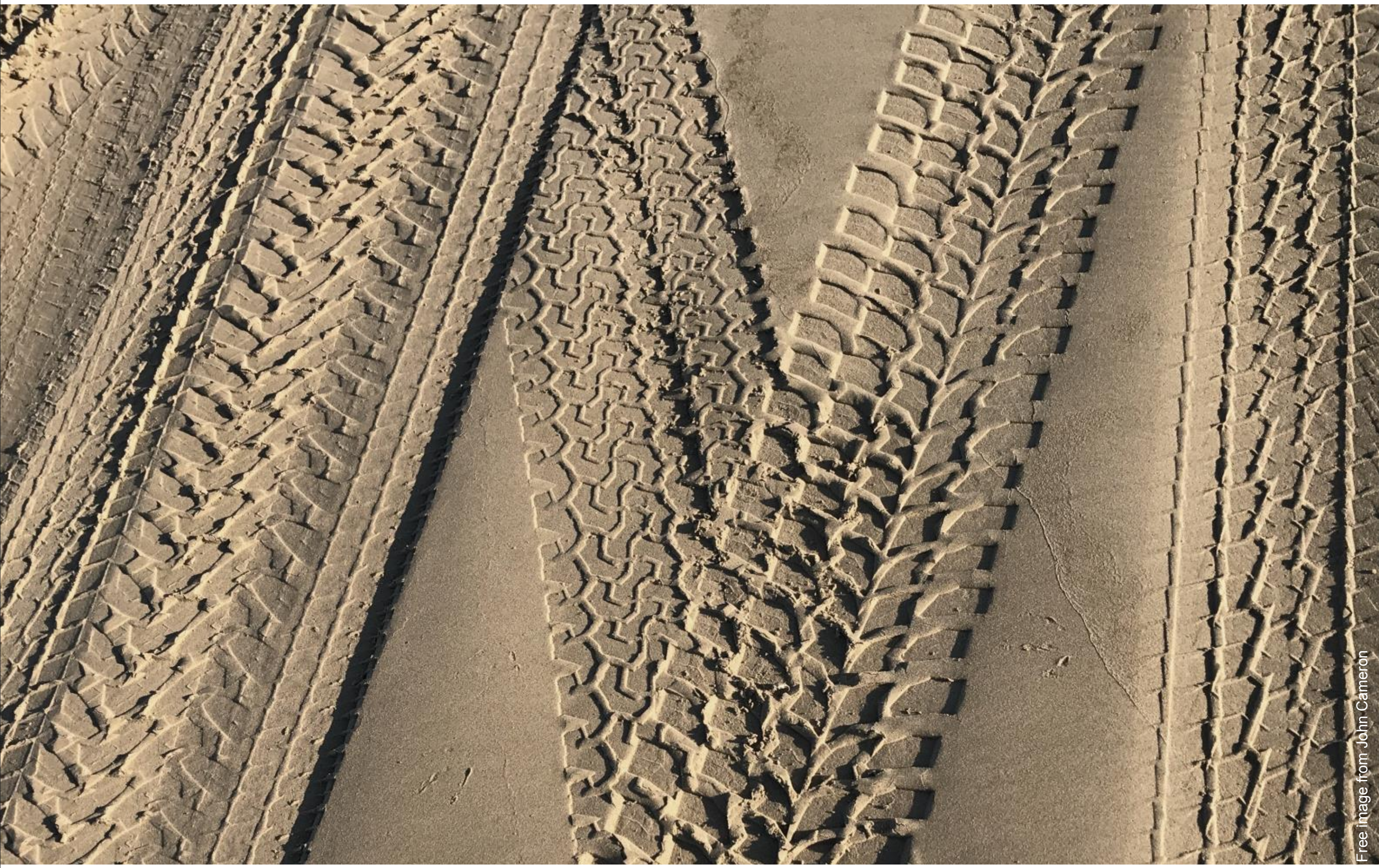

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Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and Recommendations on Influence of Future Electricity Supplies on LCA-based Building Assessments (Zhang 2023)
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023).
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023)
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023)

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Summary

The method of life cycle assessment (LCA) applied to buildings involves the integration of a great amount of process along in the building life cycle. Hence, the assessment of transport, construction and deconstruction process can be a complex task. There, the modelling strategies to assess this process should consider aspects involved such as fuel consumptions, distances, loading capacity, etc.
One of the main obstacles are the difficulties in modelling, predicting, and estimating process (e.g., energy and fuel consumption, distances assumptions) before the building is built.

Thus, based on a literature review and a specific survey conducted within the Annex 72 participant countries, the present report provides an overview about the modelling of transport, construction, deconstruction strategies, and its integration in the building LCA.

The report starts with a contextualization and limitation of the scope of the process here analysed and integrated in the building LCA. Secondly, includes a literature review considering how existing works integrates the modelling of transport, construction and deconstruction processes in building and construction products (Environmental Product Declarations, EPD). Thirdly, a survey among the Annex participant is conducted to in deep analyse of the modelling strategies. Fourthly, the results of the survey are discussed and possible solutions to deal with the detected challenges are proposed. To conclude a set of recommendations and challenges based on these findings are proposed.

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Abbreviations

Abbreviations	Meaning
A72	IEA EBC Annex 72
EoL	End of Life
EPD	Environmental Product Declaration
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
T, C&D	Transport, Construction and Deconstruction process

Definitions

Definitions of general terms in the context of an environmental performance assessment are provided here. Many of these descriptions are based on definitions found in international standards. In some cases, definitions found in standards were modified. Topic-specific terms and definitions are explained in the topic-related sections of this report.

Life cycle Assessment (LCA): LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a building, infrastructure, product or material throughout its lifecycle (ISO, 2006).

Life cycle stage: all consecutive and interlinked stages in the life of the object under consideration. The life cycle comprises all stages, from raw material acquisition or generation from natural resources to end-of-life (ISO 21930:2017).

Information module: distinct parts for a building's life cycle for which impacts are to be declared. Each building's life cycle stage is comprised of more than one information modules.

Operational impacts: Impacts associated with energy and water consumed during a building's operation.

Embodied impacts: When an environmental impact of a product is characterized as "embodied" it does not mean that it is really embodied in the product itself. It is used in a metaphorical sense to describe the impacts caused by life cycle stages of a product other than the operation (embodied in a virtual sense).

Refurbishment: planned large scale (substantial) modification and improvements to an existing construction works to bring it up to an acceptable condition. Refurbishment can be undertaken to facilitate continuation of the current function, including technical modernization and a change of space plan, or a change of function to new use. Synonymous: deep renovation, deep retrofit (prEN 15978-1: 2021).

Environmental Product Declaration (EPD): claim which indicates the environmental impacts and aspects of a product, providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information (prEN 15978-1:2021).

Component: item manufactured as a distinct unit to serve a specific function or functions. A building component is a part of a building, fulfilling specific requirements/functions (e.g. a window or a heating system). The service life of a building component can be shorter than the full service life of the building. Building components are sometimes referred to as "building elements" (ISO 21931-1:2022).

System boundary: boundary representing what building parts and life cycle stages are included and what not in the building assessment (adapted from EN 15978:2011).

Design phase or design step or design stage: The design process is typically paced by different design steps, in which lifecycle-based environmental performance assessment can be integrated to various extents. For example, in the early design phase, the first steps are the strategic definition of the project and the preliminary studies, that have to be made in order to get to the concept design. In the detailed design phase, the next step is the developed design, which is followed by a precise technical design step where all the detail technical solutions are developed and the documentation for the procurement is prepared. A detailed description of the various design steps can be found in A72 report by Passer et al. (2023).

1. Introduction

The application of the LCA in buildings includes the integration of different type of information about the building including all the “products, process and services related to the building and along its life cycle” (EN, 2011). While some information about the LCA modules can be directly extracted from (predefined and normalized) data sources, accountancy of inputs and outputs for Transports (T) process (Modules A4 and C2) and construction and deconstruction (C&D) (Modules A5 and C1) are complex and demand specific modelling strategies. It should be noted that these processes can also be included in several use stage modules (such as B2, B3, B4 and B5) which consists of removal and transport to disposal or recycling location of the removed building components as well as transport and installation of the replaced/repaired components (see Figure 1.1). Therefore, in the case of C1, C2 for the old component removal as well as A4, A5 for the new component installation are included in the modeling.

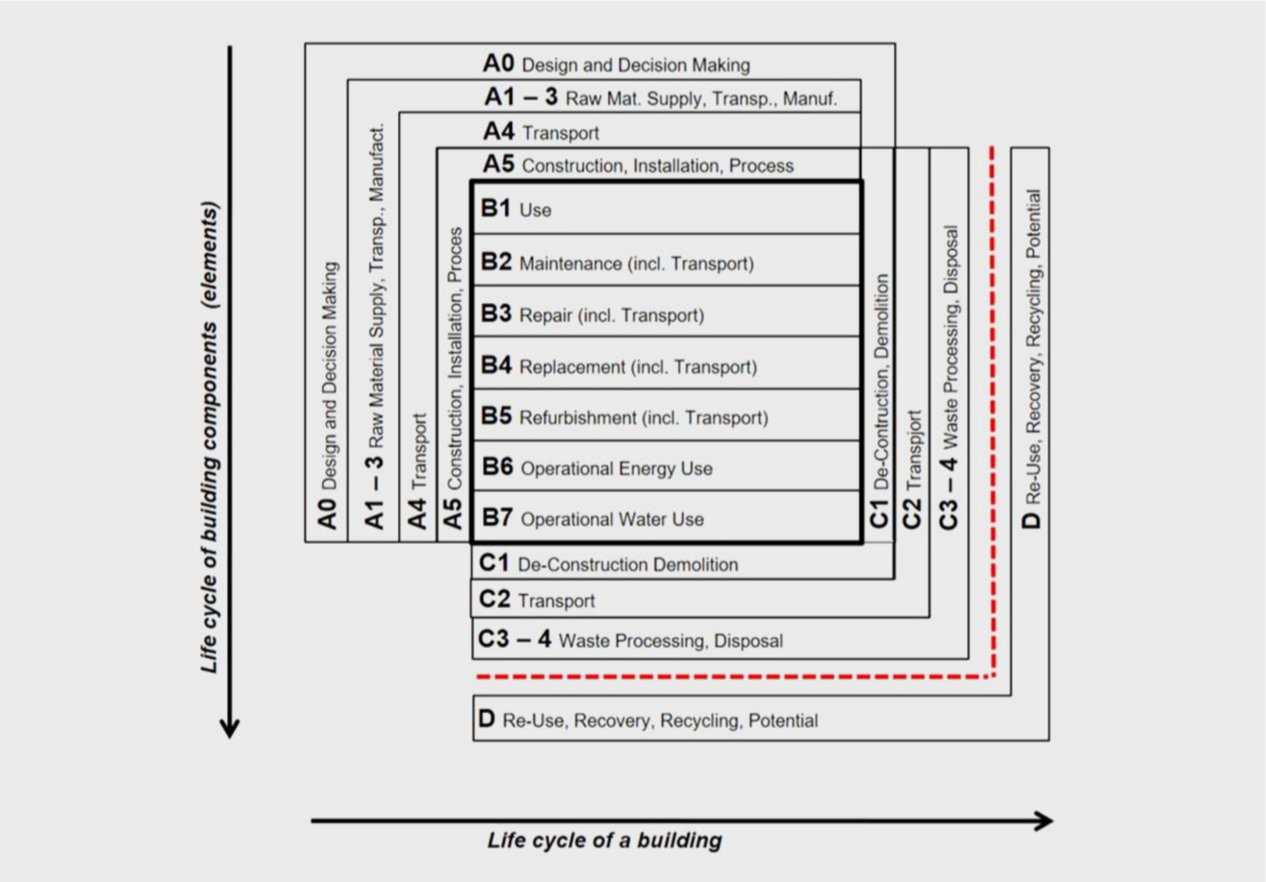

Figure 1.1. LCA information modules according to EN 15643:2021, EN 15978 (EN, 2011) building standard, and EN 15804 (EN, 2012) and ISO 21931 (ISO, 2017) building component/element standard [1](Source: (Lützkendorf, 2019).

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[1] Modules C1, C2 as well as A4 and A5 are included also in B4 (and in specific cases in B5).

In order to consider the number of activities, processes and services that should be integrated in the modelling of Transport, Construction & Deconstruction (T, C&D) process in modules A4, A5, C1, C2 and T, C&D in the use stage modules (B2, B3; B4;B5) of the EN 15978 (EN, 2011) proposes a list of items to guide the process (see Table 1.1). Table 1.1 contains a description of the system boundary of each module and suggests the number and type of activities, processes and services that should be included in the LCA. The listed items show the complexity and difficulty in including them in the LCA application.

Table 1.1. According to EN 15978 (EN, 2011) system boundary of each information module should cover:

LCA Module	**System boundary extracted from EN 15978** (EN, 2011) **(activities, processes, and services to be included)**
A4	- transport of construction products and materials from the factory gate to the building site, including any transport to and return journeys of vehicles from the site, intermediate storage, and distribution, - transport of construction equipment (cranes, scaffolding, etc.) to and from the site, - all impacts and aspects related to losses due to the transportation (i.e., production, transport and waste management of the construction products and materials that are damaged or otherwise lost during transportation).
A5	- preliminary activities to prepare the site e.g., site clearance and levelling, connection to utilities, - storage of construction products and materials, including the provision of heating, cooling, humidity, etc., - transport of construction products and materials, waste, and equipment within the site, - temporary works, including temporary works located off-site as necessary for the construction installation process, - on site production and/or processing and/or assembly of materials, products, and components, - provision of heating, cooling, ventilation, humidity control etc. to site facilities during the construction process, - ground works and excavations, - works for the erection/installation of the construction products and materials into the building including ancillary materials not counted in the EPD of the products e.g., releasing agents (oils and greases) in formworks for concrete, formworks discarded at the end of the project, - energy and water use for construction processes/activities, - waste management processes of other wastes generated on the construction site. This includes all processes (including transportation from the building site) until final disposal or until end of waste state is reached, - production, transportation end of life treatment/disposal of products and materials wasted during the construction and installation process, - landscaping, and may include (as additional information) transport of construction workers to and from the site

T, C&D **of** B2, B3, B4 and B5	- Transport of the components and auxiliary products to replace the old ones, the impacts and aspects of loosed materials during the transport (needed for maintenance, repair, replaced, refurbishment process). - Replacement/ Maintenance/ repairing works of components and auxiliary products (deconstruction/removal of existing components and installation of replacement components). - Transport of removed components and other material/product waste to landfill or reuse/recycling locations.
C1	- on-site operations and operations undertaken in temporary works located off-site as necessary for the deconstruction processes after decommissioning up to and including on-site deconstruction, dismantling and/or demolition.
C2	- all impacts due to transportation to disposal and/or until the end-of-waste state is reached. This includes transport to and from possible intermediate storage/processing locations.

For the sake of simplification, A4-A5 and C1-C2 are dealt with in the following. This expressly includes the transports and construction site processes at use stages. An overview of the activities related to transport and construction processes dealt with in this report is provided in Table 1.2 and a related scheme in Figure 1.2.

Thus, this report discusses:

- the different ways of modelling the Transport (A4 and C2), Construction and Deconstruction (A5 and C1) modules at the beginning, during and at the end of the life cycle, including the scope of the activities described in Table 1.1.
- the implications of using different modelling options.

The report also provides an overview of the current national application in the context of the Annex 72 participant countries and analyze the possible consequences of using different modelling strategies and illustrate possible solutions to deal with them. Based on the results of survey conducted within the context of Annex 72 (where the different LCA National methods and modules included were exanimated), countries contributing to this task declared how they consider of some of these T, C&D modules when conducting LCA. Hence, the present report includes contributions from the following countries Australia (AU), Brazil (BZ), Belgium (BE), Canada (CA), Switzerland (CH), Germany (DE), Spain (ES), France (FR), Hungary (HU), New Zealand (NZ), Portugal (PT) and United Kingdom (UK).

Table 1.2. Scope of the activities related to transport and (de)-construction process discusses in this report and the correlation with the LCA modules.

Activity	Module(s) that fully or partly contain transport processes in their boundary	Here discussed
Activities related to transport processes		
Transport in the upstream chains	A2	No
Transport of construction and/or ancillary products from manufacturers, suppliers or storage facilities, construction equipment to the construction site	**A4**, B2, B3, B4, B5	Yes
Transport of construction site equipment to the construction site	**A5**, B4, B5	Yes
Transport of construction workers to/ from the construction site	**A5**, (B2), (B3), B4, B5	No*
Transport from the construction site to disposal or waste processing facilities	B3, B4, B5, **C2**	Yes
Transport of building users during building operation (mobility)	B8	No
Transport on the waste processing and/or disposal facilities	C3, C4	No
Activities related to construction processes		
Preliminary works (excavation, earthworks, etc.)	**A5**	Yes
Installation of construction products and technical systems	**A5**, B3, B4, B5	Yes
Deinstallation of construction products and technical systems	B3, B4, B5, **C1**	Yes
(Re-)application of finishes (e.g., paint) or other products	B2, (B4), (B5)	No
Heating and lighting consumed on site	**A5, (B4), (B5)**	Yes

* Not mandatory in EN 15978:2011, and not significant in the context of this guideline

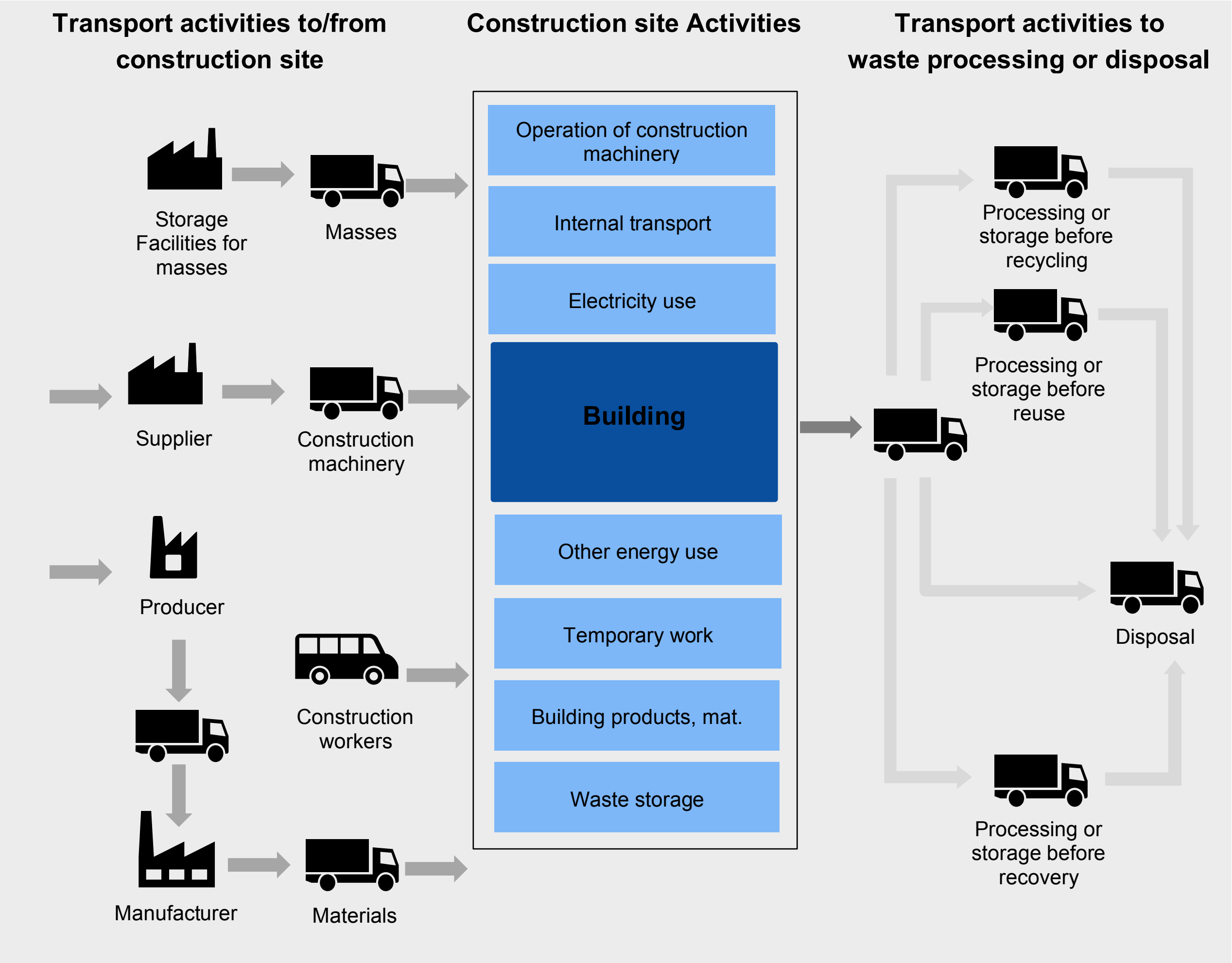

Figure 1.2. Scheme of the activities related to transport and (de) construction process (based on (Vrije Universiteit Brussel et al., 2020))

2. Status of the Discussion

2.1 Literature Review

2.1.1 Modelling of T, C & D processes in LCA

During the last years, many researches have addressed the impact calculation of the construction activities by using the LCA method (EeB Guide Project, 2012). In this vein, different related aspects have been considered, such as national and regional implementation and benchmarks (Schlanbusch et al., 2016; Schlegl et al., 2019); methodological issues such as temporal scope of buildings, uncertainties, dynamic weighting systems, probabilistic approach in retrofitting, parametrization (Favi et al., 2017; Hoxha et al., 2017; Morales et al., 2020; Østergaard et al., 2018; Steubing et al., 2020; Su et al., 2019); BIM-LCA integration (Bueno & Fabricio, 2018; Hollberg et al., 2020); construction alternatives (Balasbaneh et al., 2019; Kamali et al., 2019; Shirazi & Ashuri, 2020).

Many of these studies affect the ways to handle aspects related to the T, C & D process such as those involved in modelling A4, A5, C1 and C2 modules (EN 15978 (EN, 2011)). There, far from following a harmonised methodology to conduct the inventory analysis, different approaches and assumptions are identified. In the following paragraphs, some of the most recent and relevant LCA studies have been analysed from the point of view of the modelling and calculation procedure.

Note that in many cases, especially non-European research, the EN 15978 (EN, 2011) standard is not followed. In those cases, a distribution of the system boundaries according to the EN 15978 (EN, 2011) stages and modules of information was assumed:

1. **Construction process stage: Transport to manufacture to the site (A4 module EN 15978).** Even that these modules can be neglected or not included but justified reasons (EeB Guide Project, 2012), there has been detected (Asdrubali et al., 2013; Balasbaneh et al., 2019; Lavagna et al., 2018; Zabalza Bribián et al., 2011) different options to include them in the LCA implementation to buildings. Different assumptions are made to calculate the distance and means of transport involved in this module. According to Lavagna et.al 2018 (Lavagna et al., 2018), A usual practice is to consider an average distance of 50 km for massive materials (e.g. (Asdrubali et al., 2013)) and 100 km for other materials (e.g. (Zabalza Bribián et al., 2011)). Other studies such as Shirazi & Ashuri (Shirazi & Ashuri, 2020) conduct the calculation of transport distances of each material by using Google maps. Pacheco-Torres et al. (Pacheco-Torres et al., 2014) obtain the transport data from EPDs, and other study (Shadram et al., 2016) considers both. Kamali & Hewage (Kamali et al., 2019) includes the transport of workers to the construction site in this module. Many LCA studies (Favi et al., 2017; Pacheco-Torres et al., 2014) do not include a detailed description of the modelling of transport and its impact calculation procedure.
2. **Construction process stage: Construction and Installation process (A5 module EN 15978)** The impacts produce during construction and installation in buildings is commonly not taking into account in recent LCA studies (Favi et al., 2017; Morales et al., 2020), and when considering the calculation procedure is not clearly detailed (Balasbaneh et al., 2019; Kamali et al., 2019; Pacheco-Torres et al., 2014; Shirazi & Ashuri, 2020). Other studies (Asdrubali et al., 2013; Beccali et al., 2013; Lavagna et al., 2018; Scheuer et al., 2003) that consider this module, such as Lavagna et.al 2018 (Lavagna et al., 2018), estimate the impact of electricity consumption in the assembly phase as: a) 2%

of the embodied energy of all building materials; and b) 4% of the construction materials are wasted on the construction site.

3. **T, C and D in the Use stage: (B2, B3; B4 and B5 module EN 15978)**
   T, C & D process during the use phase are usually neglected in recent LCA researches (Favi et al., 2017; Kamali et al., 2019; Shirazi & Ashuri, 2020). In other study (Pacheco-Torres et al., 2014) the modelling assumptions and calculations procedure are not enough detailed.
4. **End of Life stage: Deconstruction/Demolition (C1 module EN 15978)**
   The impacts produced during the deconstruction/demolition process are usually considered but, generally the followed procedure is not described in detail (Balasbaneh et al., 2019; Lavagna et al., 2018; Morales et al., 2020; Pacheco-Torres et al., 2014; Shirazi & Ashuri, 2020). On the other hand, many cases (Favi et al., 2017; Kamali et al., 2019) just neglected it. This can be the end of life of the entire structure or of an individual component.
5. **End of Life stage: Transport (C2 module EN 15978)**
   The modelling of impacts produced by the transportation of demolition waste and building elements from the construction site to the final disposal (e.g. recycling plant, landfill (the most usually considered)), in many research (Morales et al., 2020; Pacheco-Torres et al., 2014; Shirazi & Ashuri, 2020) the processes under C2 are not described in detail. When the procedure is more comprehensively described such as in (Balasbaneh et al., 2019; Lavagna et al., 2018), the means of transport are defined (generally truck or lorry) and the distance to the final disposal points (landfill) is estimated (usually around 10 km). In contrast, many studies (Favi et al., 2017; Kamali et al., 2019) do not considered the transport of building materials to the final disposal/recycling points.

When considering the modelling of transport modules (A4 and C2), several aspects should be taken into account:

a. establish the location of manufacturers, site construction and final disposal/recycling points of building component/elements.
b. calculate the transport distances (there is a wide range of approaches to model the distances: from general estimations up to accurately definitions e.g. google maps);
c. calculate the mass/volume to be transported (e.g., capacity utilisation and bulk density of transported products);
d. define the means of transport, fuels type and consumption, and their environmental impacts.

The impacts related to construction and deconstruction process (A5 and C1 modules) are usually neglected. However, when they are modelled, the calculation procedure and assumptions are generic and diverse. The preliminary results of the literature review show the heterogeneity and differences in the modelling of A4, A5, C1 and C2 modules, which reinforce the statement of establishing harmonised procedures to model and calculate their impacts.

2.1.2 Modelling of T, C & D process in construction products EPDs

The modelling of transports (A4 and C2) and construction, and deconstruction process (A5, C1) is also addressed by the construction EPDs. Considering the system boundaries, different types of EPDs can be identified (see Figure 2.1). Thus, according to the EN 15804 standard (EN, 2012) there are five possible types of EPD: 1) cradle to gate; 2) cradle to gate with mandatory C1-C4 and D; 3) cradle to gate with options (C1-C4 and D); 4) cradle to gate with options (A4 and A5); and 5) cradle to grave with mandatory D.

A selection of case studies was performed to identify the main modelling strategies used in the construction products EPDs. The selection of EPDs was focused on the published in the EPD® (EPD, n.d.) and based on the contributing countries where EPDs with information on these modules were available: Australia (AU), Brazil (BZ), Belgium (BE), Canada (CA)[2], Switzerland (CH), Germany (DE), Spain (ES), France (FR), Hungary (HU), New Zealand (NZ), Portugal (PT) and United Kingdom (UK). It included the selection of two different type of EPD per country, preferably one cradle to gate and one cradle to grave. Table 2.1 and Table 2.2 include a summary of the obtained results.

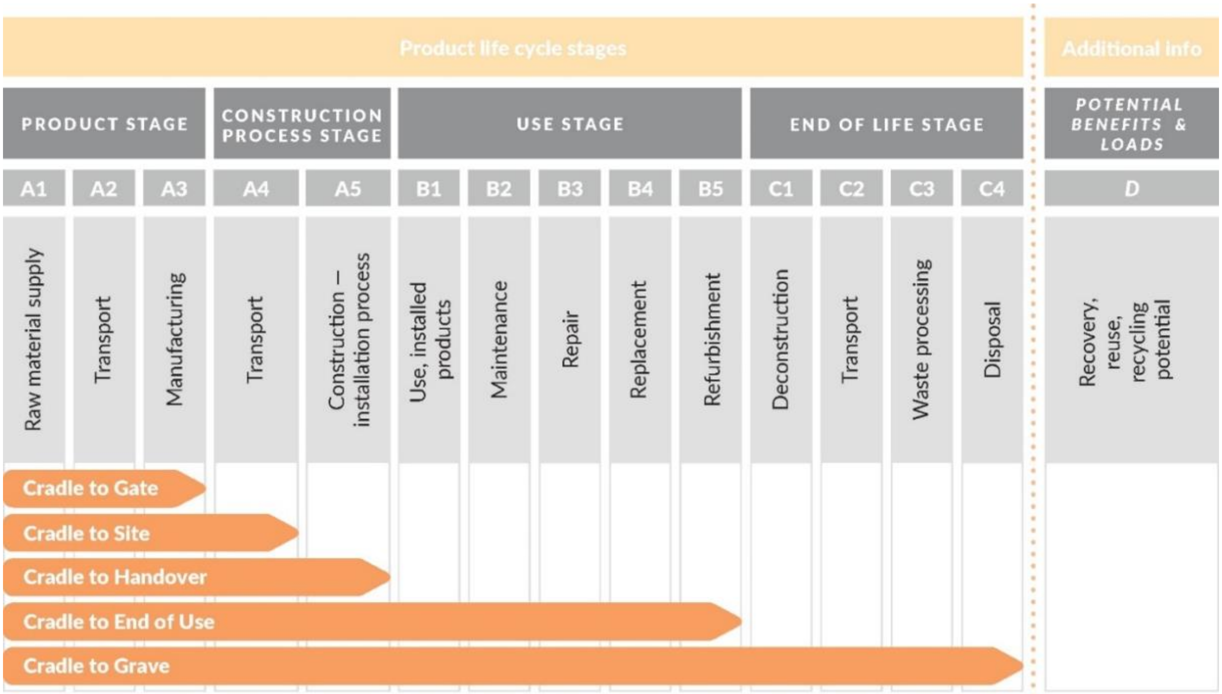

Figure 2.1. LCA system boundaries according to EN 15804 (EN, 2012) standard. (Sources: based on Overview report IEA EBC Annex 57 (IEA EBC, 2016) and (Balouktsi & Lützkendorf, 2016)

For buildings, the system boundary “cradle to handover” was already recommended in the result of Annex 57 (IEA EBC, 2016). The background is the handling of prefabricated constructions in the interest of transparency and comparability. If structures are mainly produced on the construction site, the associated impacts must be assigned to A5. In a predominantly prefabricated building, some processes are assigned to A3 and others to A5. In the latter case, it is not the transport of building materials but the transport of prefabricated parts that is assigned to module A4. System boundaries such as cradle to gate and cradle to site cannot adequately consider the special features of a construction method with prefabricated parts. A system boundary cradle to handover is also typical for the determination of construction costs.

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[2] No EPD was found in the Environdec library for construction products.

Table 2.1. Modelling of transports in construction product EPDs (selected examples based on based on analysing public available EPDs of construction porducts manufactured in the countries that have particpated in the survey)

Country	Construction Product	Type of EPD	Modelling of transport modules A4		C2	
AU	**External cladding products** James Hardie® Industries Ltd	Cradle to Grave with options	Distribution by truck and sea freight from James Hardie's gate calculated based on national annual sales volumes by state and conservative average transport distance assumptions. The typical cladding load per truck transport kilometer was calculated based on 100% utilization of a typical heavy truck (i.e. 30t cladding on 30t capacity truck) for national distribution, and based on 50% utilization of a typical heavy truck for local distribution (i.e. 15t cladding on 30t capacity truck)			
	Hot Dip Galvanizing Galvanizers Association of Australia	Cradle to Site with options	Transport to the customer is calculated based on a mix of transport distance data provided by galvanizers and assumed distances of 100 km by articulated truck.		Demolition waste is transported 100 km by truck for processing.	
BE	**Flexible sheet for waterproofing- Alkorplan A (1,2 mm)** Renolit	Cradle to Grave with options	Fuel type and consumption of vehicle	Truck, diesel 0,03 liter / tkm	Fuel type and consumption of vehicle	Truck, diesel 0,03 liter / tkm
			Capacity utilisation (including empty returns)	50 %	Capacity utilisation (including empty returns)	50 %
			Bulk density of transported products (packaging included)	1,95 Kg per m² (thickness 1.2mm)	Bulk density of transported products (packaging included)	1,75 Kg per m² (thickness 1.2mm)
			Distance	800km	Distance	800km
	Flexible Bitumen Sheets For Roof Waterproofing European Waterproofing Association	Cradle to Grave with options	Average distance for product delivery to the construction site was collected with the aid of EWA online tool 300 km covered by a 32-t truck		Distance covered by a European average EURO 5 lorry 16 t with diesel engine: 150 km to recycling; 100 km to incineration site; 50 km to disposal	
BZ	**Forrovid Boreal** ISOVER - Saint-Gobain do Brasil Produtos Industriais e para Construção	Cradle to Gate with options	Fuel type and consumption of vehicle	Average truck trailer with a 24t payload, diesel consumption 38 liters for 100 km	Assume that the waste going to landfill will be transported by truck with 24 tons payload, using diesel as a fuel consuming 38 liters per 100km. Distance covered is 25 km	
			Distance	1633 km		
			Capacity utilisation (including empty returns)	100 % of the capacity in volume 30 % of empty returns		
			Bulk density of transported products	60 kg/m3		
			Volume capacity utilisation factor	1		
	Concrete FCK 30 MPA BR.1 10+-2 Votorantim Cimentos	Cradle to Gate	Neglected		Neglected	
CH	**Alba® hydro 80 GYPSUM BLOCK** Rigips AG	Cradle to Grave with options	Fuel type and consumption of vehicle	Truck with a 27-ton average payload Diesel consumption 0.158l/tkm	On average, Gypsum waste is transported 220 km by truck to the recycling facility, 60 km by truck and 150 km by rail to the landfill facility and 30 km by truck, 10 km by ship and 50 km by rail to the incineration facility.	
			Distance	144 km by truck		
			Capacity utilisation (including empty returns)	85% volume capacity		
			Bulk density of transported products	1000 kg/m3		
			Volume capacity utilisation factor	1		
	BASWA Phon Baswa Acoustic	Cradle to Grave with options	Transport by road and Fuel consumption	Articulated lorry, 40 t total weight, 27 t max Diesel 0.350 kg/km	A distance of 60 km has been assumed for the transport to final disposal.	
			Transport by sea and Fuel consumption	Container ship ocean, 27.500 dwt pay load. Heavy fuel oil 99.9 kg/km		
			Distance by road	1,500 km		
			Distance by sea	3,350 km		
			Volume capacity utilization (road) - Panels	63%		

Volume capacity utilization (road) - Plasters	32%

Table 2.1. Modelling of transports in construction product EPDs (cont.)

Country	Construction Product	Type of EPD	Modelling of transport modules		
			A4		C2
DE	**CONTRAFLAM LITE 30 Vetrotec. Saint Gobain**	Cradle to Gate	Neglected		Neglected
	FKD-U RS C2 Knauf insulation	Cradle to Gate with options	Average transport distance	600 km	Truck-trailer, Euro 3, 34 - 40t gross Weight / 27t payload capacity/ 40 L for 100 km. (if 100 % utilization). 50 % of the weight capacity. Average distance: 50 km
			Type of fuel and vehicle consumption or type of vehicle used for transport	Truck Euro 6 (28 – 32 t / 22 t payload). 140 L for 100 km.	
			Capacity utilization (including 30% Of empty returns)	36 % of the weight capacity	
ES	**Arena Apta** Saint-Gobain Isover Ibérica	Cradle to Grave with options	Fuel type and consumption of vehicle	Truck with a 16-32 tonne average payload Diesel consumption 0.38 litres per km	Truck with trailer with an average load of 16-32t and a diesel consumption of 38 liters per 100 km. EURO 6. 25km average distance to landfill
			Distance	450 km by truck	
			Capacity utilisation (including empty returns)	100 % of the capacity in volume 30 % of empty returns	
			Bulk density of transported products	20-200 kg/m3	
			Volume capacity utilisation factor	1	
	Exterior Paints JUNO Paint Manufacturer	Cradle to Grave with options	Fuel type and consumption of vehicle	Truck of more than 32 tn. Fuel consumption: 31,1 L/100 Km Ship transport for Canarian and Balearic Islands	16-32 tn truck. Fuel consumption: 25 l/100 Km Distance: 50 km
			Distance	Truck: 358 Km Ship: 842 km	
			Capacity utilisation (including empty returns)	% assumed in Ecoinvent	
			Bulk density of transported products	1,38 kg/l (for Junokril mate)	
			Volume capacity utilisation factor	1	
FR	**MINERVAL® A 12 mm** Saint-Gobain Eurocoustic	Cradle to Grave with options	Fuel type and consumption of vehicle	Average truck trailer with a 24t payload, diesel consumption 38 liters for 100 km	Assume that the waste going to landfill will be transported by truck with 24 tons payload, using diesel as a fuel consuming 38 liters per 100km. Distance covered is 25 km.
			Distance	1500 km	
			Capacity utilisation (including empty returns)	100 % of the capacity in volume, 30 % of empty returns	
			Bulk density of transported products	259 m² per pallet and 22 pallets per truck	
			Volume capacity utilisation factor	<1	
	Climatop triple glazing unit Saint-Gobain Glass France	Cradle to Gate	Neglected		Neglected
HU	**Rigips RBI 12.5mm Moisture Resistant Board** Saint-Gobain Construction Products Hungary	Cradle to Gate with options	Fuel type and consumption of vehicle	Truck, diesel , 0.33 litres per km	Gypsum waste is transported the following distances by road from construction / demolition sites to end of life treatment or disposal. Hungary; 20 km Slovakia; 50 km Serbia; 50 km Macedonia; 50 km Kosovo; 35 km
			Distance	250 km	
			Capacity utilisation (including empty returns)	100 %	
			Bulk density of transported products	848 (kg/m3)	
			Volume capacity utilisation factor	1	
	Rigips Habito 12.5 mm plasterboard board Saint-Gobain Construction Products Hungary	Cradle to Gate with options	Fuel type and consumption of vehicle	Truck, diesel, 0.33 litres per km	34 - 40t gross weight / 27t payload capacity Diesel driven, Euro 0 - 5 mix, cargo, average sulfur content: EU = 10 ppm 42.5 km from construction/demolition site to landfill
			Distance	774 (km) by truck 190 (km) by ship	
			Capacity utilisation (including empty returns)	100 %	
			Bulk density of transported products	960 (kg/m3)	
			Volume capacity utilisation factor	1	

NZ	**Ultracem** **Holcim**	Cradle to Gate	Neglected	Neglected

Table 2.1. Modelling of transports in construction product EPDs (cont.)

Country	Construction Product	Type of EPD	Modelling of transport modules		
			A4		C2
NZ	**Gypsum plasterboard** Winstone Wallboards	Cradle to Grave with options	Includes distribution from Winstone Wallboards manufacturing sites in Auckland and Christchurch through its distribution centres. GIB® plasterboard is distributed through builder's merchants and direct delivery to construction sites.		Includes transport of waste plasterboard to landfill after demolition of the wall or building where it was used. 100% of plasterboard waste and the waste from installation materials is assumed to be sent to landfill (i.e. worst case). Plasterboard is assumed to be disposed of in a municipal landfill rather than an inert demolition waste landfill as plasterboard is not required to be separated from other waste in New Zealand. The assumed transport distance is 50 km with capacity utilisation of 50%.
PT	**Stamped pre painted steel ceiling plate** Gabelex	Cradle to Grave with options	Fuel type and consumption of vehicle or vehicle	Truck, diesel, Average 27 tons payload. Driving share 70% motorway, 23 % rural, 7% urban.	Transport to waste processing a distance of 50 km by truck has been taken into account
			Distance	493 (km)	
			Capacity utilisation (including empty returns)	85 %	
			Bulk density of transported products	-	
			Volume capacity utilisation factor	1	
UK	**Glasroc F FIRECASE** BPB United Kingdom Limited	Cradle to Grave with options	Fuel type and consumption of vehicle or vehicle	44 tonne articulated large goods vehicle (including payload of 24 tonnes) Diesel consumption 38 litres per 100 km travelled	44 tonne articulated large goods vehicle (including payload of 24 tonnes) Diesel consumption 38 litres per 100 km travelled 32 km from construction/demolition site to waste handler
			Distance	240 km	
			Capacity utilisation (including empty returns)	100% volume capacity 30% empty returns	
			Bulk density of transported products	904 kg/m3 (13.56 kg/m2)	
			Volume capacity utilisation factor	1	

	Carpet tile EcoWorx®	Cradle to Grave with options	The modelling derives from three factors: 1. Transport by truck from the Shaw production facility to port (542 km) by truck. Calculated as Ecoinvent v 3.4 Cut-off - transport, freight, lorry, unspecified//[GLO] market for transport, freight, lorry, unspecified 2. Transport by ship from Savannah, GA USA to Southampton, UK (6643 km). Calculated as Ecoinvent v 3.4 Cut-off: transport, freight, sea, transoceanic ship//[GLO] market for transport, freight, sea, transoceanic ship 3. The average distance EcoWorx® carpet tile travels from the ports of arrival to installation sites is 200 km by road to the use site. The assumed means of transport is a generic truck (Ecoinvent v 3.4 Cut-off: transport, freight, lorry, unspecified//[GLO] market for transport, freight, lorry, unspecified). This process assumes a load factor of 50%. In other words, the truck is assumed to be fully loaded on the way to the construction site and empty upon return.	To model a representative scenario, it is assumed that 100% will go to landfill and that the transport distance is 250km by road.

Table 2.2. Modelling of construction and deconstruction in construction product EPDs

Country	Construction Product	Type of EPD	Modelling of construction / deconstruction modules			
			A5		C1	
AU	**External cladding products** James Hardie® Industries Ltd	Cradle to Gate with options	Energy (electricity) consumption for construction	0.2 kWh of electricity per m2	Energy (electricity) consumption for deconstruction	0.2 kWh of electricity per m2
			Diesel fuel consumption for machinery	included	Diesel fuel consumption for machinery	included
			Waste disposed to landfill.	5% of the cladding delivered to site		
	Hot Dip Galvanizing Galvanizers Association of Australia	Cradle to Grave with options	Neglected		Neglected	
BE	**Flexible sheet for waterproofing- Alkorplan A (1,2 mm)** Renolit	Cradle to Grave with options	Additional material consumption	300g polyurethane (PU) is used per m2, overlaps (5%) and installation losses (3%)	Neglected	
			Waste and packaging materials	Distance 50 km		
			Fuel type and consumption of vehicle	Truck, diesel 0,03 liter / tkm		
			Products (packaging and installation losses only)	0,26 Kg per m² (thickness 1.2mm)		
	Flexible Bitumen Sheets for Roof Waterproofing European Waterproofing Association	Cradle to Grave with options	Include the cutting waste production, transport and waste processing and Disposal. The transportation of the waste generated at the building site takes into account a European average EURO 5 lorry 16 t with diesel engine 150 km to recycling 100 km t incineration site 50 km to disposal)		Neglected	
BZ	**Forrovid Boreal**	Cradle to Gate with options	Wastage of materials on the building site before waste processing, generated by the product's installation	5 %	Neglected	
			Distance	25 km to landfill by truck		

	ISOVER - Saint-Gobain do Brasil Produtos Industriais e para Construção		Output materials	Packaging wastes are 100 % collected and modeled as recovered matter Glass wool losses are landfilled	
	Concrete FCK 30 MPA BR.1 10+-2 Votorantim Cimentos	Cradle to Gate	Neglected		Neglected
CH	**Alba® hydro 80 GYPSUM BLOCK** Rigips AG	Cradle to Grave with options	Ancillary materials for installation	Jointing compound 0.77 kg/m^2	Not detailed
			Water use	0.64 litres/m^2	
			Wastage of materials on the building site before waste processing	Gypsum Blocks: 4 kg, 0.04 kg jointing compound	
			Output materials	Gypsum Blocks: 0.424 kg to internal recycling, 3.4 kg to landfill, 0.176 kg to incineration Jointing compound: 0.004 kg to internal recycling, 0.034 kg to landfill, 0.002 kg to incineration	

Table 2.2. Modelling of construction and deconstruction in construction product EPDs (cont.)

Country	Construction Product	Type of EPD	Modelling of construction / deconstruction process		
			A5		C1
CH	**BASWA Phon** Baswa Acoustic	Cradle to Grave with options	Water	1.01E-03 m^3	No contribution on impact categories of this module
			Energy consumption	Global mix power (low tension) 2.38E-01 MJ / 4.16E-01 MJ	
			Packaging	Plastic (29% recycling - 32% incineration - 39% landfill) Carboard (75% recycling - 12% incineration - 13% landfill) Wood - Pallet (30% recycling - 32% incineration - 38% landfill) Metal (74% recycling - 12% incineration - 14% landfill	
DE	**CONTRAFLAM LITE 30 Vetrotec. Saint Gobain**	Cradle to Gate	Neglected		Neglected
	FKD-U RS C2 Knauf insulation	Cradle to Gate with options	Loss of materials in construction site	2%	The common manual dismantling impact of insulation is considered as very small and can be neglected in C1.
			Packaging Wooden pallet	40% recycled, 60% incinerated	
			Packaging Plastic sheet	40% recycled, 60% incinerated	
ES	**Arena Apta** Saint-Gobain Isover Ibérica	Cradle to Grave with options	Product packaging waste is 100% collected and processed into recovered material. Mineral wool losses or waste are transport to landfill. A distance of 50km has been considered both to the manager (recoverable material) and to the landfill (in the case of final disposal). Wastage of materials on the building site 5%.		No contribution on impact categories of this module
	Exterior Paints JUNO Paint Manufacturer	Cradle to Grave with options	Auxiliary materials for installation	Brush, roll or spray gun	No contribution on impact categories of this module
			Use of water	0,029 L/FU (for Junokril mate)	
			Wastage of materials on the building site before waste processing	Product wastage (2%): kg / FU Wooden pallet: 9,18E-03 kg / FU Polyethylene container with metal handle (15L): 2,93E-02 kg / FU	

				Polyethylene Film: 2,60E-03 kg / FU	
			Output materials	Product losses are 100% landfilled, Packaging waste is 100% recycled	
FR	**MINERVAL® A 12 mm** Saint-Gobain Eurocoustic	Cradle to Grave with options	Wastage of materials on the building site before waste processing	5 % of stone wool 58 g of pallets (packaging)/m² of ceiling slabs 4 g of cardboard (packaging)/m² of ceiling slabs 10 g of polyethylene (packaging)/m² of ceiling slabs	Neglected
			Output materials	Packaging wastes are 100 % collected and recycled Stone wool losses are landfilled	
			Energy use in this stage is neglected due to the low contribution.		
	Climatop triple glazing unit Saint-Gobain Glass France	Cradle to Gate	Neglected		Neglected

Table 2.2. Modelling of construction and deconstruction in construction product EPDs (cont.)

Country	Construction Product	Type of EPD	Modelling of construction / deconstruction process		
			A5		C1
HU	**Rigips Rigips RBI 12.5mm** Saint-Gobain Construction Products Hungary	Cradle to Grave with options	Ancillary materials for installation	Jointing compound 0.33 kg/m2 board, tape 1.60m /m2 board, screws 11 /m2 board	No information is provided
			Water use	0.165 litres/m2 board	
			Wastage of materials on the building site before waste processing	Board: 0.41 kg (5 % scrap rate at installation) Screws: 0 kg Jointing Compound: 0.0165 kg Jointing Tape 0.0003 kg	
		Cradle to Grave with options	Output materials as results of waste processing at the building site	Board: 0.41 kg to landfill Screws: 0 kg. Jointing Compound: 0.0165 kg to landfill. Jointing Tape: 0.0003 kg to landfill	No information is provided
		Cradle to Gate with options	Materials for installation	Jointing tape: 1.60 linear metres Joint filler: 0.33kg. 11 Screws	No information is provided
			Water use	0.165 m3	
			Wastage of materials on the building site before waste processing	Rigips Habito: 0.60 kg Pallet: 0.52 kg. Jointing tape: 0.08 linear metres. Joint filler: 0.0165kg. 0.4 Screws	
			Output materials	Rigips Habito: 0.60 kg to landfill Pallet: 0.52 kg to landfill Jointing tape: 0.08 linear metres to landfill. Joint filler: 0.0165kg to landfill 0.4 Screws to landfill	
NZ	**Ultracem** Holcim	Cradle to Gate	Neglected		Neglected

	Gypsum plasterboard Winstone Wallboards	Cradle to Grave with options	Includes the materials used to install the plasterboard (plaster, jointing tape, screws and water) and the production and disposal of offcuts from installation, including a combination of composting and landfill. During installation, 15% of the plasterboard is assumed to be lost as offcuts. 25% of these offcuts are sent to industrial composting and 75% to landfill. The transport distance to landfill and composting is assumed to be 50 km with capacity utilization of 50%. The consumables materials assumed per m^2 in the installation are: Jointing compound (0.1924 kg), Jointing tape (0.0108 kg), Screws (8 screws, each 2.6 g) (0.0208 kg), Water (0.1202 L).		Neglected
PT	**Stamped pre painted steel ceiling plate** Gabelex	Cradle to Grave with options	Materials for installation	Not considered	The de-construction and/or dismantling of products take part of the demolition of the entire building. For ceiling tiles and grids the environmental impact is assumed to be very small. Thermal energy for deconstruction is included at 0.05 MJ per kg of deconstructed material.
			Water use	None	
			Wastage of materials on the building site before waste processing	0,21 kg of steel 0,161 kg of packaging waste	
			Output materials	0,20 kg of steel for recycling (95%) 0,011 kg of steel send to landfill (5%) 0,161 kg of packaging waste landfilled 0,110 kg of wood pallet for re-use	

Table 2.2. Modelling of construction and deconstruction in construction product EPDs (cont.)

Country	Construction Product	Type of EPD	Modelling of construction / deconstruction process		
			A5		C1
UK	**Glasroc F FIRECASE** BPB United Kingdom Limited	Cradle to Grave with options	Materials for installation	Screws: 0.015 kg Jointing Compound: 0.35 kg Jointing Tape: 0.00063 kg	Neglected
			Water use	0.11 m^3	
			Wastage of materials on the building site before waste processing	15mm Glasroc F FIRECASE: 1.356 kg Screws: 0 kg Jointing Compound: 0.035 kg Jointing Tape: 0.000063 kg Pallet: 0.487 kg	
			Output materials	15mm Glasroc F FIRECASE: 0.231 kg to recycling 15mm Glasroc F FIRECASE: 1.125 kg to landfill Screws: 0 kg Jointing Compound: 0.035 kg to recycling Jointing Tape: 0.000063 kg to landfill Pallet: 0.487 kg to recycling	
			Materials EoL scenarios	83% of construction and demolition waste is sent to landfill with the remaining 17% recycled.	
	Carpet tile EcoWorx®	Cradle to Grave with options	No energy use is allocated to the installation process because the fitting of EcoWorx® on site is manual work. During the installation process approximately 90ml of adhesive is used per unit.		It is assumed that no materials or energy is used for de-constructing EcoWorx®. Removal of tiles is a manual process requiring no energy or chemical use as a release bond adhesive or loose lay is the normal installation method.

Considering the modelling of transport in A4 and C2 modules, it is noticed that similar type of information is provided to describe the modelling and scenario definition such as fuel consumption, type of vehicle, dataset, distances, capacity utilization (including empty returns), bulk density of transported products, volume capacity utilization factor. It is also noted that the assumptions for distances and means of transports are related to the country and the geographical scope of the EPD, it means that the most "frequent scenarios" are considered. The assumptions for A4 and C2 mostly includes similar scenario (vehicles: trucks and fuel consumptions: diesel 0.33 per km). However, the representativeness of these "frequent scenario" regarding the real/actual scenario (including distances between the manufacturer and the construction site /type of transport/ fuel consumption) cannot be assured. In this vein, it was detected that the information about the real location of the manufacturing point (production site) is not explicitly included all the EPD analyzed.

Results showed in Table 2.1 indicate that the modelling of A5 module is mostly considered (in all cradle-to-grave EPDs), in contrast use stage modules and C1, are mostly neglected. It is noticed that the provided information to describe the modelling and scenario definition for A5 module mostly included: ancillary materials for installation, water use, wastage of materials on the building site before waste processing, output materials. In some cases, information about energy consumption (BASWA Phon, CH) is provided, as well as material EoL scenarios (Glasroc F FIRECASE, UK). Other cases such as Gypsum plasterboard (NZ), Arena Apta (ES), Flexible Bitumen Sheets (BE) include information about the transportation of waste (e.g., distance). The module C1 is hardly considered, except for example, **External cladding products (AU**), that considers similar information for deconstruction and construction process.

Table 2.1 and Table 2.2 confirm that the information contained in the selected EPDs to model A4, A5, C1 and C2 include similar variables (such as fuel consumption, distances, wastage, bulk density of transported products, output materials), and consider a similar level of detail for assumptions and scenario definition. Thus, it can be assumed that for modelling the stages (A4, A5, C1 and C2) it was considered a detailed number of input and output process (in several cases illustrated by flowcharts or schemas), as far as possible to real situation. The relevance of considering an accurate and detailed modelling is mainly to avoid double-counting and reduce unexpected mistakes.

2.1.3 Relevant questions

In contrast with the previously analyzed construction EPDs, in the building, the amount of information and the complexity to manage it can be higher. Thus, at present and according to previous Sections **2.1.1 and 2.1.2**, different modelling alternatives to deal with the Transport (T) and Construction and Deconstruction (C&D) process in a building LCA. When modeling the life cycle of buildings, the following detected options exist regarding the transport processes (A4 and C2) and the processes on the construction site (A5 and C1), whereby different approaches are possible in each case and can be organized into four groups, described below (Table 2.3):

Table 2.3. Recognition of the rage of possible options to deal with modelling T, C&D process.

Option	General definition of the modelling Option	Modelling alternatives that can involve the option
Option 0: Not modelled	Not modelling of distances and process.	• Not modelled or Ignored • Deliberately neglected because they are negligibly small
Option 1: Generic modelling	One or two generic values covering different building elements/components or building materials. Appropriate for: – When distances and means of transports are not relevant, the data is missing, or products stem from the same location. – Construction and deconstruction processes are not relevant, or the data is missing.	• Consideration via default values. Example: (Kuittinen & Häkkinen, 2020)
Option 2 Simplified modelling	Values for different building elements/components or building materials are grouped and modelled in a simplified way. Appropriate for: – When distances and means of transports can be grouped or simplified for similar products. – When the comparison of different materials and technical solution is relevant for the decision-making. – When construction and deconstruction process have similar characteristics for certain products.	Modeled at building level using different scenarios. Examples: (Asdrubali et al., 2013; Soust-Verdaguer et al., 2018)
Option 3 Detailed modelling	Specific values for elements/components or building materials are used. Appropriate for: – When distances and means of transports are known / close to real scenario, for all the products and ser-vices. – When construction and deconstruction processes are known / close to real scenario, for all the products and services. – When transport scenarios in product-related EPDs are appropriate and consistent.	• Modelled in detail and on a case-by-case basis at the building level. Example: (Shadram et al., 2016) • Modeled in detail and on a case-by-case basis at the building level using for example the real fuel consumption in transport of In both cases EPDs for transport processes and for construction site processes can be extracted for example from the Ökobaudat (Federal Ministry of the Interior Building and Home Affairs (BMI), n.d.).

Regarding the different strategies used for the modelling of T, C & D process (see Table 2.3) several aspects are identified as crucial for the analysis:

1. Calculation methods, assumptions, and scenarios for modelling the process.
2. The calculation methods define the complexity or simplicity
3. Treatment of the uncertainties and variabilities in the modelling of transport, and construction, deconstruction, and replacement processes. Depending on the availability of information a modelling option can be more appropriated for a certain phase of the building (design, pre-construction, post-construction). Early design stages require generic scenarios, detailed design stages and post - construction stages detailed scenarios. Through the analysis of different national methods, can this statement be confirmed?
4. Relevance and consequences of its integration in the LCA results. The use of a certain option can be related to the relevance or irrelevance in the total LCA results in a certain context.

In this context, the following questions arise:

a. What are all the possible options to model T, C & D modules?
b. Which are the main causes of neglection of the modules? How big is the error if transports and construction / deconstruction site processes are neglected?
c. Which default values are there in which country?
d. Should the processes be modeled using information from EPDs or, better, directly?
e. Are there EPDs for transport and construction site processes that can be used?
f. Would it be possible to define harmonized guidelines to model them?

2.1.4 Main Problems

When conducting the building LCA, the problem arises that the effort required to describe and calculate the process involved in modules A4, A5, C1 and C2 can be considerable, especially to model and systematize these complex processes. The present section is focused on detection the main aspects and characteristics of the modelling principles applied in the different national methods, analyses differences and similarities, and propose recommendations to address the detected challenges.

2.2 Existing Approaches in Annex Participant Countries

2.2.1 Overview on national application based on the results obtained from National methods survey

The present section is focused on identifying the current status on the integration of modules A4, A5, C1 and C2 (EN 15978) and T, C & D process in use stage (EN, 2011) to implement the LCA in the context of Annex 72 participating countries. Based on results obtained in the national survey about LCA methodologies conducted in the context of the IEA EBC Annex 72 (see report “Survey on the use of national LCA-based assessment methods for buildings in selected countries” (Balouktsi & Lützkendorf 2022)), countries which are integrating and not integrating T, C & D process in the LCA application were identified

2.2.2 Survey focused on the modelling of T, C & D modules

Following the results of the national survey about LCA methodologies (see (Balouktsi & Lützkendorf 2022)), another expert survey (see Appendix) was conducted to collect the most relevant aspects on the national application of T, C & D modules. It involved the draw up and send out of a questionnaire to the Annex 72 participant countries, focused on two possible cases: countries which include T, C & D modules and countries that neglect them. For those countries which includes T, C & D modules, the survey was focused on identifying: the basis of the scenario definition, the main assumptions, the data sources, and the data granularity. For those countries which has not included T, C & D modules in the application of LCA, the survey search for detecting the basis/reasons of the neglection.

The survey contained eight main questions and explores the different ways of integration and modelling of the LCA modules and systematize the information obtained. Ten IEA-EBC Annex 72 participant countries contributed to the survey including: Australia (AU), Brazil (BZ), Belgium (BE), Canada (CA), Switzerland (CH), Germany (DE), Spain (ES), France (FR), Hungary (HU), New Zealand (NZ), Portugal (PT) and United Kingdom (UK).

2.2.3 Results regarding transport modules

The first part of the results obtained from the questionnaire was based on identifying which countries include or NOT the modelling of the transport modules and on describing the modelling options.

Table 2.4. Answers to Q1 and Q2. Modelling options used to integrate modules A4 and C2 in the assessment

	NOT model	Model		
LCA Module		Option 1	Option 2	Option 3
A4	CH, DE	AU, BZ, CA, FR	BE, ES, HU, UK, NZ	(BE), PT
C2	UK, DE	AU, CA, FR, HU, UK	BE, BZ, ES, NZ	(BE), PT

Option 1. Generic modelling, **Strategy 2**. Simplified modelling, **Strategy 3.** Detailed modelling

Regarding Q1 (Table 2.4) countries mostly modelled A4 and C2 modules, however countries such as Switzerland expressed those transports to regional storage site in Switzerland (this applies also for construction products manufactured abroad) is covered in the construction materials datasets, and do not include the modelling of transport in A4 module. Delivery to building site is often unknown and of low importance. In exceptional cases (helicopter transports) A4 may be included. In the national method of UK module A4 is a mandatory stage to be included in order to meet the minimum requirements laid out in the RICS Professional Statement (RICS, 2017). Although module C2 is not mandatory and exceeds the minimum requirement in the document linked above but its inclusion is nonetheless strongly encouraged.

Q2 (Table 2.4), Q4 (Table 2.5) and Q5 (Table 2.6) are focused on identifying which type of Option (**Option 1.** Generic model, **Option 2**. Simplified model, **Option 3.** Detailed model) is used for modelling transport A4 and C2, and if default locations of the manufacturers of the main building materials and the sorting/recycling or end of life disposal points are assumed, in case for example there is no available information about it. The **Generic modelling** (Option 1) means that the method only can consider a possibility, or a range of possibilities based on the variability of the supplier, manufacturer or sorting/recycling or end of life disposal points regardless the location of the construction site. The **Simplified modelling** (Option 2) means that the method can include a range of variables for the location of the supplier, manufacturer or sorting/recycling or end of life disposal points and a range of variables of the construction site. The **Detailed modelling** (Option 3) means that a more exact calculation procedure is proposed.

Table 2.5 Answers to Q3 (end of 2019) Specifications on the modelling of A4 and C2 modules.

Country	AU	BE	BZ	CA	CH	ES	FR	HU	NZ	PT	UK
Which are the considered products and materials? Do you have any cut-off rules for that?	Basically, all building materials which counted embodied impacts. If not considered in the A1-A3, it is not considered in A4.	For each product and material, a transport and waste category are selected. Based on the transport and waste category, transport scenarios are calculated for both A4 and C2.	All products and materials are included.	All material used in the building were included (including materials for the use stage and A5 – loss during construction modules). Transport of the construction equipment was not included.	-	All products and materials are included.	All products are concerned	Data taken from Ecoinvent	The main materials in structures, walls, roofs, floors (for example), are included Currently, we do not consider fixings, sealants, adhesives.		Information in Table 3 of the document (RICS, 2017).
Which transport distances do you considered?	If not specified, it is, in general, assumed less than 200km away of building material supplied to the site.	Transport distances depend on the selected material category. 3 transport steps are considered (directly from factory to site, from factory to supplier and from supplier to site)	Depends on the location of the construction site	See Q2	10 to 20 km	Depends on the location of the construction site	See annex	described above	From manufacturer gate to construction site in central Auckland, Wellington or Christchurch.		Information in Table 7 (for A4) and Table 11 (for C2) of the document (RICS, 2017).
Which means of transport do you considered?	Basically 'rigid truck'.	Depending on the transport step, the materials are subdivided according to 4 means of transport * Lorry > 32 ton (EURO 5) * Lorry 16-32 ton (EURO 5) * Lorry 7.5-16 ton (EURO 5) * Lorry 3.5-7.5 ton (EURO 5)	All means potentially applicable: within the country: lorry; international transport by ship to port of entrance plus road transport within the country.	See Q2	Lorry, 20-28 tons, fleet average	Depend on the mean of transport: truck, lorry, ship or rail	truck	described above	Road, ship, rail		This information can be found in Table 7 (for A4) and Table 11 (for C2) of the document (RICS, 2017).
Which fuels and consumption hypothesis do you considered?	Mainly diesel	Diesel (EURO 5)	Taken from Ecoinvent latest version available at the time of assessment, calibrated by national annual reports	Average consumption per ton kilometer from the Ecoinvent datasets were used.	diesel, 24.57kg/100km (=29.42 litre/100km)	Taken from Ecoinvent 1.2	Like in Ecoinvent 2.2	Taken from Ecoinvent	Underlying data for fuel consumption, based on data in EcoInvent 3.1.		Carbon conversion factors are taken from official UK government publications.
Do you include the return load (return trip of transports)?	Yes	This included in the average load assumed in the Ecoinvent records	Yes, this is assumed by Ecoinvent datasets	Yes, datasets rely on average load factors that include the average share of empty return trips.	Average payload: 5.8tons, including return trip	Yes	Average load factor of Ecoinvent	Yes	No	Lorry loading factor of 85% and does not consider average lorry journeys to consider the return trips. Therefore, the environmental impact of each transport per km is divided by this amount (85% of the payload of each vehicle). This assumption allows the modelling of empty return trips (up to 200 km) by considering a simulated full load (85%) transport along an additional distance equal to 70% of the coming trip, resulting in a total distance of 1.7 times the latter. Only a parcel of 70% of the environmental impacts of the return trip is considered because an	Partially. In fact, the carbon conversion factors consider average rigid HGV with average laden. This means that the mode of transport that should be assumed is an average heavy goods vehicle (HGV) with 50 per cent load to account for the vehicles coming to site empty and leaving with a 100 per cent load.

										unloaded truck has a consumption of about 70% of a fully loaded truck.	
Which data sources or database do you considered for impacts calculation?	Australian national LCI data (called AusLCI) and Ecoinvent version 3.0 (if not available in AusLCI)	Ecoinvent 3.3	Ecoinvent latest version available at the time of assessment	For the small size lorry transport, an ecoinvent dataset was used. For the regular lorry transport, an internal model from Groupe AGÉCO which is representative of transport in North America is used.	KBOB LCA data DQRv2:2016 (retrieved from www.ecoinvent.org, https://db.ecoinvent.org/download/KBOB%20DQRv2_2016.zip?area=3e2c0806caa3c Most recent version available: UVEK LCA data DQRv2:2018	Ecoinvent 1.2	Ecoinvent 2.2	Ecoinvent 3.5	CML	ELCD v3 database	This information is given in Section 3.3.1 of the document (RICS, 2017). In short: Type III environmental declarations and datasets in accordance with EN15804 or ISO21930 or ISO 14067 or ISO 14025, 14050, 14044 or PAS 2050.
Do you include any other relevant aspects? Can you specify?		More information in (Allacker et al., 2018)	Includes only transport of material that ends up in the building, including incorporated wastage. Replacement waste is included in the operational phase.	All aspects from the Ecoinvent datasets were used.	Demolishing efforts are included in C1, same efforts and emissions per kg material.			no	Includes transport of material that ends up in the building, as well as transport of the material that becomes waste at the construction site.	**Use of ELCD datasets**	

Table 2.5 includes the resulting answers for Q3, provide a detail description of how each national method considered the range of products and materials included, the cut-off rules, the transport distances considered, means of transport considered, the fuels and consumption hypothesis considered, the integration or not of return load (return trip of transports), the data sources or database considered for impacts calculation, finally is focused on identifying other relevant aspects related.

For modelling A4 the UK propose (Option 2) a calculation method for the transport emissions based on [A4] = Material or system mass (a) × transport distance (b) × carbon conversion factor (c).", proposed in the document (RICS, 2017). For reuse/recycling elsewhere a 50km local transport is assumed whereas for landfill/incineration the average between the two closest landfill sites is assumed, more detailed information about it is provided in (RICS, 2017). Average distances and means of transport are used, if project-specific information is unavailable; it is based on groups of materials (e.g. locally manufactured vs. globally manufactured). Table 11 of the document (RICS, 2017) include more information about it. For Q5, C2 the scenarios are not material-specific but EoL-specific.

Table 2.6. Answers to Q4. Consideration of default location of the manufacturers of the main building materials

	Country
Yes	BE, CA, ES, FR, HU, NZ, UK
No	AU, BZ, CH

For modelling A4 New Zealand propose a simplified calculation (Option 2) method based on a spreadsheet that include example transport distances (Branz, n.d.; Dowdell et al., 2016). The model considers default transport distances depending on the location of the construction site (Auckland, Wellington, Christchurch) and the manufacturer. The model also defines two urban distances, two regional distances, four inter-regional distances and three international distances. More information about the model is provided in the SR351 study (Dowdell et al., 2016). For modelling C2 New Zealand assume a 20 km distance to landfill/clean fill (Option 2). Distances to recycling facilities vary depending on the material, for example, steel and aluminum scrap are exported overseas by ship. Australia uses a simplified average (Option 1) distance delivered from distributor and site, and transportation distance is quantified with return.

In France (Option 1) the user can choose between 4 transport distances; the following default values are proposed: Distance from manufacture to building site, 100 km, Distance from Building site to landfill, 20 km, Distance from Building site to incineration, 20 km, Distance from Building site to recycling, 100 km. Transport by truck is considered. A similar criterion is used by Hungary (Option 1), where materials are classified into 4 transportation categories depending on the number and location of manufacturing plants (50 km lorry for materials produced locally; 150 km lorry+30 km van for national production with 1-2 factories; 800 km freight rail+30 km van for imported products transported by rail; 800 km lorry+ 30 km van for imported materials transported on road). Nationally produced materials are checked where the factories are in the country and based on the number of factories, classify materials into categories. These categories are used for each material independent of the actual location of the building. For C2 only one transport category is considered: 20 km lorry.

Table 2.7. Answers to Q5. Consideration of default location of the sorting/recycling or end of life disposal points.

	Country
Yes	BE CA, ES, FR, UK, NZ
No	AU, BZ, CH, HU

Spain and Brazil (Option 2) use for A4 an average distance and transport distances depending on the project location and for C2 distances are defined according to the location of the final disposal point and the building site. Canada uses an average (Option 1) distance according to project location (urban, suburban, rural, etc.). A distance of 25 km for concrete with a small size lorry transport truck was used and a distance of 225km was used for all the other material with a regular lorry transport truck. For A4 use default distances between the supplier and the site construction and for C2 use an average distance of 50km with regular lorry truck transportation.

Switzerland does not consider a default location of manufacturers of the main building materials, but foreign production and import transports are taken into account. It is applied a generic option for modelling C2 which use one default transport distance and one means of transport per waste management option (landfill, incineration, separation/recycling).

Belgium (Option 3) considered that the location of the manufacturers is indirectly included based on the average transport distances which are assumed for each material category. The location of the sorting/ recycling or EOL disposal plants is indirectly included based on the average transport distances which are assumed for each waste category. More details about the modelling Option of both LCA modules is provided in (Allacker et al., 2018). Portugal defined specific rules for modelling the return (empty or full) trips in A4 and C2 modules. It is used ELCD datasets, which defines a lorry loading factor of 85% and does not consider average lorry journeys to consider the return trips. Therefore, the environmental impact of each transport per km is divided by this amount (85% of the payload of each vehicle). This assumption allows the modelling of empty return trips (up to 200 km) by considering a simulated full load (85%) transport along an additional distance equal to 70% of the coming trip, resulting in a total distance of 1.7 times the latter. Only a parcel of 70% of the environmental impacts of the return trip is considered because an unloaded truck has a consumption of about 70% of a fully loaded truck. Thus, it is possible to estimate and consider the environmental impacts of the empty return trip (considering the real distances provided by the manufacturer) and allocate them to each ton of raw material delivered at the factory (or to each ton of waste stream collected in the same place or ton of construction material supplied on site).

2.2.4 Results in 2.2.2 modules A5, C1 and T, C&D process in use stage

The second part of the questionnaire was focused on identifying which countries include or NOT the modelling of the modules **A5, C1 and T, C&D process in use stage,** and on describing the modelling options.

Regarding Q1 (Table 2.8) countries mostly modelled C&D process, however countries such as Switzerland considered A5 of minor importance; cutting losses (wastes during construction) are neglected because the amounts of materials needed are determined coarsely and generously. Furthermore, there are no empirical data on material specific cutting losses/wastes. In UK national method modules A5 and B4 (use stage) are mandatory stages to be included in order to meet the minimum requirements laid out in the RICS Professional Statement (RICS, 2017). However, C1 is not mandatory and exceeds the minimum requirement in the document linked above but its inclusion is nonetheless strongly encouraged. In Hungary C1 is neglected due to the missing data for modelling this stage.

Table 2.8 (answers to Q7) shows that the mostly used strategies to model C&D process (A5, use stage, C1) modules were **Option 1** and **Option 2**. The **Generic modelling** (Option 1) means that the method only can consider a possibility or a limited range of possibilities. The **Simplified modelling** (Option 2) means that the method can include simplified formulas for the calculation of impacts of the process depending on a variable (e.g., weight of materials, price of the building construction, etc.). The **Detailed modelling** (Option 3) means that a more exact calculation procedure is proposed.

Table 2.8. Answers to Q1 and Q7. Strategies to integrate model C&D process.

	NOT model	Type of Option		
LCA Module		Option 1	Option 2	Option 3
A5	CH, DE	AU, BZ, CA, UK, HU, ES	AU, BE, NZ, FR	(AU)
T, C&D process in use stages	-	AU, ES	AU, BE, NZ, UK.	(AU)
C1	FR, HU,DE	AU, CA UK, ES	AU, BE, NZ, FR	(AU), BZ

Option 1. Generic modelling, Option 2. Simplified modelling, Option 3. Detailed modelling

Table 2.9 shows the resulting answers for Q6 and includes the modeling options mainly use to model C&D process (A5, use stage and C1 modules). The table includes a summary of the principles and more data sources containing further information about it. Results show the diversity on the modelling of C&D process. Regarding module A5, countries such as Belgium and Hungary include the energy consumption and fuel (diesel consumption) and materials losses, Canada define a fixed percentage of impacts and do not include fuel consumption, and Switzerland neglect it integration. Australia and Belgium define different modelling options depending on the type of LCA application (generic, simplified, or detailed). The UK method (RICS, 2017) considers mandatory the integration of any energy consumption for site accommodation, plant use and the impacts associated with any waste generated through the construction process, its treatment and disposal and provide, in absence of more specific information about the emissions of the construction process the average for building construction site emissions, a general value related to the project value, and a table with the elements service life. For Germany A5 and C1 are not considered in BNB/DGNB. However, Ökobau.dat (*ÖKOBAUDAT*, n.d.) provides data for a few selected construction activities: excavators per m^3, pumping of concrete per m^3.

For modelling T, C&D process at use stages several countries include the impact of the demolition, waste transport and waste management of the removed components and the production, transportation and construction of the new components, such as Belgium (OVAM et al., 2018). The UK includes transportation to site and installation of the replacement items (RICS, 2017). On the other hand, Switzerland, Canada, Australia, France, Hungary are not including T&C processes in use stage (B4 module). Other countries such as the UK include an average rate in absence of more specific information. Canada (crusher use) based on concrete volume in the building. Other machinery is modeled with average consumptions per m^2 of floor based on Groupe AGECO experience.

Table 2.10 includes the resulting answers for Q8, provide a detail description of how each national method considered the range of construction, deconstruction and replacement works considered, the type of machinery and machinery works considered, the fuels and energy machinery consumption assumptions, the data sources or database considered for impacts calculation, finally is focused on identifying other relevant aspects related.

Table 2.9. Answers to Q6. Modeling principles mainly used to include **C&D modules.**

LCA module	Country	Modelling principle
A5	**AU**	For detailed LCA for A5, use productivity of major equipment (e.g., hour/unit of work, m^3 etc. for crane, electric ladder etc.) then quantified the energy consumption of its equipment. For simplified LCA, use an assumption taken from literature (5-10% of whole LCA).
	BE	This module includes the following processes: • Impact of material losses (global add-on of 5% on all material quantities) • Impact of construction activities (e.g. excavation and electricity consumed for cellulose blowing)
	BZ	Literature data per m2 of construction of office buildings. Average national information per m2 of residential buildings. Other building typologies would use the best fit among the mentioned approaches.
	CA	For A5, we used a fixed percentage of the impacts from A1 to A4 (10%). No calculation regarding fuel consumption was included for this module.
	CH	Not taken into account.
	DE	Not taken into account. National data for excavations per m^3 and pumping concrete per m^3 is available.
	ES	Modelled following Kellenberger et al. (Kellenberger et al., 2007).
	FR	The user chooses a surplus % of materials, 5% is proposed as default value. This corresponds to broken elements on the construction site, surplus of ready mixed concrete at the end of the day, parts of panels that remain unused after cutting the right size etc.
	HU	Material losses are included (2-5% depending on material) and in the previous version of the tool 8 MJ/m^3 electricity + 50 MJ/m3 diesel was included for the construction process of the building.
	NZ	The Construction site waste (module A5) v1, and Building end-of-life (module C1) v1 datasheets can be downloaded from (Branz, n.d.). For more information about how these have been developed in the document (Dowdell & Berg, 2016).
	UK	The average for building construction site emissions, in the absence of more specific information is 1400kgCO2e/£100k of project value. The carbon emissions associated with any waste generated during the construction process should be accounted for in accordance with the principles outlined for the product and transport stage [A1–A3] and [A4]. More specifications about it is detailed in (RICS, 2017).
T, C&D process in use stages	**BE**	It covers the impact of the demolition, waste transport and waste management of the removed components and the production, transportation, and construction of the new components. Information related to the life span of work sections can be found on the TOTEM website (OVAM et al., 2018).
	BZ	**No information related to the modelling of T, C&D process is provided**
	CA	**No information related to the modelling of T, C&D process is provided**
	CH	No energy consumption for replacement but for demolishing work of replaced building elements and materials.
	ES	Modelled following Kellenberger et al. (Kellenberger et al., 2007) and reference service life of products.

	FR	**No information related to the modelling of T, C&D process is provided**
	HU	**No information related to the modelling of T, C&D process is provided**
	NZ	The Construction site waste (module A5) v1, and Building end-of-life (module C1) v1 datasheets can be downloaded from (Branz, n.d.). For more information about how these have been developed in the document (Dowdell & Berg, 2016).
	PT	**No information related to the modelling of T, C&D process is provided**
	UK	Specifications about it is detailed in (RICS, 2017).
C1	**AU**	Used equipment productivity for detailed LCA or assumption for simple LCA.
	BE	Module C1 includes the impact of the deconstruction and demolition. The composition of the materials and the method of connecting with other materials/work sections determines the type of demolition process
	BZ	Used generic values for machinery, under a specific time, applicable to the case, as instructed by local demolition companies surveyed each time. Typically, a crusher for the concrete demolition and scissors for steel frame.
	CA	Used a generic value for machinery under a specific time. One machinery was for the concrete demolition (crusher) and another regular machinery for all the other demolition works.
	CH	**-**
	ES	Modelled following Kellenberger et al. (Kellenberger et al., 2007).
	FR	Not included.
	HU	Neglected due to missing data.
	NZ	The Construction site waste (module A5) v1, and Building end-of-life (module C1) v1 datasheets can be downloaded from (Branz, n.d.). For more information about how these have been developed in the document (Dowdell & Berg, 2016).
	UK	An average rate of 3.4 kgCO2e/m2 GIA (rate from monitored demolition case studies in central London) based on aggregated data should be used in the absence of more specific information. Section 3.5.4.1 page 26 for C1, in the document (RICS, 2017).

Table 2.10. Answers to Q8. Specifications on the modelling C&D process.

Country	AU	BZ	BE	CA	CH
Which construction, deconstruction and replacement works do you considered?		**Inclusions:** We include construction of all elements set out in the module A5 datasheet. We use data from literature and average national data for construction equipment/machinery. Shuttering/formwork. We include all construction activities as long as sufficiently informed (such as excavation) **Exclusions:** We do not include smaller items (fixings, sealants, adhesives) and corresponding wastage. unless clearly identified in the bill of materials. Other current exclusions include: Packaging of construction materials. We do not include construction office activities.	Various deconstruction processes have been defined for different materials based on Ecoinvent 3.3. The impact of replacement is calculated as the sum of the impact of the demolition, waste transport and waste management of the removed components and the production, transportation and construction of the new components	A5: no construction work was modeled C1: Concrete crushing, material handling	Replacement works are not considered, only replacement materials
Which type of machinery and machinery works do you considered?	Excavator, backhoe etc. for foundation (earth) work, Crane hoist, conveyer, forklift for construction material handling	Average fuel/electricity/water data per m2 of construction from literature or national reports.	The impact of construction activities is limited to a few processes such as excavation works, and the electricity consumed for cellulose blowing	Machinery for material handling (lifts, air compressors, cranes…) and concrete crusher during deconstruction.	General diesel consumption of building machines used in demolishing
Which fuels and energy machinery consumption hypothesis do you considered?	Mainly fueled with diesel for machinery.	Diesel for machinery and equipment, unless clearly informed otherwise (electricity). Fuel datasets from Ecoinvent.	The fuels and consumption values are based on Ecoinvent 3.3	Average consumption per hour from the Ecoinvent datasets were used.	see above
Which data sources or database do you considered for impacts calculation?	Mainly AusLCI (national LCI database) or ecoinvent (ver 3.0 if not available in AusLCI)	Ecoinvent (latest version publicly available)	Ecoinvent 3.3	Average machine operation from the ecoinvent database were used.	see above
Do you include any other relevant aspects? Can you specify?	Australian team has worked for some missing impacts from A3, A5 and B1. Please see the attached.		More information in (Allacker et al., 2018)	-	-

ES	FR	HU	NZ	UK
Based on Kellenberger et al. (Kellenberger et al., 2007)	Waste production	For construction only material losses are included, plus a general value for the construction process taken from an Ecoinvent report. For replacement only the materials, their transport and disposal are considered, not the replacement process itself.	We include construction of the elements set out in the module A5 datasheet. We do not include smaller items such as fixings, sealants, adhesives, therefore wastage of these materials is also not included currently. Other current exclusions include: Packaging of construction materials. Energy used for site machinery/power tools/site office. Shuttering/formwork. Excavation activities.	**A5**: As mentioned this is a weak point of the RICS document where an average tablelinked to project value is used. Even if detailed and project-specific assessments are encouraged I suspect that in practice the average figure is most often used. Use stage: must take into account any carbon emissions associated with the anticipated replacement of building components, including any emissions from the replacement process. All emissions arising from the production, transportation to site and installation of the replacement items must be included. This extends to cover any losses during these processes, as well as the carbon associated with component removal and EoL treatment. **C1**: again, an area of weakness of the document which suggests an average figure. The risk is that in practice most people would just use the suggested figure although the standard does encourage to collect project-specific data.
Based on Kellenberger et al. (Kellenberger et al., 2007)	None	Only a general value is considered	See above. For deconstruction, we include energy required for this, which is allocated to structural materials only. Data are based on an Athena Institute publication. For further information (Dowdell & Berg, 2016), (Appendix D4)	**A5**: See previous answer and section 3.5.2.2 of the document linked in Q1. 3.5.3.4 of the document linked in Q1 and below. **C1**: N/A
Based on Kellenberger et al. (Kellenberger et al., 2007)	None	Only a general value is considered	Machinery is powered by diesel. Use of secondary data from EcoInvent 3.1, in particular the dataset called "Diesel, burned in building machine".	**A5**: N/A **C1:** N/A
Ecoinvent 1.2	Ecoinvent 2.2	Ecoinvent 3.5	EcoInvent 3.1	**A5**: site waste rates for different materials should be determined based on the standard wastage rates provided by the WRAP Net Waste Tool (UK specific). **Use stage**: scenarios should be based on data from facilities management and maintenance Option reports, façade access and maintenance Option, life cycle cost reports, O&M manuals, guidance (e.g. CIBSE Guide M and BCIS Life expectancy of building components), international standards (e.g. ISO 15868-5: 2008 Buildings and constructed assets – service life planning, and manufacturers' documentation). Also lifespans value are given in Table 9 of the document. **C1**: N/A/
-	Treatment of building site waste	No	Please see SR351 study report and Appendix D of the SR350 study report.	-

3. Suggested Solutions and Typologies

3.1 Analysis of Results and Layout of Possible Solutions for Modelling Transports

Based on the results obtained in the previously described survey, this section includes the compilation of the information about the modelling of modules A4 and C2 (EN 15978) (EN, 2011).

a) Level of consideration of the modules A4 and C2 in the LCA application
The results confirm that most of the contributing countries include the modelling of A4 and C2 modules. The causes of neglection of A4, in the Swiss method are because delivery to building site is often unknown and of low importance, however exceptional cases that include helicopter transports, can consider the A4 impacts. For the German method A2 and C2 are not taken into account in BNB/DGNB (System, 2019). However, Ökobau.dat (*ÖKOBAUDAT*, n.d.) provides average environmental data in tonnes*km for different types of transport to assist in calculations. For example, for small truck: “The dataset refers to the transport of 1000 kg cargo on a distance of 1 km by truck (EURO 5) with 12-14 t permissible total weight and 9.3 t payload in forwarding traffic with a utilisation ratio of 85%. The extraction and processing of the fuel is included. The production of the vehicle is not included in the balancing”.

b) General assumptions
Regarding the obtained results, the number of modelling options varies between countries, but is similar for both modules in each national method. Most of the contributing countries use Option 1[3] (AU, CA, FR, HU, UK) and Option 2 (ES, NZ, UK, BE), (the same Option for both), except the UK that applies Option 1 (for A4) and Option 2 (for C2). Despite Belgium applies the most detailed model, the use of simplifications and average distances is also detected.

The results show that the national methods that integrate **Option 1**, have the following common statements: all countries included all the materials and products, the Option is the same for all the materials and products, distances are generic and not so detailed (due to the high level of uncertainty), trucks and lorries are mostly considered as mean of transports, and return trips are always considered.

Regarding **Option 2**, countries that apply it have the following common statements: all included all the materials and products, different manufacturing points and intermediate points are considered, different means of transports are considered (except the air transports) and retry of transport is partially considered.

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[3] The **Generic modelling** (Option 1) means that the method only can consider a possibility, or a range of possibilities based on the variability of the supplier, manufacturer or sorting/recycling or end of life disposal points regardless the location of the construction site. The **Simplified modelling** (Option 2) means that the method can include a range of variables for the location of the supplier, manufacturer or sorting/recycling or end of life disposal points and a range of variables of the construction site. The **Detailed modelling** (Option 3) means that a more exact calculation procedure is proposed.

c) Particular statements, detected hotspots and proposal possible solutions

c.1) Consideration of transport distances

Regarding the consideration of transport distances, it is noticed that there is a high influence of the local characteristics of each country, which can be related to the location of natural resources (raw materials), location of manufacturers, location of recycling/final disposal points, type of transports, distribution networks, and also the existence of previous studies, references and other data sources, the level of maturity in the LCA application in the construction sector, among others. For example, in the definition of default distances it can be considered that the average transport distances are proportional to the most frequent distances between the construction site and the manufacturers/final disposal points and the size of the country (Switzerland use 20km approx. and Australia use 200km). Thus, the influence of the related impacts can be considered as relevant or neglected such as in Switzerland.

Furthermore, other aspects that can be relevant in modelling of transport distances are the level of complexity in the distribution networks and the consideration of manufacturers/final disposal points. For example, in countries such as New Zealand with a limited number of cities and distribution networks, the developed model can easily identify manufacturers/final disposal points to calculate transport distances. On the other hand, countries such as Spain, with a great number of manufacturers and complex distribution networks, more difficulties are detected to define a model that allows to obtain reliable results for transport distances. Therefore, it is recommended for defining simplified modelling options **(in Option 1 and Option 2)** to develop tables with average/most frequent locations for both manufacturing points (including distribution points, if exist) and final disposal points (and recycling points, if exist) of the most frequent materials. Thus, depending on the level of detail and level of accuracy of the information provided can be **Option 1** or **Option 2**. It is also recommended to harmonize the methods to identify and simplify the distribution networks and manufacturing/final disposal points, in order obtain impacts values as far as possible to the real situation, reducing uncertainties and possible undesirable mistakes.

For detailed strategies (**Option 3**) which mostly uses real or close to real transport distances, it is recommended to harmonize the methods to measure and calculate the impacts of real distances. As well as the consideration of intermediary suppliers and the distribution networks and the consideration of manufacturers/final disposal points.

c.2) Data sources

Results show that regardless the modelling Option the most used data source (for transport impacts and fuel consumption) is the Ecoinvent database. Depending on the country the version of the database can be different. For example, New Zealand use Ecoinvent 3.1 and Belgium Ecoinvent 3.3 (Ecoinvent, 2016). However, two exception has been detected, UK uses their own datasource and Austrailia use their own national database AusLCI (Australian Life Cycle Inventory, n.d.), and Ecoinvent version 3.0 in case there is not available data. When modelling transports, the use of different data sources and databases can conduct to different results, it is recommended to verify the data consistency of the transport related data sources to control possible differences and unexpected variations.

c.3) Means of transport

Results show that the trucks are considered the most used mean of transport, and other means of transports such as the railway and air transports were scarcely considered. This can be due to the extensive use of this mean of transport in the construction sector, or because it can be a simplification of the supply chain of materials and products. It is also noticed that each country uses the means of transports according to their own requirements and characteristics. Countries with a great dispersion in the location of cities such as New Zealand can obtain more significant transport impacts than other countries with a more compact city network, such as Switzerland or Belgium. It is detected that depending on the modelling Option the level of accuracy in the definition of the mean of transport increases. Countries such as Belgium, detailly organised trucks transports based on the tonnage. A possible solution to deal with the uncertainties related to the means of transports, can be to make tables that relate products/materials/distances considering the most frequent means of transport, adapted to the design phases and type of LCA (simplified or complete) and depending on the level of detail and level of accuracy of the information.

c.4) Consideration of impacts of transports in design stages

The possibility of considering the transport impacts in the selection of materials/products can be relevant in several context and for several building materials (such as timber). How can transport impacts be considered in design stages? Can be the selection of materials and products conditioned by them? The local context in modelling A4 and C2 modules can completely change the LCA results. In this vein, the same building can obtain very different impact values depending on the country where it is located, and the materials and products that were used. It is recommended to develop robust and reliable models that can help designer to guide the decision-making specially for those countries where the impacts of transports are relevant.

c.5) Modelling options and design stages

Probably the main differences in the modelling of A4 and C2 modules can be related (as previously mentioned) to the pre-existence of studies on the field, references and other data sources, the level of maturity in the LCA application in the construction sector, among others. It is important to highlight that the modelling Option should be related to the level of definition and data granularity about the building and depending on the type of LCA application (simplified or complete). The scope of the strategies is different when working in early design stage (LCA is a decision-making tool) than when the building is detailly design. Thus, it is recommended to correlate the modelling option with the design stage, level of definition and granularity of the information about the building. Moreover, the integration of experts on the area can avoid making simplifications that conduct to undesirable mistakes. It is also recommended that each country define the scope of the design stage and type of LCA application (from early design stage up to construction/use stage) to establish most properly modelling Option based on the existing certainties and the needed data accuracy.

Other alternative to deal with the modelling options of transports and the design phases, is the one proposed to be implemented in Sweden (out of the scope of the survey participant countries) for the “Climate declarations for buildings” (Sweden National Board of Housing Building and Planning, 2020). The document proposes to focus the effort on detailed modelling options for transports of the **three** more relevant materials and components (greatest proportion of weight or volume). For the rest of materials and components both generic and actual/specific data can be used when modelling A4 module (see section 4.3.11-12).

3.2 Analysis of Results and Layout of Possible Solutions for Modelling C&D Process

Based on the results obtained in previous survey, this section is focused on compile the information obtained on the modelling C&D process (EN 15978)) (EN, 2011).

a) Level of consideration of C&D process in the LCA application

The results confirm that most of the contributing countries consider modules A5 and C1, with few exceptions. For example, Switzerland considered A5 of minor importance, cutting losses (wastes generated during construction) are neglected because the amounts of materials needed are previously determined coarsely and generously during the design stage. For Germany A5 and C1 are not considered in BNB/DGNB. However, Ökobau.dat (*ÖKOBAUDAT*, n.d.) provides data for a few selected construction activities: excavators per m^3 and pumping of concrete per m^3. Furthermore, there are no empirical data on material specific cutting losses/wastes. In other countries, such as the UK this is a mandatory stage to be included in order to meet the minimum requirements laid out in the RICS Professional Statement (RICS, 2017). France and Hungary neglect C1, mostly due to missing data. In other countries, such as the UK, despite being not a mandatory, its inclusion is nonetheless strongly encouraged.

b) General assumptions

Results shows that the number of modelling options also varies between countries and between LCA modules. Thus, the most common situation is to alternate strategies (Option 1, Option 2, Option 3[4]) according to the modules considered. For example, countries such as Australia, use these three modelling options in these three modules. However, not much detailed about the strategies and further information about them is provided. Other countries apply different strategies according to the modelled modules. For example, Belgium uses a generic option for modelling construction process and more detailed modelling for modules B4 (use stage) and C1 (Option 2). The UK uses a generalized modelling for A5 and C1, and a simplified modelling for T, C&D process in module B4. Spain uses generic and simplified modelling strategies.

b.1) Construction process (Module A5)

The assumptions considered for the quantification of impacts in A5 module are diverse. The main Option in most countries is to consider a percentage of construction wastes applied to the material supplied to the work. France, for example, uses a percentage of surplus materials chosen by the user, and in other case a 5% is proposed as default value. This corresponds to broken elements on the construction site, surplus of ready mixed concrete at the end of the day, parts of panels that remain unused after cutting the right size. Belgium includes the processes related to impacts of material losses (global add-on of 5% on all material quantities) and the impacts of construction activities (e.g., excavation and electricity consumed for cellulose blowing). Hungary uses similar Option; material losses are included (2-5% depending on material) and in the previous version of the tool 8 MJ/m3 electricity + 50 MJ/m3 diesel is included for the construction process of the building.

Canada uses a fixed percentage of the impacts from A1 to A4 (10%) and no calculation regarding fuel consumption is included in this module. Some countries such as Australia, through detailed LCA, uses productivity of major equipment (e.g., hour/unit of work, m^3 etc. for crane, electric ladder etc) for quantifying the energy consumption of its equipment, and through simplified LCA, uses an assumption to estimate it (5-10% of whole LCA).

New Zeeland includes the construction process of the elements set out in the module A5 datasheet (Branz, n.d.). However, smaller items such as fixings, sealants, adhesives, and material waste of these process are not included. Other exclusions are the packaging of construction materials, the energy used for site machinery/power tools/site office, the shuttering and formworks, and the excavation activities. The UK uses

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[4] The **Generic modelling** (Option 1) means that the method only can consider a possibility or a limited range of possibilities. The **Simplified modelling** (Option 2) means that the method can include simplified formulas for the calculation of impacts of the process depending on a variable (e.g., weight of materials, price of the building construction, etc.). The **Detailed modelling** (Option 3) means that a more exact calculation procedure is proposed.

in case of inexistence of specific data, a generic assumption where a simplified average figure of 1400kgCO2e/£100k of project value (RICS, 2017).

b.2) T, C&D process in Use Stage

The modelling of T, C&D process in Use Stage (Module B2-B5) is scarcely detected. Countries such as Belgium, Spain or UK are examples of its integration. For example, Belgium includes a complete list of replacement of worn building components elements that can found in (OVAM et al., 2018). It covers the impact of the demolition, waste transport and waste management of the removed components and the production, transportation, and construction of the new components. However, no energy consumption for replacement is considered, but for demolishing work of replaced building elements and materials.

b.3) Deconstruction (Module C1)

The assumptions taken into account for modelling C1 module are diverse. Australia uses equipment productivity for detailed LCA and assumptions for simplified LCA. Belgium includes the impact of the deconstruction and demolition. The composition of the materials and the method of connecting with other materials/work sections define the type of demolition process. Canada uses a generic value for machinery under a specific time. One machinery is considered for the concrete demolition (crusher) and another regular machinery for all the other demolition works. Crusher use is based on concrete volume in the building. Other machinery is modelled with average consumptions per m^2 of floor based on experience of construction companies (e.g. Groupe AGECO). Switzerland considers general diesel consumption of building machines used in demolishing. New Zealand defines building end-of-life datasheets (Branz, n.d.), energy required for deconstruction is included, allocated to structural materials only. Data are based on an Athena Institute publications (*Athena Sustainable Materials Institute*, n.d.) , contained in the SR350 study report (Appendix D4) (Berg et al., 2016). The UK considers a generic assumption, based on an average rate of 3.4 kgCO2e/m2 GIA (monitored from demolition case studies in London is suggested).

c) Specific statements, detected hotspots and proposal for possible solutions

c.1) Construction, deconstruction works

The results show that the consideration of construction, deconstruction and replacement works are different among the contributing countries. Australia for example, considers all construction, replacement and deconstruction works. Belgium includes various deconstruction processes defined for different materials and based on Ecoinvent (Ecoinvent, 2016). The impacts of replacement are calculated as the sum of the impact of the demolition, waste transport and waste management of the removed components and the production, transportation and construction of the new components. Canada does not model construction work; however, in demolition works (C1 module) construction concrete crushing and material handling are considered. Switzerland do not consider replacement works, only include the replaced materials. France considers waste production, therefore, treatment of building site waste, and C1 is not considered. Hungary for construction process only consider material losses, plus a general value for the construction processes taken from an Ecoinvent reports (ecoinvent, 2020). For replacement only the materials, their transport and disposal are considered, the replacement works (installation of materials and products) are not included. New Zealand for construction of the elements propose a datasheet (Branz, n.d.), which exclude some small items and works (such as excavation activities). Although the UK encourage detailed and project-specific assessments for A5 and C1 module, it propose an average figure linked to project value in (RICS, 2017), which promote a simplification of the calculation of the impacts regardless, for example the materials and products, type of building construction, among others. It can be considered a weak point to be applied in complete LCA and detailed design stage. For use stage all emissions arising from the production, transportation to site and installation items must be included. This extends to cover any losses during these processes, as well as the carbon associated with component removal and EoL treatment. It is recommended to harmonize the criteria to define the considerations for construction, replacements and deconstruction works. The harmonization can include a common definition of the works and process and establishing different levels of detail and accuracy in the modelling of the process. These can be related to the definition of default values, which is also proposed to be implemented in Sweden (out of the scope of the survey participant countries) for the "Climate declarations for buildings" (Sweden National Board of Housing Building and Planning, 2020). There, default values for different types of buildings are under development, real values might be used as well (Sweden National Board of Housing Building and Planning, 2020).

c.2) Type of machinery and machinery works

Results shows that the consideration of type of machinery and machinery works are heterogeneous. Australia mainly considers excavator, backhoe for foundation (earth) works and crane hoist, conveyer, forklift for construction material handling. Belgium method included other impact of construction activities, limited to a few processes such as excavation works, and the electricity consumed for cellulose blowing. Canada includes machinery for material handling (lifts, air compressors, cranes, etc.) and concrete crusher during deconstruction (Allacker et al., 2018). Switzerland use in demolishing general diesel consumption of building machines. France do not consider this aspect and Hungary considered only a general value. New Zealand, for deconstruction include energy consumption to demolish structural materials only, based on (Berg et al., 2016). As in the previous point c.1) it is recommended to harmonize the criteria to define the type of machinery and machinery works. The harmonization can include a common definition of the works (e.g., excavation) and sources (e.g., electricity) and establishing different levels of detail and accuracy in the modelling of the process.

c.3) Data sources and database considered for impacts calculation

The results show that data sources about fuel consumption, among others, are mostly extracted from Ecoinvent databases. Australia mainly considers fuelled with diesel for machinery, and mainly considers AusLCI (AusAgLCIinitiative, 2011) and Ecoinvent 3.0 (Babaizadeh et al., 2015) (if not available in AusLCI). Belgium includes the fuels and consumption values based on Ecoinvent 3.3 (Ecoinvent, 2016). Canada uses an average consumption per hour from the Ecoinvent datasets. Switzerland general diesel consumption of building machines used in demolishing also based on Ecoinvent. France do not include any specific hypothesis for fuel consumption and use Ecoinvent 2.2 (Dupuis et al., 2017) as a data source. Hungary only consider a general value for fuel consumption and use Ecoinvent 3.5. New Zealand use machinery powered by diesel use from secondary data from Ecoinvent 3.1. Canada average machine operation from the Ecoinvent.

The survey also collected information about other data sources used by national methods. The results show difference in the level of maturity and definition of the data sources and scenarios definition. Countries such as the UK declare the use of various data sources (BCIS, n.d.; British Standards, 2008; CIBSE, 2008; RICS, 2017) for defining for example wastage rates, lifespan, among others. As previously detailed above (for modelling transports), the use of different data sources and databases can conduct to different results, it is recommended to verify the data consistency of the fuels consumption and other related data sources to control possible differences and unexpected variations.

c.4) Modelling options and design stages

Results obtained demonstrate the heterogeneity in the modelling of C&D process, specially related to the integration of wastage, the data sources, the consideration of transports, fuel consumptions, among others. The key aspects of the problem are not only related to the modeling itself but also about the accuracy and level of detail of the data and how all the variables and aspects involved in these complex processes are included.

A possible solution to deal with the different modelling options can be to relate them with the level of detail of the building information or design phase. Hence, the modelling options can be applied depending on the design phase, and considering the joint model proposed within IEA EBC Annex 72 (ST2) “Common definition of design steps & project phases”, generic and simplified options should be used in the early design phases and the detailed modelling options in detail design phases. Thus, the accuracy and reliability of results will be aligned with the level of detail of the building information.

3.3 Final Recommendations and Conclusions

The present study illustrated and compared the different options to model T, C & D process in the LCA of buildings and products (EPD). The study was based on the description of the current references and main studies on this field, as well as a collection of modelling options conducted among the Annex 72 participant countries (survey). The results of this survey show the heterogeneity in the modelling of T, C & D process and the strong incidence of local data sources, national methods, and geographical and regional characteristics. There, it has been detected that the main causes of neglection of transport are related to the use of local or regional materials (such as Switzerland) and the C&D process causes of neglection were related to the missing data (inexistence of data) such as France or Hungary. The errors regarding their neglection depend on the context characteristics and the type of construction technology. This report provides evidence of several examples related.

The use of default values for C&D process has been detected in countries such as UK, Finland, Spain or Sweden (with some specific characteristics), other modelling options such as the generic EPD (e.g. Ökobaudat (Federal Ministry of the Interior Building and Home Affairs (BMI), n.d.)) can be useful to adapt the specific countries characteristics to modeling C & D. While, for modelling transport the use of default values and simplified scenarios were related to reducing efforts on modelling the supply and distribution chain, which has been detected in countries such as New Zealand or Spain.

The review of the information about modelling of T, C & D process contained in the construction products EPD provide evidence of the heterogeneity in the level of detail of the information (see Table 1.1 and 2.1). Despite that current EN 1580:2012 + A2:2019 (Fernádez-García et al., 2016) standards include (in Section 7.3) a (dataset) description of the scenario assumptions which can be useful to harmonize and to increase guaranties when comparing different products, the information related to T, C & D of construction products was not presented on a systematic/heterogeneous way. It means that not all the EPDs include the modelling of T, C & D process (e.g., cradle-to-gate EPD type), and also because the provided information is not enough to adapt the modelling of the process to the specific characteristics of the buildings and construction products. Thus, in case that the information included in the EPD is not enough to complete the required information the use of specific EPDs of transport and C&D process (e.g. Ökobaudat (Federal Ministry of the Interior Building and Home Affairs (BMI), n.d.)) is also possible solution.

Hence, we conclude that (at least at the moment) it cannot be possible to define one harmonized option to model T, C & D process. It would be possible to define a range of harmonize options and provide some recommendations to define them, thus, two possible paths arise. The FIRST one relates the definition of harmonized modelling options with the design phases; therefore, the generic and simplified modelling options can be applied in early design phases, and detailed modelling stages can be used at detailed design phases, therefore, three correlations can be implemented by following these criteria:

a. Harmonized Generic Modelling (Option 1) for being applied during the early design phases of the project (Preliminary Concept), where the GFA and the volume of the building are known. A generic Option could be to quantify the impacts per square meter and LCA modules, depending on the type of building and main materials. Another Option could be obtaining impacts in each module by applying a percentage to the whole LCA or to another LCA module (such as A1-A3).

b. Harmonized Simplified Modelling (Option 2) for being applied during the early design phases of the building project, when the building systems and the main building elements and components are known (for example, the type of foundation, structure, envelope, etc.). This simplified modelling option could be classified according to the type of module. For example, in the case of module A5, the construction wastes generated could be obtained from a percentage of materials.

c. Harmonized Detailed Modelling (Option 3) for being used during the detailed design stage of the project, when the building systems and materials are defined and detailly measured. This detailed option could be classified according to the LCA module. For example, in the case of module A5, the construction wastes generated could be obtained in a detailed way using detailed construction waste quantification models, as close as possible to real situation and similar for example to those applied in the construction products EPD.

The SECOND path can relate the modelling of T, C & D process with the element/component's representativeness in the building, and combine generic, simplified and detail modelling options regarding their relevance in the building. Thus, detailed modelling options can be used for the main building materials/elements/components and generic and simplified for those that are lees representative. There, the accuracy of impact results of transport/ construction/deconstruction can be proportional to the number of materials involves.

The following recommendations for action are proposed grouped by actors (stakeholder) involved.

Policy, regulation and law makers, developers / providers of sustainability assessment systems, national standardization bodies:

- include transport and construction processes (A4-5) in the minimum assessment scope and provide default values to compensate for possible lack of data and assist the method users during early design stages. These are activities to be controlled and verified today when new buildings are constructed, together with A1-3.
- determine, publish, and periodically update LCA data for transport and construction processes.
- determine, publish, and periodically update reference values for mean transport distances.
- determine, publish, and periodically update LCA data for construction machinery, essential construction processes, the operation of the construction site equipment and typical construction site activities (e.g. pumping water, heating buildings).

Construction product manufacturers:

- in EPDs specify several variants for modules A4, A5, C1 and C2 or provide calculation rules for A4 and C2 (depending on transport distances and means of transport).

Researchers:

- develop default values for modules A4-5 and C1-2 expressed per m2 of building per kg of product (other units can also be used depending on the product).

What is important to consider when modelling transport related modules A4/C2, as well as construction process related modules A5/C1?

- the scope of transport and construction activities covered by the method shall be clearly declared.
- In order to prevent misinterpretations when comparing variants with a high level of prefabrication with variants with assembling on the construction site, the initial embodied impacts represented by the system boundary “cradle to handover” (A1-5) *B4, C3-4* shall be fully covered as part of the minimum requirements.
- For early design stages generic or simplified modelling shall be allowed (see Table 3, Option 1 and 2) and supported by providing de-fault values and/or fixed assumptions to the users of the method. For late design stages detailed modelling shall be mandated for A4 at the minimum. There, a clear description on how to consider empty returns shall be included.
- The use of different data sources and databases can lead to different results; therefore, the method shall recommend specific allowable data sources or provide such values.
- If the inclusion of activities C1/C2 is mandated by a method for completeness, default values shall be provided per m^2 (built area) or m^3 or tons. For far-future activities such as C1/C2 is unreasonable to mandate putting time and resources into calculating them even at late design stages. They are too uncertain. The module C1 could be estimated using impact factors or resources consumtion by m^2 (built area), m^3 (voluem of demolished materials) or tons. The module C2 could be estimated using impact factors or resources consumption per ton, ideally there should still be parameters for t/m^3.
- To increase transparency and provide a systematic approach for modelling complex processes A5-C1 shall be use guidelines/rules for the data collection and data set (e.g., list of activities and energy consumption per activity or building element).

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Appendix. Questionnaire of modeling of Modules A4, A5, C1 and C2

Q1 Do you include the following EN 15978 modules (mark with X)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes		No		
A5	Yes		No		
Use stage (B2-B5)	Yes		No		
C1	Yes		No		
C2	Yes		No		

Q2 Which Option do you mainly use to model EN 15978 transport modules *(A4 and C2) (mark with X):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for A4 and C2 you should include A4 and C2 separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the following aspects in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	
Which transport distances do you considered?	
Which means of transport do you considered?	
Which fuels and consumption hypothesis do you considered?	
Do you include the return load (return trip of transports)?	
Which data sources or database do you considered for impacts calculation?	
Do you include any other relevant aspects? Can you specify?	

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the manufacturers of the main building materials?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the sorting/recycling or end of life disposal points?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	

Provide reference document or brief description (if possible)

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* (Q6) close to (mark with X):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the following aspects in the previous Option*(Q6):

Which construction, deconstruction and replacement works do you considered?	
Which type of machinery and machinery works do you considered?	
Which fuels and energy machinery consumption hypothesis do you considered?	
Which data sources or database do you considered for impacts calculation?	
Do you include any other relevant aspects? Can you specify?	

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

(AU) AUTRALIA

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No		
A5	Yes	X	No		
Use stage (B2-B5)	Yes	X	No		
C1	Yes	X	No		
C2	Yes	X	No		

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]	X	Simplified average distance delivered from distributor and site. Then, transportation distance is quantified with return.
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.

[2] include more than 2 or 3 possible distances, means of transport, etc.

[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	Basically all building materials which counted embodied impacts. If not considered in the A1-A3, it is not considered in A4.
Which transport distances do you considered?	If not specified, it is, in general, assumed less than 200km away of building material supplied to the site.
Which means of transport do you considered?	Basically 'rigid truck'.
Which fuels and consumption hypothesis do you considered?	Mainly diesel.
Do you include the return load (return trip of transports)?	Yes we does.
Which data sources or database do you considered for impacts calculation?	Australian national LCI data (called AusLCI) and Ecoinvent ver 3.0 (if not available in AusLCI)
Do you include any other relevant aspects? Can you specify?	

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	X	

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicating the estimate location and a brief description of the hypotheses.

YES		NO	X	We don't have any default location for recycling or sorting.

Provide reference document or brief description (if possible)

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

For detailed LCA for A5, we use productivity of major equipment (e.g., hour/unit of work, m3 etc. for crane, electric ladder etc.) then quantified the energy consumption of its equipment. But simple version of LCA, we use an assumption taken from literature (5-10% of whole LCA).
For B4, it is quantified the lifespan of each element and products of building. For example, it will be replaced every 10 years for glass, 15 years repainting etc.
For C1, we use equipment productivity for detailed LCA or assumption for simple LCA.

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]	X	Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible)
Detailed modeling [3]	X	Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	
Which type of machinery and machinery works do you considered?	Excavator, backhoe etc. for foundation (earth) work, Crane hoist, conveyer, forklift for construction material handling
Which fuels and energy machinery consumption hypothesis do you considered?	Mainly fueled with diesel for machinery.

Which data sources or database do you considered for impacts calculation?	Mainly AusLCI (national LCI database) or ecoinvent (see 3.0 if not available in AusLCI)
Do you include any other relevant aspects? Can you specify?	Australian team has worked for some missing impacts from A3, A5 and B1. Please see the attached. We are happy to contribute our work for this if required.

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

(BE) BELGIUM

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	x	No		
A5	Yes	x	No		
Use stage (B2-B5)	Yes	x	No		
C1	Yes	x	No		
C2	Yes	x	No		

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]	x	Allacker K, Debacker W, Delem L, De Nocker L, De Troyer F, Janssen A, Peeters K, Van Dessel J, Servaes R, Rossi E, Deproost M, Bronchart S (2018) Environmental profile of building elements [update 2017]. OVAM, Mechelen

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	For each product and material, a transport and waste category is selected. Based on the transport and waste category, transport scenarios are calculated for both A4 and C2
Which transport distances do you considered?	Transport distances depend on the selected material category. 3 transport steps are considered (directly from

	factory to site, from factory to supplier and from supplier to site)
Which means of transport do you considered?	Depending on the transport step, the materials are subdivided according to 4 means of transport * Lorry > 32 ton (EURO 5) * Lorry 16-32 ton (EURO 5) * Lorry 7.5-16 ton (EURO 5) * Lorry 3.5-7.5 ton (EURO 5)
Which fuels and consumption hypothesis do you considered?	Diesel (EURO 5)
Do you include the return load (return trip of transports)?	This included in the average load assumed in the Ecoinvent records
Which data sources or database do you considered for impacts calculation?	Ecoinvent 3.3
Do you include any other relevant aspects? Can you specify?	/

Provide reference document (if possible)
Allacker K, Debacker W, Delem L, De Nocker L, De Troyer F, Janssen A, Peeters K, Van Dessel J, Servaes R, Rossi E, Deproost M, Bronchart S (2018) Environmental profile of building elements [update 2017]. OVAM, Mechelen

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

The location of the manufacturers is indirectly included based on the average transport distances which are assumed for each material category.

YES	x	NO	

Provide reference document or brief description (if possible)
Allacker K, Debacker W, Delem L, De Nocker L, De Troyer F, Janssen A, Peeters K, Van Dessel J, Servaes R, Rossi E, Deproost M, Bronchart S (2018) Environmental profile of building elements [update 2017]. OVAM, Mechelen

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

The location of the sorting/ recycling or EOL disposal plants is indirectly included based on the average transport distances which are assumed for each waste category.

YES	x	NO	

Provide reference document or brief description (if possible)
Allacker K, Debacker W, Delem L, De Nocker L, De Troyer F, Janssen A, Peeters K, Van Dessel J, Servaes R, Rossi E, Deproost M, Bronchart S (2018) Environmental profile of building elements [update 2017]. OVAM, Mechelen

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

Model A5

This module includes the following processes:

- Impact of material losses (global add-on of 5% on all material quantities)
- Impact of construction activities (e.g. excavation and electricity consumed for cellulose blowing)

Use stage (Module B4)

This module includes the replacement of worn building components. It covers the impact of the demolition, waste transport and waste management of the removed components and the production, transportation and construction of the new components. Information related to the life span of work sections can be found on the TOTEM website (https://www.totem-building.be/)

Module C1

Module C1 includes the impact of the deconstruction and demolition. The composition of the materials and the method of connecting with other materials/work sections determines the type of demolition process

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Allacker K, Debacker W, Delem L, De Nocker L, De Troyer F, Janssen A, Peeters K, Van Dessel J, Servaes R, Rossi E, Deproost M, Bronchart S (2018) Environmental profile of building elements [update 2017]. OVAM, Mechelen

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]	x	Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]	x	Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

Generic option for module A5

Detailed modeling for modules B4 and C1

[1] include a general hypothesis.

[2] include more than 2 scenarios/hypothesis.

[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	• Various deconstruction processes have been defined for different materials based on Ecoinvent 3.3 • The impact of replacement is calculated as the sum of the impact of the demolition, waste transport and waste management of the removed components and the production,

	transportation and construction of the new components
Which type of machinery and machinery works do you considered?	The impact of construction activities is limited to a few processes such as excavation works and the electricity consumed for cellulose blowing
Which fuels and energy machinery consumption hypothesis do you considered?	The fuels and consumption values are based on Ecoinvent 3.3
Which data sources or database do you considered for impacts calculation?	Ecoinvent 3.3
Do you include any other relevant aspects? Can you specify?	/

*** in case you use a different Option for each LCA module you should include separately answers.**

Provide reference document (if possible)

Allacker K, Debacker W, Delem L, De Nocker L, De Troyer F, Janssen A, Peeters K, Van Dessel J, Servaes R, Rossi E, Deproost M, Bronchart S (2018) Environmental profile of building elements [update 2017]. OVAM, Mechelen

(BZ) BRAZIL

Q1 Do you include the following EN 15978 modules (mark with X)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes		No		
A5	Yes		No		
Use stage (B2-B5)	Yes		No		
C1	Yes		No		
C2	Yes		No		

Q2 Which Option do you mainly use to model EN 15978 transport modules *(A4 and C2) (mark with X):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

*** in case you use a different Option for each LCA module you should include separately answers.**

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the following aspects in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	

	Which transport distances do you considered?	
	Which means of transport do you considered?	
	Which fuels and consumption hypothesis do you considered?	
	Do you include the return load (return trip of transports)?	
	Which data sources or database do you considered for impacts calculation?	
	Do you include any other relevant aspects? Can you specify?	
	Provide reference document (if possible)	

Q4 Concerning the previous (Q2) Option, do you consider a default location of the manufacturers of the main building materials?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the sorting/recycling or end of life disposal points?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	

Provide reference document or brief description (if possible)

Q6 **Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in A5, C1 EN 15978 modules and use stage*** (provide brief **description, if possible):**

*** in case you use a different Option for each LCA module you should include separately answers.**

Provide reference document (if possible)

Q7 Is this previous Option* (Q6) close to (mark with X):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

*** in case you use a different Option for each LCA module you should include separately answers.**

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the following aspects in the previous Option*(Q6):

Which construction, deconstruction and replacement works do you considered?	
Which type of machinery and machinery works do you considered?	
Which fuels and energy machinery consumption hypothesis do you considered?	
Which data sources or database do you considered for impacts calculation?	
Do you include any other relevant aspects? Can you specify?	
* in case you use a different Option for A5, B4 and C1 you should include A5, B4 and C1 separately answers.	
Provide reference document (if possible)	

(CA) CANADA

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No	
A5	Yes	X	No	
Use stage (B2-B5)	Yes	X	No	
C1	Yes	X	No	
C2	Yes	X	No	

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]	X	Provide reference document or brief description (if possible) •For A4, we used an average distance according to project location (urban, suburban, rural, etc.). For this specific project, a distance of 25km for concrete with a small size lorry transport truck was used and a distance of 225km was used for all the other material with a regular lorry transport truck. •For C2, we used an average distance of 50km with regular lorry truck transportation.
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	All material used in the building were included (including materials for the B4 and A5 – loss during construction

	modules). Transport of the construction equipment was not included.
Which transport distances do you considered?	See Q2
Which means of transport do you considered?	See Q2
Which fuels and consumption hypothesis do you considered?	Average consumption per ton kilometer from the ecoinvent datasets were used.
Do you include the return load (return trip of transports)?	Yes, datasets rely on average load factors that include the average share of empty return trips.
Which data sources or database do you considered for impacts calculation?	For the small size lorry transport, an ecoinvent dataset was used. For the regular lorry transport, an internal model from Groupe AGÉCO which is representative of transport in North America is used.
Do you include any other relevant aspects? Can you specify?	All aspects from the ecoinvent datasets were used.
Provide reference document (if possible)	

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?

If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES	X	NO		We used default distances between the supplier and the site construction (see Q2).

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?

If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES	X	NO		We used default distances between the building and the end-of-life facilities.

Provide reference document or brief description (if possible)

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

•For A5, we used a fixed percentage of the impacts from A1 to A4 (10%). No calculation regarding fuel consumption was included for this module.

•For B4, we used a ratio according to material lifespan (round up (building lifespan / material lifespan))-1) *(material impacts A1 to A5).

•For C1, we used a generic value for machinery under a specific time. One machinery was for the concrete demolition (crusher) and another regular machinery for all the other demolition works.

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]	X	Provide reference document or brief description (if possible) •For C1, crusher use was based on concrete volume in the building. Other machinery was modeled with average consumptions per m2 of floor based on Groupe AGECO experience.
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	A5: no construction work was modeled C1: Concrete crushing, material handling
Which type of machinery and machinery works do you considered?	Machinery for material handling (lifts, air compressors, cranes…) and concrete crusher during deconstruction.
Which fuels and energy machinery consumption hypothesis do you considered?	Average consumption per hour from the ecoinvent datasets were used.
Which data sources or database do you considered for impacts calculation?	Average machine operation from the ecoinvent database were used.
Do you include any other relevant aspects? Can you specify?	

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

(CH) SWITZERLAND

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes		No	X	Transports to regional storage site in Switzerland (this applies also for construction products manufactured abroad) is covered in the construction materials datasets. Delivery to building site is often unknown and of low importance. In exceptional cases (helicopter transports) A4 may be included.

A5	Yes		No	X	Considered of minor importance; cutting losses (wastes during construction) are neglected because the amounts of materials needed are determined coarsely and generously. Furthermore, there are no empirical data on material specific cutting losses/wastes.
Use stage (B2-B5)	Yes	X	No		
C1	Yes	X	No		
C2	Yes	X	No		

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]	X	This only applies for C2 transports, for which 1 default transport distance and one means of transport per waste management option (landfill, incineration, separation/recycling) is used.
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for A4 and C2 you should include A4 and C2 separately answers.

[1] include 1 or 2 general distances, means of transport, etc.

[2] include more than 2 or 3 possible distances, means of transport, etc.

[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	
Which transport distances do you considered?	10 to 20 km
Which means of transport do you considered?	Lorry, 20-28 tons, fleet average
Which fuels and consumption hypothesis do you considered?	diesel, 24.57kg/100km (=29.42 litre/100km)
Do you include the return load (return trip of transports)?	Average payload: 5.8tons, including return trip
Which data sources or database do you considered for impacts calculation?	KBOB LCA data DQRv2:2016 (retrieved from www.ecoinvent.org, https://db.ecoinvent.org/download/KBOB%20DQRv2_2016.zip?area=3e2c0806caa3c Most recent version available: UVEK LCA data DQRv2:2018
Do you include any other relevant aspects? Can you specify?	demolishing efforts are included in C1, same efforts and emissions per kg material.

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	X	Foreign production and import transports are taken into account.

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	X

Provide reference document or brief description (if possible)

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

A5: not taken into account
B4: standard lifetimes per building element as reported in SIA 2032, Annex C (normative), no energy consumption for replacement but for demolishing work of replaced building elements and materials.

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	replacement works are not considered, only replacement materials
Which type of machinery and machinery works do you considered?	general diesel consumption of building machines used in demolishing
Which fuels and energy machinery consumption hypothesis do you considered?	see above

Which data sources or database do you considered for impacts calculation?	see above
Do you include any other relevant aspects? Can you specify?	

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

(DE) GERMANY

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes		No	**X**	Both the latest BNB and DGNB systems in Germany do not include modules A4-5 as well as C1-2 in their minimum system boundaries. Reasons for this exclusion are not clearly stated in BNB/DGNB guidelines but lie in problems with data acquisition and an assumed insignificance of such impacts with regard to the overall result. The possible inclusion in the next version is currently investigated.
A5	Yes		No	**X**	See above under A4
Use stage (B2-B5)	Yes	**X**	No		Both the latest BNB and DGNB systems in Germany do include module B4. The basis is default values for the service life of building components and building equipment
C1	Yes		No	**X**	See above under A4
C2	Yes		No	**X**	See above under A4

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]	**(X)**	A4 and C2 are not taken into account in BNB/DGNB. Therefore, since default distances are not provided per material type by BNB/DGNB systems, it is assumed that if one wishes to include these modules in an assessment, detailed modelling will be applied in relation to this parameter. Ökobau.dat provides average environmental data in tonnes*km for different types of transport to assist in calculations. For example, for small truck: *"The dataset refers to the transport of 1000 kg cargo on a distance of 1 km by truck (EURO 5) with 12-14 t permissible total weight and 9.3 t payload in forwarding traffic with a utilisation ratio of 85%. The extraction and processing of the fuel is included. The production of the vehicle is not included in the balancing."* (see: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=510e8761-8b2d-46a5-b8df-

6d1ac321ce92&version=20.19.120&stock=OBD_2021_II&lang=en)

* in case you use a different Option for A4 and C2 you should include A4 and C2 separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	
Which transport distances do you considered?	
Which means of transport do you considered?	
Which fuels and consumption hypothesis do you considered?	
Do you include the return load (return trip of transports)?	
Which data sources or database do you considered for impacts calculation?	
Do you include any other relevant aspects? Can you specify?	

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	**X**

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	**X**

Provide reference document or brief description (if possible)

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

A5 and C1 are not taken into account in BNB/DGNB. However, Ökobau.dat provides data for a few selected construction activities:

(1) excavators per m^3 (e.g. https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=f4d930b5-ebe0-4b12-9de0-e2ee391be029&version=20.19.120&stock=OBD_2021_II&lang=en)
(2) pumping of concrete per m^3 (e.g. https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=f

dcb26f9-1f0c-4766-ad94-c093e5d259e1&version=20.19.120&stock=OBD_2021_II&lang=en)

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	replacement works/construction processes are not considered, only replacement materials and components
Which type of machinery and machinery works do you considered?	So far data are provided only for excavation and pumping of concrete. Diesel Excavators are considered, e.g. for Excavator of 15kW “*The dataset includes the production and consumption of diesel necessary for the excavation of 1m^3 of dirt (0.305 kg diesel per m3 of sand soil)*”
Which fuels and energy machinery consumption hypothesis do you considered?	n.a.
Which data sources or database do you considered for impacts calculation?	See Q6
Do you include any other relevant aspects? Can you specify?	n.a.

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

(ES) SPAIN

Q1 Do you include the following EN 15978 modules (mark with X)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No		
A5	Yes	X	No		

Use stage (B2-B5)	Yes	X	No	
C1	Yes	X	No	
C2	Yes	X	No	

Q2 Which Option do you mainly use to model EN 15978 transport modules *(A4 and C2) (mark with X):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

*** in case you use a different Option for each LCA module you should include separately answers.**

[1] include 1 or 2 general distances, means of transport, etc.

[2] include more than 2 or 3 possible distances, means of transport, etc.

[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the following aspects in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	
Which transport distances do you considered?	
Which means of transport do you considered?	
Which fuels and consumption hypothesis do you considered?	
Do you include the return load (return trip of transports)?	
Which data sources or database do you considered for impacts calculation?	
Do you include any other relevant aspects? Can you specify?	

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the manufacturers of the main building materials?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the sorting/recycling or end of life disposal points?
If your answer is YES, please indicating the estimate location and a brief description of the hypotheses.

YES		NO	

	Provide reference document or brief description (if possible)
Q6	Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):
	* in case you use a different Option for each LCA module you should include separately answers.
	Provide reference document (if possible)
Q7	Is this previous Option* (Q6) close to (mark with X):

Generalize hypothesis [1]	X	Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8	Can you specify how do you integrate the following aspects in the previous Option*(Q6):	
	Which construction, deconstruction and replacement works do you considered?	
	Which type of machinery and machinery works do you considered?	
	Which fuels and energy machinery consumption hypothesis do you considered?	
	Which data sources or database do you considered for impacts calculation?	
	Do you include any other relevant aspects? Can you specify?	
	* in case you use a different Option for each LCA module you should include separately answers.	
	Provide reference document (if possible)	

(FR) FRANCE

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No		
A5	Yes	X	No		
Use stage (B2-B5)	Yes	X	No		
C1	Yes		No	X	
C2	Yes	X	No		

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]	X	Provide reference document or brief description (if possible) See annex of this document
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.

[2] include more than 2 or 3 possible distances, means of transport, etc.

[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	All products are concerned
Which transport distances do you considered?	See annex
Which means of transport do you considered?	truck
Which fuels and consumption hypothesis do you considered?	Like in ecoinvent 2.2
Do you include the return load (return trip of transports)?	Average load factor of ecoinvent
Which data sources or database do you considered for impacts calculation?	Ecoinvent 2.2
Do you include any other relevant aspects? Can you specify?	

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicating the estimate location and a brief description of the hypotheses.

YES		NO		The user is free to choose this location and the corresponding transport distance, see annex

Provide reference document or brief description (if possible)

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO		The user is free to choose this location and the corresponding transport distance, see annex

Provide reference document or brief description (if possible)

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

See annex

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.

[2] include more than 2 scenarios/hypothesis.

[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	Waste production
Which type of machinery and machinery works do you considered?	none
Which fuels and energy machinery consumption hypothesis do you considered?	none
Which data sources or database do you considered for impacts calculation?	Ecoinvent 2.2
Do you include any other relevant aspects? Can you specify?	Treatment of building site waste

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Annex: French EQUER method

Q2: The user informs 4 transport distances, the following default values are proposed:

Distance from manufacture to building site, 100 km

Distance from Building site to landfill, 20 km

Distance from Building site to incineration, 20 km

Distance from Building site to recycling, 100 km

Transport by truck is considered.

Q6: For A5, the user chooses a surplus % of materials, 5% is proposed as default value. This corresponds to broken elements on the construction site, surplus of ready mixed concrete at the end of the day, parts of panels that remain unused after cutting the right size etc.

For B4, the user informs 8 life spans, the following default values are proposed:

Doors and Windows (inside and facades), 30 years

Painting and finishes (inside and facades), 10 years

Equipment, 20 years

Other elements, same as whole building = 80 years or other value, 100 years

(HU) HUNGARY

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No		
A5	Yes	X	No		
Use stage (B2-B5)	Yes	X	No		
C1	Yes		No	X	We have no data for this stage.
C2	Yes	X	No		

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible): A4: Materials are classified into 4 transportation categories depending on the number and location of manufacturing plants (50 km lorry for materials produced locally; 150 km lorry+30 km van for national production with 1-2 factories; 800 km freight rail+30 km van for imported products transported by rail; 800 km lorry+ 30 km van for imported materials transported on road) C2: only one transport category: 20 km lorry
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	data taken from ecoinvent
Which transport distances do you considered?	described above
Which means of transport do you considered?	described above
Which fuels and consumption hypothesis do you considered?	taken from ecoinvent
Do you include the return load (return trip of transports)?	yes
Which data sources or database do you considered for impacts calculation?	ecoinvent 3.5
Do you include any other relevant aspects? Can you specify?	no

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES	X	NO	

Provide reference document or brief description (if possible)
For nationally produced materials we check where the factories are located in the country and based on the number of factories we classify materials into categories. These categories are used for each material independent of the actual location of the building.

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES		NO	X

Provide reference document or brief description (if possible)
Only one transport category is used

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

A5: material losses are included (2-5% depending on material) and in the previous version of the tool 8 MJ/m3 electricity + 50 MJ/m3 diesel was included for the construction process of the building
B4: replacement is calculated based on default lifetime of materials/ elements
C1: neglected due to missing data

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generic modelling[1]	X	Provide reference document or brief description (if possible) see above
Simplified modeling [2]		Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option*(**Q6)**:

Which construction, deconstruction and replacement works do you considered?	For construction only material losses are included, plus a general value for the construction process taken from an ecoinvent report. For replacement only the materials, their transport and disposal are considered, not the replacement process itself.
Which type of machinery and machinery works do you considered?	only a general value is considered
Which fuels and energy machinery consumption hypothesis do you considered?	only a general value is considered
Which data sources or database do you considered for impacts calculation?	ecoinvent 3.5
Do you include any other relevant aspects? Can you specify?	no

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

(NZ) NEW ZEALAND

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No		
A5	Yes	X	No		
Use stage (B2-B5)	Yes	X	No		
C1	Yes	X	No		
C2	Yes	X	No		

Q2	Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):	

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible) – **please see Module A4 Summary worksheet in the accompanying "Construction transport (module A4) v1.xlsx" spreadsheet for example transport distances**
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	**Please see materials/products listed in the "Construction transport (module A4) v1 datasheet. We include the main materials in structures, walls, roofs, floors (for example). Currently, we do not consider fixings, sealants, adhesives.**
Which transport distances do you considered?	**From manufacturer gate to construction site in central Auckland, Wellington or Christchurch.**
Which means of transport do you considered?	**Road, ship, rail**
Which fuels and consumption hypothesis do you considered?	**Underlying data for fuel consumption, based on data in EcoInvent 3.1.**
Do you include the return load (return trip of transports)?	**No.**
Which data sources or database do you considered for impacts calculation?	**CML**
Do you include any other relevant aspects? Can you specify?	**Includes transport of material that ends up in the building, as well as transport of the material that becomes waste at the construction site.**

Provide reference document (if possible)

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

Please look at Section 3 of the accompanying SR351 study report for an explanation of how we have derived these transport distances.

YES	X	NO	

Provide reference document or brief description (if possible) **- SR351 study report accompanies this questionnaire**

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES	X	NO	

Provide reference document or brief description (if possible)

We assume a 20 km distance to landfill/cleanfill. Distances to recycling facilities vary depending on the material, for example, steel and aluminium scrap are exported overseas by ship.

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

Please go to www.branz.co.nz/builidnglca and select "Data". In there, you will see a list of all our datasheets, which provide scenario information for building LCA. You can download the Construction site waste (module A5) v1, Building materials replacement (module B4) v2 and Building end-of-life (module C1) v1 datasheets, to see how we have provided these data.
For information about how these have been developed, please see the accompanying SR351 study report.

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option* **(Q6)** close to (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible)
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	**We include construction of the elements set out in the module A5 datasheet.** **We do not include smaller items such as fixings, sealants, adhesives, therefore wastage of these materials is also not included currently.** **Other current exclusions include:**

	Packaging of construction materials. **Energy used for site machinery/power tools/site office.** **Shuttering/formwork.** **Excavation activities.**
Which type of machinery and machinery works do you considered?	**See above.** **For deconstruction, we include energy required for this, which is allocated to structural materials only. Data are based on an Athena Institute publication. For further information, please see accompanying SR350 study report (Appendix D4)**
Which fuels and energy machinery consumption hypothesis do you considered?	**Machinery is powered by diesel. We use secondary data from EcoInvent 3.1, in particular the dataset called “Diesel, burned in building machine”.**
Which data sources or database do you considered for impacts calculation?	**EcoInvent 3.1**
Do you include any other relevant aspects? Can you specify?	**Please see SR351 study report and Appendix D of the SR350 study report.**

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible) **Key documents are SR351 study report and SR350 study report (Appendix D). Also, for data, please see datasheets (as set out above)**

(UK) UNITED KINGDOM

Q1 Do you include the following **EN 15978 modules** (mark with **X**)?
If your answer is NO justify by describing the reason of neglection.

A4	Yes	X	No		This is a mandatory stage to be included in order to meet the minimum requirements laid out in the RICS Professional Statement available here.
A5	Yes	X	No		This is a mandatory stage to be included in order to meet the minimum requirements laid out in the RICS Professional Statement available here.
Use stage (B2-B5)	Yes	X	No		This is a mandatory stage to be included in order to meet the minimum requirements laid out in the RICS Professional Statement available here.
C1	Yes	X	No		This is not mandatory and exceeds the minimum requirement in the document linked above but its inclusion is nonetheless strongly encouraged.
C2	Yes	X	No		This is not mandatory and exceeds the minimum requirement in the document linked above but its inclusion is nonetheless strongly encouraged.

Q2 Which Option do you mainly use to model **EN 15978 transport modules** *(A4 and C2) (mark with **X**):

Generalize hypothesis [1]		Provide reference document or brief description (if possible)
Simplified modeling [2]	X	Provide reference document or brief description (if possible) From the standard above: “Transport emissions should be calculated as follows: [A4] = Material or system mass (a) × transport distance (b) × carbon conversion factor (c).”
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include 1 or 2 general distances, means of transport, etc.
[2] include more than 2 or 3 possible distances, means of transport, etc.
[3] include a detailed modeling of transports.

Q3 Can you specify how do you integrate the **following aspects** in the previous (Q2) Option:

Which are the considered products and materials? Do you have any cut-off rules for that?	You can find this information in Table 3 of the document above.
Which transport distances do you considered?	You can find this information in Table 7 (for A4) and Table 11 (for C2) of the document above.
Which means of transport do you considered?	Also this information can be found in Table 7 (for A4) and Table 11 (for C2) of the document above.
Which fuels and consumption hypothesis do you considered?	Carbon conversion factors are taken from official UK government publications.
Do you include the return load (return trip of transports)?	Partially. In fact, the carbon conversion factors consider average rigid HGV with average laden. This means that the mode of transport that should be assumed is an average heavy goods vehicle (HGV) with 50 per cent load to account for the vehicles coming to site empty and leaving with a 100 per cent load.
Which data sources or database do you considered for impacts calculation?	This information is given in Section 3.3.1 of the linked document. In short: Type III environmental declarations and datasets in accordance with EN15804 or ISO21930 or ISO 14067 or ISO 14025, 14050, 14044 or PAS 2050.
Do you include any other relevant aspects? Can you specify?	

Provide reference document (if possible)

Same link of Q1.

Q4 Concerning the previous (Q2) Option, do you consider a default location of the **manufacturers of the main building materials**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES	X	NO	

Provide reference document or brief description (if possible)

Please see Table 7 (for A4) of the document linked in Q1. Basically, if project-specific information is unavailable, average distances and means of transport are provided based on groups of materials (e.g. locally manufactured vs. globally manufactured).

Please see Table 11 (for C2) of the document linked in Q1. Basically, for C2 the scenarios are not material-specific but EoL-specific.

Q5 Concerning the previous (Q2) Option, do you consider a default location of the **sorting/recycling or end of life disposal points**?
If your answer is YES, please indicate the estimate location and a brief description of the hypotheses.

YES	x	NO	

Provide reference document or brief description (if possible)

From the document linked in Q1:

For reuse/recycling elsewhere a 50km local transport is assumed whereas for landfill/incineration the average between the two closest landfill sites is assumed.

Q6 Which Option, modeling principles or hypothesis do you mainly use to include T, C&D process in **A5, C1 EN 15978 modules and use stage*** (provide brief description, if possible):

Please see the following sections of the documents linked above:

Section 3.5.2.2 page 20 for **A5**
Section 3.5.3.4 page 22 for **Use stage**
Section 3.5.4.1 page 26 for **C1**

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Q7 Is this previous Option*** (Q6)** close to (mark with **X**):

Generalize hypothesis [1]	X	Provide reference document or brief description (if possible) This is the answer for **A5** where a simplified average figure (taken from a BRE publication) of 1400kgCO2e/£100k of project value is given in absence of more specific information.

		This is also the answer for **C1** where an average rate of 3.4 kgCO2e/m^2 GIA (monitored from demolition case studies in London is suggested)
Simplified modeling [2]	X	Provide reference document or brief description (if possible) This is the answer for **B4**, where indicative component lifespans are given (see Table 9 of the document linked above).
Detailed modeling [3]		Provide reference document or brief description (if possible)

* in case you use a different Option for each LCA module you should include separately answers.

[1] include a general hypothesis.
[2] include more than 2 scenarios/hypothesis.
[3] include a detailed modeling.

Q8 Can you specify how do you integrate the **following aspects** in the previous Option***(Q6)**:

Which construction, deconstruction and replacement works do you considered?	**A5**: As mentioned this is a weak point of the RICS document where an average figure linked to project value is used. Even if detailed and project-specific assessments are encouraged I suspect that in practice the average figure is most often used. **Use stage**: from the document above "Module [B4] must take into account any carbon emissions associated with the anticipated replacement of building components, including any emissions from the replacement process. All emissions arising from the production, transportation to site and installation of the replacement items must be included. This extends to cover any losses during these processes, as well as the carbon associated with component removal and EoL treatment. **C1**: again, an area of weakness of the document which suggests an average figure. The risk is that in practice most people would just use the suggested figure although the standard does encourage to collect project-specific data.
Which type of machinery and machinery works do you considered?	**A5**: See previous answer and section 3.5.2.2 of the document linked in Q1. **Use stage**: see previous answer and section 3.5.3.4 of the document linked in Q1 and below. **C1**: N/A

Which fuels and energy machinery consumption hypothesis do you considered?	**A5**: N/A **Use stage**: N/A **C1:** N/A
Which data sources or database do you considered for impacts calculation?	**A5**: site waste rates for different materials should be determined based on the standard wastage rates provided by the WRAP Net Waste Tool (UK specific). **Use stage**: scenarios should be based on data from facilities management and maintenance Option reports, façade access and maintenance Option, life cycle cost reports, O&M manuals, guidance (e.g. CIBSE Guide M and BCIS Life expectancy of building components), international standards (e.g. ISO 15868-5: 2008 Buildings and constructed assets – service life planning, and manufacturers' documentation). Also lifespans value are given in Table 9 of the document. **C1**: N/A/
Do you include any other relevant aspects? Can you specify?	

* in case you use a different Option for each LCA module you should include separately answers.

Provide reference document (if possible)

Always the same document linked here once more:
www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the--built-environment-november-2017.pdf

Basics and recommendations on influence of future climate change on prediction of operational energy consumption

A Contribution to IEA EBC Annex 72

February 2023

Free image from Slawomir Kowalewski on Pixabay

Basics and recommendations on influence of future climate change on prediction of operational energy consumption

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February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of the project IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

A basis for determining and assessing the operational greenhouse gas emissions of buildings (module B6 of a building related LCA) and other impacts on resource depletion and environment already during design is the realistic prognosis of the operational energy demand. Important input variables are the outside temperatures during the heating and cooling periods as well as the thermal comfort requirements of the users. As a result of the already occurring global warming, changes in the local climate will occur at the site of specific buildings. This raises the question of what basis can and should be used to determine the operational energy demand in the future. The presentation and discussion of corresponding possibilities is the subject of this background report.

The report includes the description of the most used techniques for the introduction of global warming expected climate variations within the context of building energy simulation through the downscaling of existing global circulation models' outputs and the manipulation of existing weather data files. It discusses future provisional assessments of the air temperature variations throughout the current century as well as the analysis of existing literature that estimates potential energy use variation in heating and cooling throughout different climate zones in the world.

The main results highlight an increase in energy use for cooling in all the locations highlight the trend in rising temperatures throughout the globe that may reach up to 4.5 degrees Celsius at the end of the century, if compared to the current situation.

This will have significant implications on the energy use to operate buildings, with severe (up to 40%) increase in cooling energy use by the end of the century and peak power requirements and parallel reductions in heating requirements.

Other consequences may impact traditionally heating dominated countries which may see the rise of cooling requirements, also generating the need for HVAC equipment, actually generating a significant increase not only in energy use during the operation stage, but as well in terms of embodied energy.

As the average buildings' life cycle is in the range of the climate change time scale, the global warming trend will require innovative and more climate resilient design, with smart solutions, wider use of passive building design, improved urban solutions and planning (i.e. to counteract in-creasing heat island effects) for new buildings as well as for the energy retrofitting of the existing building stock.

It is thus recommended to future-proof buildings designed today with climate change resilient technical solutions as well as through the appropriate use of building energy simulation.

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Abbreviations

Abbreviations	Meaning
AR4	Assessment Report Four
AR5	Assessment Report Five
BAU	Business As Usual
CDD	Cooling Degree Days
DRY	Design Reference Year
EWY	Example Weather Year
GCM	Global Circulation Models
GHG	Greenhouse Gas
HDD	Heating Degree Days
IPCC	Intergovernmental Panel on Climate Change
PPD	Predicted Percentage of Dissatisfied
RCM	Regional Climate Models
RCP	Representative Concentration Pathways
SRES	Special Report on Emission Scenarios
TAR	Third Assessment Report
TRY	Test Reference Year

Definitions

Global Circulation Models (GCM): they are numerical models of the main physical process in the atmosphere, oceans and land surface and represent the state of the art of the modelling and simulation of the global climate system in response to the increase of the concentration of greenhouse gases in the atmosphere. GCMs are usually based on three dimensional grids with resolution higher than 250 km, thus calculating and simulating the physics of the airflow of air and water masses: energy balances, wind flow and speed, water currents and temperature, precipitations etc.

Regional Circulation Models (RCM): RCM models are based on limited areas and use a much denser concentration of grid points for the numerical modelling and simulation, thus being able to catch specific local microclimate trends and variations, which can often be very impactful in the performances of buildings. They can usually be combined with GCMs as they use boundaries conditions deriving from GCMs.

Representative Concentration Pathways (RCP): defined respectively as RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The specific nomenclature used in the definition of the scenarios refers to the radiative forcing implemented in the modeling, defined as the change in net – downward minus upward - radiative flux (measured in Watts per square meter) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as (and most prominently so) the concentration of carbon dioxide. These scenarios are generally developed in time and extend also beyond the end of the XXII century.

1. Introduction

The effects of climate change are widespread in different areas and domains, including potential future repercussions across nearly all the sustainable development goals, as well as, substantial variations on current climate patterns will impact the standards of living for people throughout the world. Poverty, hunger, health and well-being, clean water and sanitization, affordable and clean energy, cities and communities, responsible consumption and production – are some of the most relevant Sustainable Development goals – which can, and will, be impacted by an increase of extreme weather events which has risen dramatically in the last years. Furthermore, due to a change in the average trends of most climate variables, such as, for example, the increase in average air temperatures, climate change is also creating impacts on the world beyond extreme events.

In the work of the Intergovernmental Panel on Climate Change (IPCC) (Edenhofer, Pichs-Madruga, & Sokona, 2014) it is clearly mentioned that if no decisive action is undertaken on a global scale to decarbonize economies, then business as usual scenarios identify an significant of the average air temperature increase by the end of our century even by more than 4.5 degrees. Although this approach towards a widespread decarbonisation must cover all sectors of the economy, the decarbonisation of the construction and real estate sector, which is historically one of the main sectors contributing the worldwide CO_{2eq} emissions, must be considered as one of the main targets.

Since 1970, buildings have been significantly increasing their share of total carbon emissions, which are mostly related to indirect CO_2 emissions from the use of electricity in buildings in comparison to direct emissions, which have remained constant during recent decades. Indirect emissions have instead largely increased since the '70s, with at least a quadrupling of emissions from both residential and commercial buildings (Edenhofer et al., 2014) .

According to the International Energy Agency, the building and real estate sector (International energy agency, 2019a) accounts for 36% of final energy use and 39% of energy and process related carbon dioxide emissions in 2018, with an 11% of this total being caused by manufacturing of building materials or, in other words, being energy "embodied" in the building envelope and energy systems (Cabeza, Castell, & Pérez, 2014).

The emissions from the building and real estate sector have had in the past decade an increasing trend, in particular in 2018 they have kept increasing for the second year in a row, reaching an all-time high. (International energy agency, 2019b) This was caused by extreme weather which caused an increase in the demand for heating and cooling, which accounts for roughly the 20% of the total energy use increase for 2018. It is also worth mentioning that the building and real estate sector (sometimes also called area of action "buildings") has very high potential for decarbonization, because of the widespread use of low-efficiency technologies and systems, both in terms of heating and cooling, as well as, in the quality of envelopes and the limited worldwide availability of effective policies and investments towards sustainable and high-performance buildings.

Moreover, the Pathways to Deep decarbonization project, developed by the Sustainable development solutions network (Sachs, Tubiana, & (IDDRI), 2014) stressed the necessity to limit the average temperature increase to 2°C at 2050 as per in the Paris agreement of COP21, clearly identifying the reduction threshold for carbon emissions to 56%, if compared to the 2010 levels on a global scale.

As such, short-sighted polices in the field of energy and buildings and, therefore, the embrace of un-sustainable economic pathways towards the next century could lead to potentially severe increases of energy

uses in the built environment, which could enable the vicious cycle of further increasing climate change phenomena through an increase in the emissions of carbon in the atmosphere.
This uncertainty makes the task to perform a robust and climate resilient design of sustainable buildings a challenge. The context of building performance assessment requires insight on energy demand calculations to be performed by assessing all geometrical and thermal features of the envelope and by performing specific energy calculation by taking in consideration the impact of the local weather and climate.

Practitioners usually work with weather data files only valid for the current time and buildings have a long lifespan: this means that designing buildings only for “today”, might mean that the weather conditions in the future might be largely different than what the building is designed to withstand. This could translate into increased energy uses, longer periods of thermal discomfort with higher predicted percentage of dissatisfied[1] (PPD) and fundamentally a building design which cannot adapt to climate change related future scenarios.

The building design should evolve and adapt with the climate it is supposed to withstand: it is therefore paramount to develop models to predict the evolution of global warming and its associated local consequences in the coming decades by developing designs / models and simulation tools to help building designers and energy specialists to design for the future climate change scenarios.

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[1] provides an estimate of how many occupants in a space would feel dissatisfied by the thermal conditions

2. Overview and Fundamentals

Climate change can translate into several phenomena and issues. This chapter will discuss the impact that climate change has, in terms of global warming, and on the energy use of buildings. Fundamentals of building energy simulation will be summarized, the main issues and modeling approaches towards the modeling of global warming into building simulation practice reviewed, with limits and strengths for each. Lastly the results of a selected overview of research on the energy uses for buildings during the current century will be shown and discussed.

2.1 Climate Change Modelling

Over the last two decades, IPCC has released a set of different emissions scenarios based on different assumptions. Different scenarios were developed thus in 1990 (called SA90), 1995 (IS92) and 2000 (special report on emission scenarios – SRES). These scenarios were used within the Third assessment Report (TAR) and the Assessment Report Four (AR4) and were considered as some of the most relevant references on the subject in the past decade.

In 2007, as reported in Figure 1, IPCC developed four specific emission scenarios used in the Assessment Report Five (AR5) called “Representative Concentration Pathways” (RCP), defined respectively as RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The specific nomenclature used in the definition of the scenarios refers to the radiative forcing implemented in the modeling, defined as the change in net – downward minus upward, radiative flux (measured in Watts per square meter) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as (and most prominently so) the concentration of carbon dioxide. These scenarios are generally developed in time and extend also beyond the end of the XXII century.

Thus, the four RCP scenarios can be briefly described as:

- RCP 2.6: the radiative forcing has a peak at 3 W/m^2 then declining. This scenario assumes large decarbonization actions and a substantial reduction in carbon-intensive practices in the next decades;
- RCP 4.5 and RCP 6.0 are two intermediate pathways which assume a stabilized rate of radiative forcing between 4.5 and 6.0 W/m^2 after 2100 with constant concentrations thereafter;
- RCP 8.5 represents roughly a ‘business as usual’ with radiative forcing higher than 8.5 W/m^2 at 2100 with a consecutive increase also after the beginning of the next century.

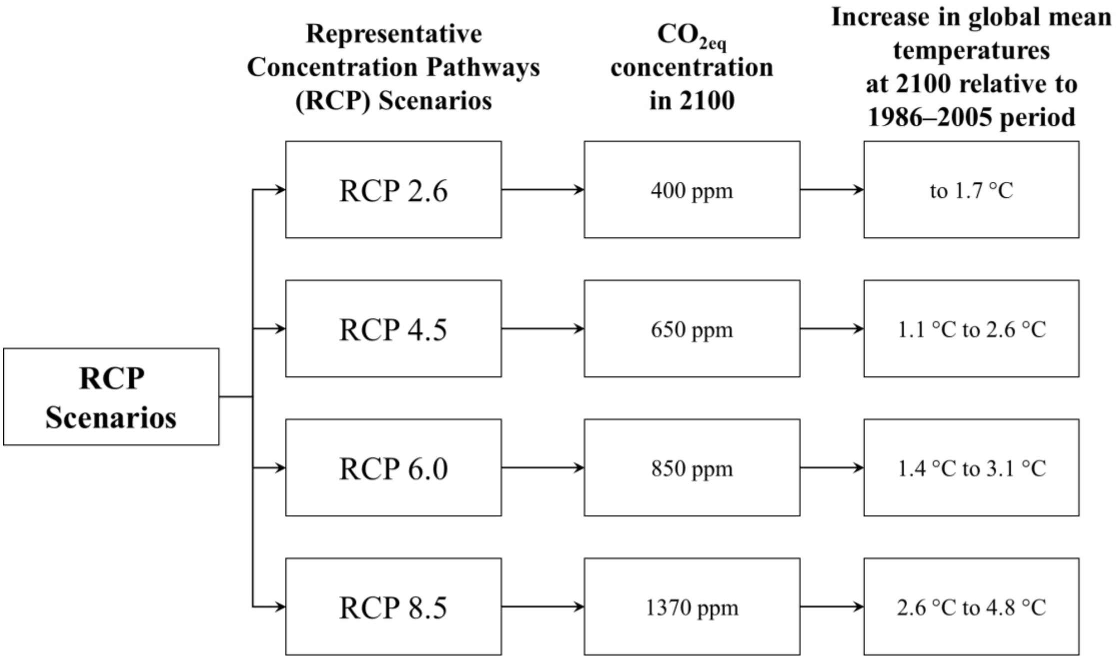

Figure 1: Representative Concentration Pathways IPCC scenarios (Edenhofer et al., 2014).

While they give an overview and aggregated information on what to expect as the perspective of global warming is concerned, these scenarios and models do not per se include climate change predictions, but rather investigate the variation of the main variables affecting climate change.

The development of variation trends for temperature and the other main climatic variables are usually achieved instead through the use of Global Circulation Models (GCM): they are numerical models of the main physical process in the atmosphere, oceans and land surface and represent the state of the art of the modeling and simulation of the global climate system in response to the increase of the concentration of greenhouse gases in the atmosphere. GCMs are usually based on three dimensional grids with resolution higher than 250 km, thus calculating and simulating the physics of the airflow of air and water masses: energy balances, wind flow and speed, water currents and temperature, precipitations etc.

However, as the focus is to develop tools and weather data files to be provided as input to the energy models for the building sector, global circulation models have in fact a resolution considered too large which makes it rather complex to identify a specific location/city. GCM outputs are usually “downscaled”, or, in other words, transposed to spatial and temporal scales lower than those provided by the original GCMs (e.g. through bilinear interpolation) (Zhu, Pan, Huang, & Xu, 2016).

Another alternative approach is called Regional Climate Models (RCM). The use of such models stems directly from the previous considerations: the local microclimate can have significant impact on the building performances, therefore using such coarse grid data can lead to some significant differences in the main climatic variables being overlooked resulting in wrong assumptions being made in the building design. RCM models are based on limited areas and use a much denser concentration of grid points for the numerical modeling and simulation, thus being able to catch specific local microclimate trends and variations, which can often have a great impact on the performances of buildings. RCM models can usually be combined with GCMs as they use boundaries conditions deriving from GCMs.

2.2 Building Energy Simulation Fundamentals

Building energy modeling and simulation is a discipline within building science, which aim at simulating all energy uses within a building with the required spatial and temporal scale (usually hourly or sub-hourly) for the investigated time span (generally one year). The models are physics – based and include detailed building geometry descriptions, construction materials, lighting features, heating, cooling and ventilation system requirements (and interconnections between them). These models also take in consideration users' related features, including occupancy features, plug loads and thermostat settings.

Most building energy simulation tools implement the Heat Balance Method, which formulates energy and moisture balances for the zone air and solve the resulting ordinary differential equations. The most common formulation of the Heat Balance of the zone air is reported in Eq.1 (Bessoudo, Tzempelikos, Athienitis, & Zmeureanu, 2010):

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i \, A_i \, (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i \, (T_{zi} - T_z) + m_{inf} Cp \, (T_{\propto} - T_z) + Q_s \qquad (1)$$

Where:

$\sum_{i=1}^{N_{sl}} Q_i$ is the sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i \, A_i \, (T_{si} - T_z)$ is the convective heat transfer from the zone surfaces;

$\sum_{i=1}^{N_{zones}} m_i \, (T_{zi} - T_z)$ is the inter-zone air mixing;

$m_{inf} Cp \, (T_{\propto} - T_z)$ is the heat transfer due to infiltration of outside air;

Q_s is the air heating/cooling systems energy output;

$C_z \frac{dT_z}{dt}$ is the energy stored in the zone air.

$C_z = \rho \, \mathrm{C}_p \, \mathrm{C}_t$

ρ is the zone air density;

C_p is the zone air specific heat;

C_t is the sensible heat capacity multiplier. If set to 1.0, this only accounts for air capacitance, but it can be increased to higher values to account for the additional capacitance in the air loop (e.g. duct work, diffusers).

This set of equations, as well as, similar formulations for surface temperature and inter-zonal heat transfer are solved simultaneously at every simulation time step, in order to identify a dynamic set of results for the variables of interest: i.e. temperature, energy use and generation.

These models are always coupled with weather models, correlating available weather data with the building modeling tool[2]. Standard meteorological years (e.g. Example Weather Year (EWY), Test Reference Year (TRY), Design Reference Year (DRY)) are sets of meteorological data reporting values for every hour in a year (thus 8760 values) for a specific location. These data sets are usually selected from a longer time period (usually longer than ten years) and for each month in the year, the most in line with the historical database is kept in the typical weather data. Solar radiation data is usually calculated from satellite data and through the use of correlation and sky models, adapted to model solar radiation on the ground and on surfaces with variable tilt and orientation, the other variables are taken from reanalysis approaches, such as ERA Interim (Berrisford P, Dee DP, Poli P, Brugge R, Fielding K, 2011). Weather data include also all other climatic variables impactful to the building energy performance e.g. humidity, wind speed and direction, water precipitations, atmospheric pressure variations, all with one hour depth.

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[2] Dynamic building simulation software (e.g. IDA ICE and EnergyPlus) uses weather files consisting of parameter describing the weather, with a temporal resolution of at least one hour. The main variables included in the weather files are: dry bulb temperature, relative humidity, dew point temperature, atmospheric pressure, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, horizontal infrared radiation form the sky, wind speed and direction and total sky cover

Building energy simulation is of particular interest in the field of the design of buildings, as a tool to model all design choices (e.g. building form, building components and materials, etc.) with the ultimate goal of guaranteeing increased comfort conditions to the occupants while saving energy and money in the process.

Another domain is the use for building labelling and certification, whereas the simulation of building performances is used to generate a certificate highlighting the most relevant indicators of performance of the building in terms of both envelope and energy systems.

Building simulation is also mostly used in the development of the design choices within the retrofit of existing buildings to improve the performance in a process that is similar to the design of new buildings.

Finally, several applications of building simulation are available for research purposes, either for the purpose of performance assessment of new building components/systems or control logics including innovative mathematical and statistical modeling, or building neighborhood and districts analyses.

3. Modelling Climate Change

3.1 General

It was previously mentioned that data generated from GCMs cannot be used directly in future building energy uses predictions. Thus, usually two different approaches are available: statistical and building simulation approaches.

Statistical studies are usually based on the development of correlations between historical time series of both climatic parameters and building energy uses. These relationships can be used as means to predict future weather conditions, however, excluding the relationship between the building envelope and the outdoor environment.

A typical example in this field is the "degree-days" approach. The methodology is usually based upon a single-measure steady-state approach aimed at quantifying building energy uses. It is also a common approach adopted by the building industries to relate the trends of building energy consumption with local climate conditions. As an example, heating degree days are usually calculated as in eq.2:

$$Degree\ Days = \sum_{1}^{n}(Ti - Te) \quad (2)$$

Where T_i and T_e are respectively internal (indoor heating setpoint temperature) and external temperature. The advantage of this method is that it is simple and fast: through the analysis of historical temperature data for a specific site, it is possible to easily have a first indication on how relevant will energy use for heating and cooling could be. Furthermore, by creating correlations between the climate data, or by developing steady state tools correlating physical properties of the envelope of a building with degree days, simplified approaches are available in literature able to estimate a decently reliable assessment of energy consumption for heating and cooling.

While these approaches can have some limits when dealing with high – performance and complex-shaped buildings, they can provide a quick and simple first assessment of the energy uses of a building. They could be used for further climate change impacts assessments to the built environment, provided they are combined with reasonable estimations of degree days variations in the next decades.

Among the downscaling techniques available are statistical techniques (e.g., interpolation of the main climate related variables), stochastic (whereas models can derive variables stochastically from a few independent weather variables), or through the use of the "Morphing" method, which applies the monthly data from GCM or RCM to hourly pre-existing weather data files, through operations of "shift", "stretch" and a combination of "shift" and "stretch".

The results achieved from the previous step were used for development of weather data files to be used for simulation of future energy performances in a non-steady state simulation environment.

However, since solar radiation, humidity, and building characteristics such as thermal mass are not considered in degree-day analysis, studies have often found that this method can lead to large deviations when compared to energy simulations (Cellura, Guarino, Longo, & Tumminia, 2018; Guarino, Tumminia, Longo, Cellura, & Cusenza, 2022).

The alternative approach towards the prediction of future energy uses for specific future time frame or future climate change scenario lies in the use of complementing building energy simulation, already briefly discussed in the previous paragraphs, with the use of specific tools and methodologies aimed at performing climate change predictions.

Usually two approaches are available: the combination of climate projections with weather "generator" approaches, that basically generate a new, future weather data file. Weather generation approaches are based on algorithms that generate time-series of weather variables ensuring compatibility with a set of statistical parameters of the original historical weather parameters distribution. Some specific examples are reported in (Mylona, 2012), the tools COPSE (Levermore et al., 2012) and PROMETHEUS (Eames, Kershaw, & Coley, 2010). The latter is used as a basis for the publication of the UK Climate Projections to create future probabilistic reference years for use within thermal building models. The main advantages of the weather generator are seen to lie in its potentially higher spatial resolution[3], its ability to inform risk analysis and that such files, unlike ones based on observed data, carry no copyright.

Another is the 'morphing' approach (Belcher, Hacker, & Powell, 2005) which means to alter existing weather data through specific parameters which are variable on a monthly base and derive directly from RCP (Representative Concentration Pathways) predictions.

This approach is based on a mathematical procedure that generates future monthly data to generate hourly weather data to be used for building energy simulation. Every climate variable (x_o) of the existing weather data is modified by either a "shift", a "stretch" or a combination of both techniques.
Shifting operation basically raises or reduces all values of the time series by a specific value for each month of interest.

For example, the future hourly atmospheric pressure (p) could be calculated directly from the present hourly value of the atmospheric pressure (p_0) and from the monthly increment in atmospheric pressure (Δp_m), as in the following equation:

$$p = p_0 + \Delta p_m \tag{3}$$

whereas the subscript "0" relates to currently used weather data files, "m" is referred to monthly data, while the absence of subscripts implies that the term refers to future data.

The operation of "stretching" refers instead to the possibility of proportionally perform variations in climate parameters by using scaling factors. It is mostly useful if the climate change forecasts are available as a fractional monthly change. For example for the global horizontal radiation (r), an increase for monthly average solar shortwave flux received at the surface (Δr_m) is obtained. A scaling factor for the month m (α_{rm}) is calculated from the absolute variation (Δr_m) and the monthly mean ($\overline{r}_{0m}$) from the baseline climate as in the following equation 4:

$$\alpha_{rm} = 1 + \frac{\Delta r_m}{\overline{r}_{0m}} \tag{4}$$

This scaling factor is then multiplied to all months m in the time series using the following equation:

$$r = \alpha_{rm}\, r_0 \tag{5}$$

where r_0 is the hourly current global horizontal radiation, r is the global horizontal radiation.

A further operation to be potentially performed is the simultaneous occurrence of both the previously described techniques. An operation of simultaneous shift and stretch is used for climatic variables such as dry-bulb temperature to reflect changes in both the daily mean and the peak daily values. For the dry-bulb temperature taken as example the following parameters are assessed: the monthly daily mean temperature variation (Δt_m), the monthly daily maximum temperature variation ($\Delta t_{max,m}$) and the monthly daily minimum temperature variation ($\Delta t_{min,m}$).

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[3] Spatial resolution is intended as a measure of the smallest object that can be analysed by a climate model (e.g. in degrees of latitude and longitude or in km).

Using $\Delta t_{max,m}$ and $\Delta t_{min,m}$, the scaling factor for the dry-bulb temperature (α_{tm}) is calculated through the following equation, using monthly mean values from both the current and future data:

$$\alpha_{tm} = \frac{\Delta t_{max,m} - \Delta t_{min,m}}{\overline{t}_{0max,m} - \overline{t}_{0min,m}} \tag{6}$$

where $\overline{t}_{0max,m}$ and $\overline{t}_{0min,m}$ are the monthly mean of the current daily maximum temperature and the monthly mean of the current minimum daily temperature, respectively (Cellura et al., 2018).

Thus, when the previous parameters have been calculated it is possible to determine the future hourly variable dry bulb temperature through the following equation:

$$t = t_0 + \Delta t_m + \alpha_{rm} (t_0 - \Delta t_{0,m}) \tag{7}$$

where t_0 is the present hourly dry-bulb temperature and $\Delta t_{0,m}$is the monthly mean temperature variation in the current climate for the month m.

Table 1 shows the methodology applied to the climate variables contained in the weather file.

Table 1: Methodology used for each modified climate variable.

EPW climate variable	Unit	Method
Dry bulb temperature	[°C]	Combination of a shift and a stretch operation
Relative humidity	[%]	Shift operation
Dew point temperature	[°C]	Calculated based on morphed dry bulb temperature and morphed relative humidity using psychometrics formulae
Atmospheric pressure	[Pa]	Shift operation
Global horizontal radiation	[Wh/m2]	Stretch operation
Direct normal radiation	[Wh/m2]	Calculated based on global horizontal radiation using solar geometry equations
Diffuse horizontal radiation	[Wh/m2]	Stretch operation
Horizontal infrared radiation form the sky	[Wh/m2]	Calculated from morphed values for cloud cover, dry bulb temperature and vapour pressure
Wind speed	[m/s]	Stretch operation
Total sky cover	[tenths of sky]	Stretch operation

3.2 Final Considerations

The different approaches tend to be recognized as effective in different domains: it is generally accepted that the morphing method is particularly effective provided the original weather data are detailed enough and able to adequately describe the variability of the local climate. However, since most commonly climate data used in building practice uses average and conservative values, statistical and stochastic approaches tend to be, more effective in the description of extreme climate change events, thus often causing higher peak power estimations for heating and cooling, although more computationally intensive (Moazami, Nik, Carlucci, & Geving, 2019).

Finally, it is useful to mention some official organizations in some countries which are currently providing future weather files, such as UK (CIBSE, 2022) or Germany (DWD, 2022).

4. Developments and Future Trends

In this section some results from research on the topic of effects of global warming to energy use will be investigated with a focus on research in the European area as an example[4]. Variation trends on temperature and the main climatic parameters will be shown, as well as, corresponding variations in energy uses for heating and cooling.

The research from (Cellura et al., 2018) is taken as example and focuses on the European context using some of the techniques mentioned in the previous section. In this case, the approach to the modeling and simulation of the effect of global warming is developed using dynamic building energy simulation. The building modeled is a simple detached building, based on one thermal zone enclosure, with non-residential use. The study develops a wide range of parametric analyses based on a set of different cities across Europe, choosing specific envelope features for the building, according to the existing local legislation in place and performs a downscaling of GCM data (CESM1(Cam5)) using the morphing method to address the impact of global warming to the cooling and heating energy needs of the building sector, across the different RCP scenarios investigated by IPCC.

The application of the morphing method to the currently available weather data files by using the climate forecasts for 2035, 2065, 2090 of the IPCC, delivers the results reported in Figures 2 and 3. In particular, Figure 2 reports variation in air dry bulb temperature for 2035 in business as usual (BAU) scenarios in both the RCP 2.6 and 8.5 IPCC scenarios. All cases report significant increases of the average air temperature. In the best case scenario (RCP 2.6) the average temperature is supposed to increase between 1.6 °C (Barcelona, Pisa, Palermo) and 1.9 °C (Thessaloniki). On the other hand, the BAU scenario shows temperature increases variable between 1.92° C in Palermo and 2.56 °C in Thessaloniki.

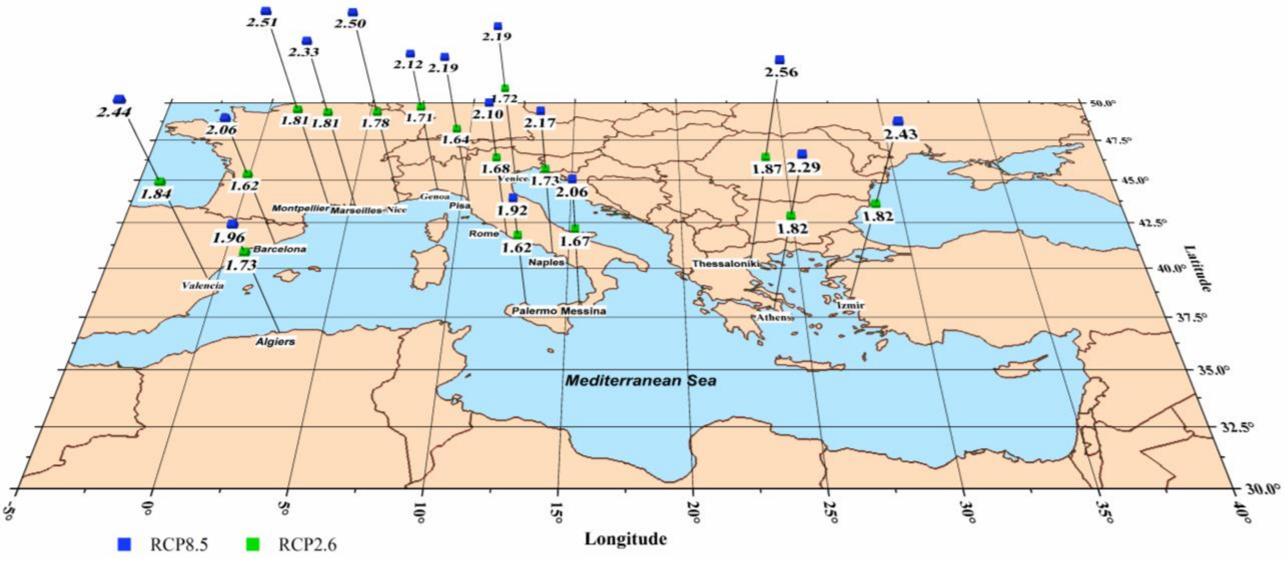

Figure 2: Variation of air temperature forecasts according to RCP 2.6 and 8.5 for 2035.

Similar trends can be found also in the case for 2090 (Figure 3), whereas the increases of average temperature become more substantial: on average the increases in the RCP 2.6 scenario is equal to 2.1 °C while it is 5.3° for the RCP 8.5. In the first case the lowest values are reported for Palermo, equal to 1.8°C, while the highest for France (2.4°C, Montpellier and Nice). Scenario 8.5 shows that the trends for Valencia

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[4] Climate Change will also have significant impacts on embodied energy use and impacts (i.e. installation of cooling devices in cold dominated countries) that are however beyond the scope of this report.

show the highest increase in average annual temperature (6.1°C) while the lowest increase is reported for Palermo (4.4 °C).

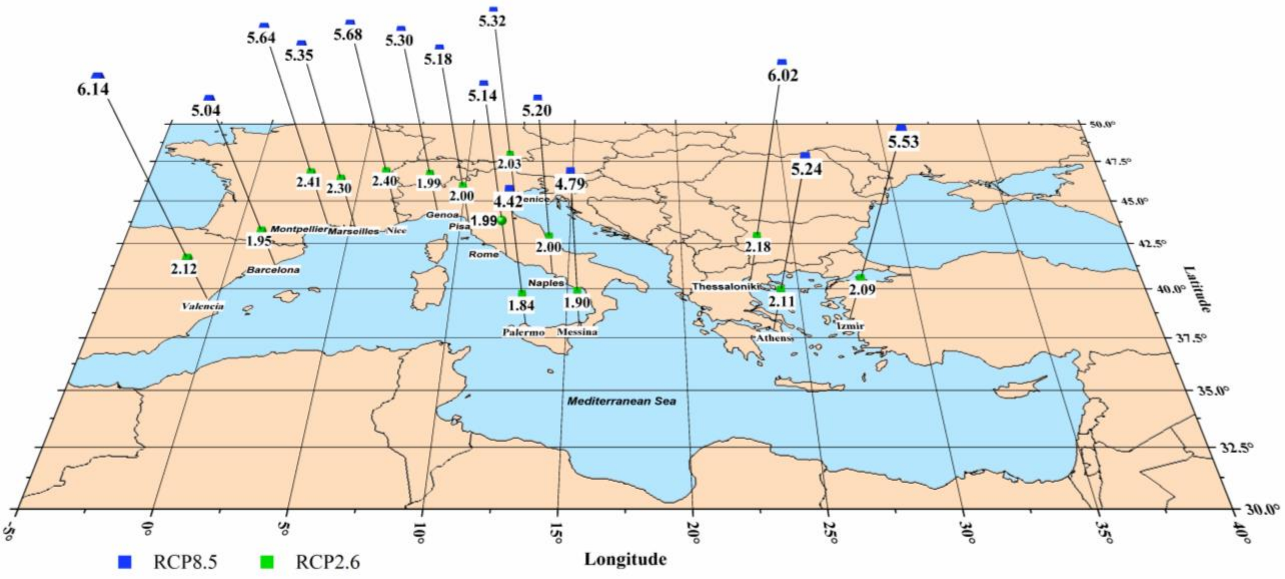

Figure 3: Variation of air temperature forecasts according to RCP 2.6 and 8.5 for 2035.

Also monthly variation data is reported in Figure 4 for all cities investigated. The RCP 2.6 data air temperature for 2090 report increases variable between 0.79°C in January (Thessaloniki) to 3.05°C in August (Nice). These data increase significantly for the case of RCP 4.5 up to 4.73 °C in July (Valencia) and 1.77 °C in November (Venice) and RCP 6.0, whereas these values reach an increase of 1.85 for January (Izmir) and 6.07 in June (Nice). The highest values fall into the RCP 8.5 category as the increase in air temperature ranges between 3.04 °C in January and 8.98 °C in Thessaloniki.

All these variations on air temperature have of course implications on the expected heating and cooling energy uses in buildings. According to the specific scenarios developed in (Cellura et al., 2018), the expected following heating and cooling demand can be traced throughout Table 2.

Table 2 shows the variability within all the investigated cities of the heating/cooling energy required to meet the heating setpoints of 20°C in winter and 26°C in summer, expressed in kWh of final nergy of cooling/heating per m^2 of walkable area. The future heating/cooling energy required requirements were calculated considering an ideal building model built in TRNSYS environment (Klein, 1988). In detail, for all the sites analysed a low-rise building model is used as ideal case study with a total heated area of 81 m^2. An isolated one-storey high building was chosen to adopt the worst conditions for cooling since climate change will most likely increase this typology of energy use in the future. Since the typical lifetime of buildings is in the range of 50–100 years and in order to ensure representativeness the buildings modelled, the building envelope features are chosen in compliance with the minimum requirements for a new non-residential building in force each country analysed (IEA, 2017). In particular, the U value for vertical surfaces varies from 0.28 W/(m^2 K) in Venice to 1 W/(m^2 K) in Thessaloniki. All walls have an internal mass layer (brick, 30 cm for external walls) and external insulation, the thickness of which varies as function of the city analysed and the regulations in force. The average global window U-value varies from 1.4 W/(m^2 K) (Venice) to 3W/(m^2 K) (Palermo).

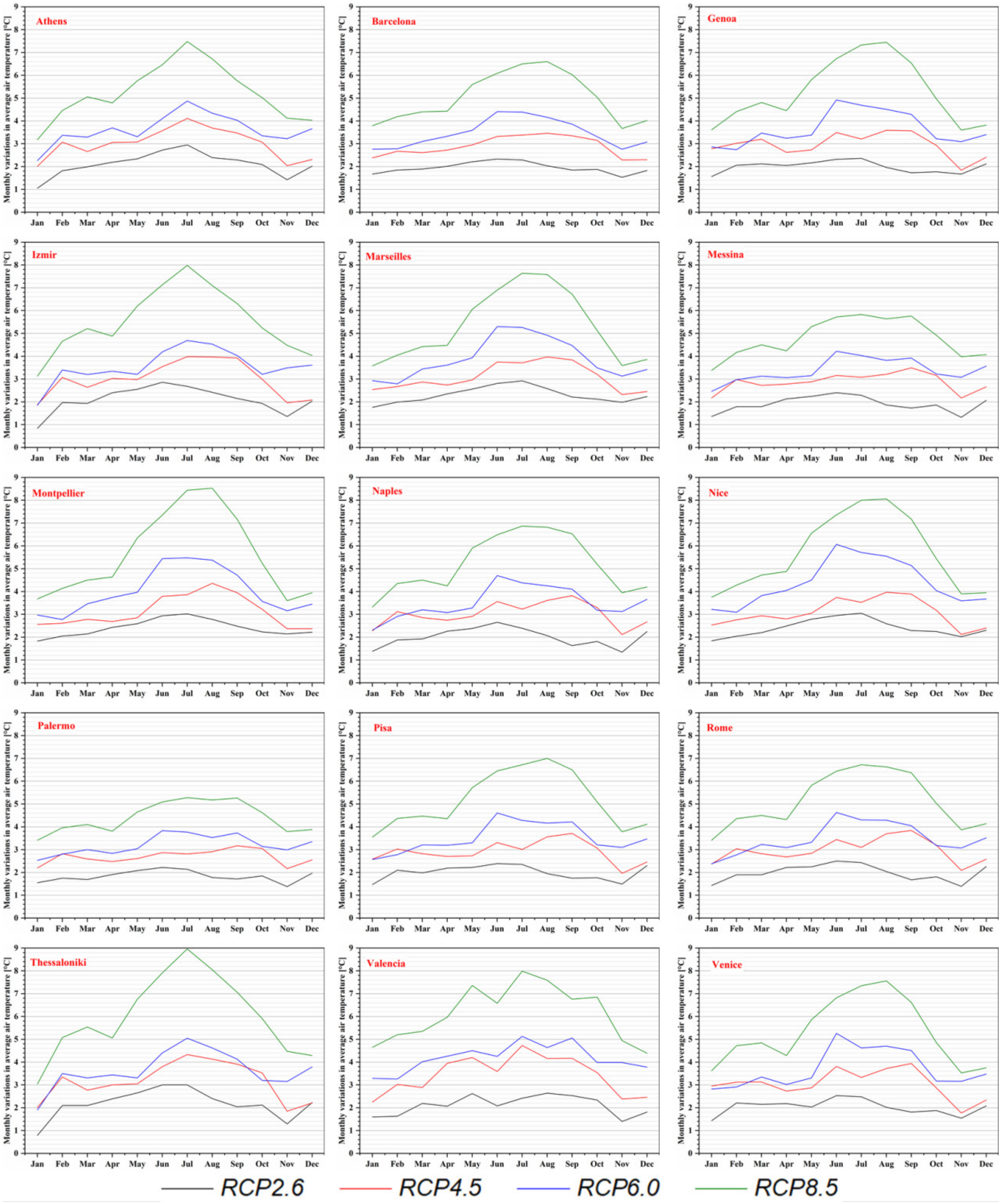

Figure 4: Monthly variations in average air temperature, scenarios RCP 2.6 to 8.5.

Table 2: Future heating and cooling energy demands.

	Today		2035							
	Heating [kWh/m^2]	Cooling [kWh/m^2]	Heating [kWh/m^2]				Cooling [kWh/m^2]			
			RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Marseille	43.33	24.98	33.52	32.88	34.65	31.81	42.73	46.67	42.05	48.02
Montpellier	43.80	18.78	35.67	34.56	36.52	32.55	36.75	41.73	36.78	42.95
Nice	30.97	16.33	21.26	20.71	20.3	19.15	31.66	35.01	32.46	37.24
Athens	33.18	35.65	24.44	24.06	24.93	22.32	57.97	58.67	54.81	62.8
Thessaloniki	59.88	26.04	48.88	45.6	50.47	44.69	49.11	46.05	45.58	55.5
Genoa	33.36	17.71	29.19	28.68	30.76	29.1	36.17	39.21	35.04	40.8
Messina	14.51	34.71	8.69	8.77	9	8.62	48.19	51.16	46.05	53.88
Naples	31.11	23.89	22.1	21.59	23.72	20.94	40.79	42.26	38.25	44.8
Palermo	13.22	29.64	6.96	6.77	7.84	6.59	43.22	44.06	41.01	46.44
Pisa	46.55	17.55	36.88	35.9	38.15	35.17	30.88	33.21	29.97	35.71
Rome	31.77	21.91	23.71	23.57	25.11	22.88	36.16	38.34	34.48	40.24
Venice	76.06	13.08	62.19	61.88	64.79	61.36	29.38	32.32	28.63	34.67
Barcelona	37.43	15.45	26.55	24.75	28.07	24.79	29.71	32.8	29.51	33.41
Valencia	24.83	23.89	22.82	22.63	22.79	20.22	48.93	51.26	47.55	53.31
Izmir	43.27	33.90	33.96	33.96	34.54	31.09	59.08	59.07	55.67	66.19

	Today		2065							
	Heating [kWh/m^2]	Cooling [kWh/m^2]	Heating [kWh/m^2]				Cooling [kWh/m^2]			
			RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Marseille	43.33	24.98	31.44	29.47	27.27	22.46	46.73	52.74	50.65	65.99
Montpellier	43.80	18.78	33.32	31.42	28.76	23.9	40.37	47.54	44.8	61.42
Nice	30.97	16.33	19.42	17.63	14.95	11.78	34.61	40.48	40.18	54.45
Athens	33.18	35.65	23.73	20.69	18.94	14.58	59.71	65.25	66.55	79.75
Thessaloniki	59.88	26.04	48.69	43.45	39.21	32.84	48.98	56.61	53.03	73.8
Genoa	33.36	17.71	28.15	25.49	24.9	20.06	38.52	45.09	41.64	57.64
Messina	14.51	34.71	8.49	7.34	6.03	5.12	51.99	56.94	55.15	71.21
Naples	31.11	23.89	21.1	18.77	17.37	13.89	42.67	47.75	46.98	62.35
Palermo	13.22	29.64	6.34	5.21	4.49	3.12	45.93	49.5	49.92	62.22
Pisa	46.55	17.55	34.37	31.88	31.21	24.43	33.5	38.34	37.47	50.78
Rome	31.77	21.91	22.52	20.4	19.09	14.99	38.53	43.38	42.28	56.1
Venice	76.06	13.08	60.56	56.1	55.73	47.62	31.8	37.39	36.03	49.45
Barcelona	37.43	15.45	24.32	21.49	20.28	15.05	33.02	37.52	35.56	48.09
Valencia	24.83	23.89	20.89	19.78	18.26	13.71	52.57	59.12	59.04	76.56
Izmir	43.27	33.90	32.41	30.49	28.15	21.78	60.53	66.76	68.29	81.94

	Today		2090							
	Heating [kWh/m^2]	Cooling [kWh/m^2]	Heating [kWh/m^2]				Cooling [kWh/m^2]			
			RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Marseille	43.33	24.98	30.34	27.5	24.38	20.87	45.86	54.51	61.47	78.97
Montpellier	43.80	18.78	31.42	29.83	26.01	22.41	39.94	49.05	56.37	76.71
Nice	30.97	16.33	17.98	16.18	12.05	10.39	34.58	41.83	50.47	67.44
Athens	33.18	35.65	22.58	18.4	14.95	11.33	60.88	70.09	74.94	96.34
Thessaloniki	59.88	26.04	46.57	40.11	37	26.42	51.71	61.9	66.66	93.21
Genoa	33.36	17.71	27.44	23.75	22.43	17.95	37.46	46.41	53.28	70.43
Messina	14.51	34.71	8.39	5.87	5.76	3.84	51.62	59.07	65.06	81.23
Naples	31.11	23.89	20.64	16.52	15.23	11.1	42.26	51.01	55.71	73.97
Palermo	13.22	29.64	6.27	4.29	3.71	2.22	45.4	52.74	57.29	70.63
Pisa	46.55	17.55	34.06	29.78	27.31	21.62	32.53	40.16	45.22	61.2
Rome	31.77	21.91	22.24	18.32	17.14	12.7	38.05	45.77	50.65	66.93
Venice	76.06	13.08	60	53.64	49.46	43.43	31.37	40	44.91	62.1
Barcelona	37.43	15.45	24.2	19.95	18.13	12.39	31.55	39.12	44.41	58.68
Valencia	24.83	23.89	21.77	18.55	14.9	10.95	51.68	66.57	71.08	96.08
Izmir	43.27	33.90	31.99	27.48	23.73	17.51	61.69	71.86	76.97	102.16

The immediate trend easily recognizable leads to a large increase in cooling in the next years with a sizable reduction instead in heating requirements as well. Table 2, in particular shows very variable results: the simulations for 2035 identify a high increase in cooling, reaching on average 81% for RCP 2.6, 91% in the case of RCP 4.5, 75% for RCP 6.0 and 104 % in the scenario RCP 8.5, if compared to current standards. On average, RCP 2.6 scenarios show an **average increase** in cooling requirements of 20.2 kWh/m^2 while for the 8.5 scenarios, this value reaches 53.5 kWh/m^2.

A similar but reversed trend is to be expected for heating demand, with reductions in impact for heating variable on average between 24.6% for the RCP 2.6 scenario up to 29.1% for scenario RCP 8.5 for 2035. For 2090 instead, on average, the decrease in heating requirements is thus expected to be reduced by 18.5% in scenario RCP 2.6, and by 27.9%, 33.8 and 58.3% respectively for the other scenarios (RCP 4.5, 6.0, 8.5).

As reported in Table 3, previous studies already analyze the effect of a warmer climate on building energy performances (Jiang, Liu, Czarnecki, & Zhang, 2019; Kikumoto, Ooka, Arima, & Yamanaka, 2015; Liu et al., 2020) in the USA (Shen, 2017; Shen & Lior, 2016), in Canada (Berardi & Jafarpur, 2020; Robert & Kummert, 2012), in Australia (Wang, Chen, & Ren, 2010), in Asia (Chan, 2011; Huang & Hwang, 2016) and in Europe (Farrou, Kolokotroni, & Santamouris, 2016; Jentsch, Bahaj, & James, 2008; Roux, Schalbart, Assoumou, & Peuportier, 2016) using as input different GCMs, climate change scenarios, future time slices. In this context, the scientific community seems to agree that climate change will have a negative effect on the energy performance of buildings (Ivan Andrić, Le Corre, Lacarrière, Ferrão, & Al-Ghamdi, 2021), but regardless of building sizing and modeling assumptions, the common perspective is that cooling in buildings is going to have a more relevant impact on building energy performances in the next decades than today.

Table 3: Summary of research on the effect of the climate change on building energy performances.

Country	Future time slices	Climate change Scenarios	Main research findings	Ref.
Southampton (UK)	2020, 2050 and 2080	UKCIP02	The study describes a method for the integration of future UK climate scenarios into the EnergyPlus weather file formats and demonstrates the importance of climate change analysis through a case study example. Simulations of a case study building (university of Southampton office building) highlight the potential impact of climate change on future summer overheating hours inside naturally ventilated buildings.	(Jentsch et al., 2008)
25 locations throughout the world	2100	IPCC TAR	The study presents a methodology to create weather files which represent climate change scenarios in 2100 and heat island impacts today, considering 25 locations throughout the world. Moreover, examples of how heat island and climate change scenarios affect the annual energy performances of small office building case study for three (cold, tropical and temperate cliomates) of the 25 locations investigated haare showed. In cold climates, the net change to annual energy use due to climate change will be positive – reducing energy use on the order of 10% or more. For tropical climates, buildings will see an increase in overall energy use due to climate change, with some months increasing by more than 20% from current conditions. Temperate, mid-latitude climates will see the largest change but it will be a swapping from heating to cooling, including a significant reduction of 25% or more in heating energy and up to 15% increase in cooling energy.	(Crawley, 2008)
Alice Springs, Darwin, Hobaùrt, Melbourne and Sydney (Australia)	2050 and 2100	IPCC TAR	The study investigates the potential impact of climate change on the heating and cooling energy requirements of residential houses in five regional climates varying from cold to hot humid in Australia.. The total heating and cooling energy requirements would vary significantly under different climate change scenarios. In the temperate climates of Sydney, for example, in 2100 the increase in the total heating and cooling energy consumption would be 120% and 530% when the global temperature increases by 2 °C and 5 °C, respectively.	(Wang et al., 2010)

Hong Kong (China)	2011-2030, 2046-2065, 2080-2099	IPCC TAR	The aim of the study is to develop a set of Hong Kong hourly weather data files for building energy simulation use, incorporating the future climate change. Moreover, the impact of climate change on building energy consumption in office and residential buildings under different emission scenarios are also evaluated. The results indicate that there will be substantial increase in air-conditioning energy consumption under the impact of future climate change, ranging from 2.6% to 14.3% and from 3.7% to 24% for office building and residential flat, respectively.	(Chan, 2011)
Montréal and Massena (Canada)	2020 - 2050	IPCC TAR	The research investigates the use of the downscaling method to generate hourly future weather data files. The impact of using these weather files on the energy performance of an NZEB case study is then assessed. The results show that the net-zero target is missed for most of the future climate change scenarios investigated.	(Robert & Kummert, 2012)
10 different cities (USA)	2040-2069	IPCC TAR	In the study, future hourly weather are used to predict future performance of renewables energy systems for low energy residential buildings in 10 different climate zones in the USA. The results show that buildings with the present configurations of renewable energy systems will be losing their capability to meet the zero-energy goal in half of the considered climate zones.	(Shen & Lior, 2016)
Taipei (Taiwan)	2020, 2050 and 2080	IPCC TAR	Hourly future weather year series for Taipei, Taiwan, are constructed. Using these future weather data, buildings thermal performances are assessed considering an ideal residential apartment building. The simulations reveale increases in cooling energy by 31%, 59%, and 82% in the three time slices investigated (2020, 2050 and 2080).	(Huang & Hwang, 2016)
Iraklio, Thessaloniki and Patra (Greece)	2020, 2050 and 2080	IPCC TAR	This paper presents results of a study of the impact of future climate change scenarios for the three climatic regions of Greece on the design of the envelope of a hotel building.The simulation results indicate a mean increase in the cooling energy demand by 34% in 2050 and 63% in 2080 if compared to today. On the other hand, heating energy demand is expected to decrease by 29% in year 2050 and 46% in year 2080.	(Farrou et al., 2016)
Macon (France)	2035, 2055, 2085	IPCC AR5	The objective of this study is to evaluate life cycle impacts of residential buildings, integrating climate change and evolution of the energy mix on the long term. The results show that heating energy demand could decrease from 24 to 44%, whereas cooling energy demand could increase also by a factor 8.	(Roux et al., 2016)
Lisbon (Portugal)	2050	IPCC TAR	The main goal of this paper is to develop a methodology for assessing the future heat energy demand on a large scale (districts/cities), taking into account both direct and indirect impacts of climate change on district heat demand. The results suggest that heat demand density could decrease within the range of 22.3–52.4% in 2050 compared to 2010, depending on weather and renovation scenario studied.	(I Andrić et al., 2016)
Philadelphia, Chicago, Phoenix and Miami (USA)	2040 - 2069	IPCC TAR	The goal of this research is understand building energy use pattern to the year of 2050 in United States by means of projecting future hourly weather data for building simulation tools. Case studies in four representative cities in the U.S. show that climate change is to have great impacts on residential and office building energy use during the years of 2040–2069. The change of yearly energy use is predicted to be variable from -1.64% to 14.07% for residential building. Moreover, the growing peak electricity load during cooling seasons is going to exert greater pressure for the future grid.	(Shen, 2017)
Guangzhou (China)	2020, 2050 and 2080	IPCC TAR	This study investigated the potential impact of climate change on the total energy consumption of housing sector in Southern China. The indoor temperatures in 2020s, 2050s and 2080s will increase by 0.82 °C, 1.91 °C and 3.41 °C, respectively. The total heating and cooling energy use of 3.5 and 5.5 star-buildings are projected to increase by 25% and 20% respectively with a 1.0 °C global warming.	(Song & Ye, 2017)
Geneva (Switzerland)	2010-2039, 2040-	IPCC TAR and IPCC AR5	The study provides an overview of the major approaches to create future weather data sets based on the statistical and dynamical downscaling of climate models. A number of weather	(Moazami et al., 2019)

	2069 and 2070-2099		data sets for Geneva were synthesized and applied to the energy simulation of 16 ASHRAE standard reference buildings (non-residential buildings), single buildings and their combination to create a virtual neighborhood. Depending on the type of building, the relative change of peak load for cooling demand under near future extreme conditions can still be up to 28.5% higher compared to typical conditions. Moreover, the analysis of the virtual neighborhood revealed that the peak electric power demand for the neighborhood can increase by 4.0%, 7.6% and 16.8% under near-term, medium-term and long-term future scenarios.	
Hong Kong (China)	2035, 2065 and 2090	IPCC AR5	The study aims to evaluate the impacts of climate change on the building energy demand and indoor thermal comfort of mixed-mode residential buildings in Hong Kong using the adaptive thermal comfort model as the thermal comfort criterion. The results indicate that by the end of this century, the indoor discomfort percentage in the cooling seasons are expected to increase from 21.9% to 36.0% and 50.4% under RCP4.5 and RCP8.5 scenarios, respectively, while the annual cooling load is expected to increase up to 278.80%.	(Liu et al., 2020)
Different location (Belgium)	2080	IPCC AR5	The study presents Heating Degree Days (HDD) and Cooling Degree Days (CDD) maps for Belgium for the current and future climate perspective considering the RCP8.5 climate change scenario. The results show a decrease of the HDDs with 27% between 1976–2004 (3189 HDD) and 2070–2098 (2337 HDD). In contrast, the CDD were found to increase with a factor 2.4 from 167 CDD to 401 CDD in the same timeline. Smaller reductions in average HDD were moreover found in urban areas compared to rural areas. For the CDD, a higher absolute increase was found for urban areas and the Northeast of Belgium.	(Ramon, Allacker, De Troyer, Wouters, & van Lipzig, 2020)
Toronto (Canada)	2070	IPCC TAR and IPCC AR5	The study investigates the effects of climate changes on the heating and cooling energy demand of buildings in the city of Toronto using ASHRAE standard reference buildings (non-residential buildings) as building models . The results show an average decrease of 18%–33% for the heating energy use intensity, and an average increase of 15%–126% for the cooling energy use intensity by 2070, depending on the baseline climatic file of use and building typology. The results also demonstrate the need to perform building modelling with sensitivity analysis of future climate scenarios in order to design more resilient buildings.	(Berardi & Jafarpur, 2020)
10 different cities (China)	every year for 2020 to 2099	IPCC AR5	The study used a building simulation-based method to predict the life cycle energy performance of residential buildings in different climate zones of China. It finds that compared with the data of the current weather files, the average temperature will increase from 5.36 °C to 2.72 °C and 2.53 °C to −0.21 °C by the end of this century in RCP 8.5 and RCP 2.6, respectively. Moreover, compared with the energy demand under the weather conditions of the current weather files, the changes in life cycle heating energy and cooling energy will be 33.9 kWh/m2 and 11.2 kWh/m2 in RCP 2.6, 40.2 kWh/m2 and 17.4 kWh/m2 in RCP 8.5.	(Zou, Xiang, Zhan, & Li, 2021)

Cooling requirements may double or triple if compared to current trends, with corresponding reductions in heating requirements. This will potentially result in a reduced use of natural gas and other fossil fuels combusted for heating and, at the same time, in the increase in electricity demand used to power cooling systems. For countries with a predominantly coal-based electricity mix, this evolution will lead to increasing levels of GHG emissions associated with building operation, if the current carbon intensity of their mix remains unchanged in the future.

These trends can also have unforeseen consequences. It is possible to expect i.e. relevant cooling in traditionally “cold” countries, with unexpected increases also of embodied energy tied to the production and acquisition of new cooling machines and HVAC systems.

This will also result in other impacts related to the ongoing global warming, resulting a vicious cycle that may lead to increase of carbon emissions and heat island effect pushed by an increase in cooling demand and thus further contributing to global warming.

Besides the provisional nature of the studies previously discussed, it is also worth discussing another relevant aspect within the methodologies of energy use assessments and in particular within morphing modeling.

It has already been previously mentioned that several provisional models exist, within the Global Circulation approaches. Choosing one model over another means to have a second layer of uncertainty which is based upon the assumptions and modeling choices performed at the GCM modeling stage, which are translated into the air temperature provisional trends and also on the energy uses for air conditioning assessments.

Figure 5 shows an example of variability between average temperature during the years in the future in the time slice investigated by RCP scenarios, by showing the monthly future projections developed by different GCM, chosen in a limited number for the sake of brevity. Increases in air temperature between the various models for e.g. RCP 4.5 amount to 2.4 °C in the case of ACCESS 1.3 and 3.3 for HadGEM”-CC at the end of the century, while these values are higher for RCP 8.5 reaching +5°C in the case of ACCESS 1.3 and HadGEM2-CC.

It is worth mentioning that while the trend in air temperature is rather common among all results from the alternative models, relevant different can be traced up to +2°C between the outputs of different models. Moreover, model ACCESS 1.3 performs forecasts that are higher than the others for about 50% of the months of investigation, while ACCESS 1.0 shows the most moderate data. This of course does not in any way aim at giving substantial and quantitative indications on the aforementioned models, since the data used refer to a specific point in a grid which covers in most cases the whole world and on a specific climatic parameter among a very wide range. However, since the focus is on the modeling of consequences in relation to global warming within the building and real estate sector, these uncertainties on one of the more relevant parameter to building energy performances need to be taken in consideration.

If dynamic building energy simulation is performed, the results from the lower section of Figure 5 can be found. The same substantial variability between energy uses for heating and cooling can be traced for both RCP 4.5 and 8.5 that was envisaged in Figure 5. In this specific case for example, RCP 4.5 results can vary as much as 35% simply by choosing one data source or another, if cooling is concerned.

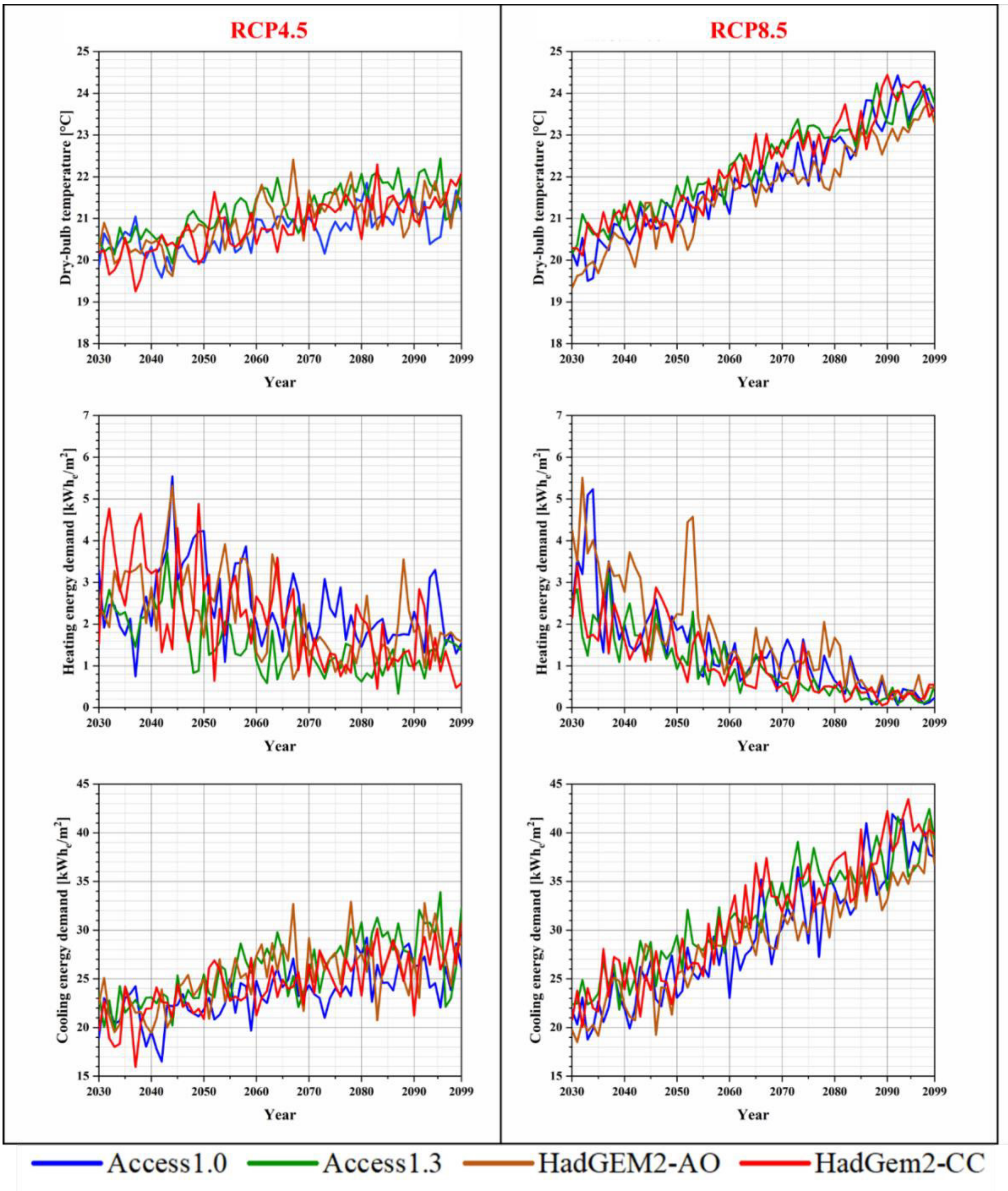

Figure 5: Variation in temperature trends between 2030 – 2090, RCP 4.5 and 8.5 for the city of Palermo – Italy and future heating and cooling energy demand within the RCP4.5 and RCP8.5 scenarios.

5. Final Remarks

Predicting the evolution of global warming in the next decades is by itself a very complicated matter with considerable implications and potential ramifications for the political, technical, environmental domains. The application to the construction and real estate sector of climate change analyses are paramount: since buildings usually have an expected life span of around a century, meaning what is being built today needs to be able to withstand the evolution of climate in the coming decades/century, therefore pointing to the research gap of climate resilience which needs to be integrated and considered in building and energy systems design for the future. Furthermore, appropriate modeling and techniques which are able to quantitatively integrate these considerations early in the design phase in order to correctly size systems and design buildings.

The approach towards the modeling of the effects of climate change is usually performed through the use of specific modeling techniques, mostly developed within climate science research with coarse resolution and mostly oriented to large scale variations of the parameters of interest. Specific techniques of downscaling are able to derive averaged values for use in more specific applications for site specific analyses, otherwise other techniques involving more refined and detailed meshing and calculations are available and usable, either making a combined use of GCM and RCM or through statistical trend analyses and future projections. The techniques used for future climate assessment in the building sector include statistical means and morphing of existing and available datasets, with a wide range of variability and different potential results in using all these techniques.

Nevertheless, the approaches proposed are most of the time limited to the use of specific research domains, where it is now in most cases accepted that the constraints coming from global warming should be included in the design of buildings, but these are concerns that do not properly invest the practitioner’s community. This is for sure due to the limited availability of easy to use (and not time-consuming) tools that may allow practitioners to simply implement these kinds of analyses into their design.

While this is understandable, it is of undeniable concern in the near future that severe spikes in cooling needs could put the current energy systems in crisis. Furthermore, this aspect could be more severe in countries with the highest construction rates (especially in northern Africa and in Asia), which tend to often use well known 'International' architectural styles without including bioclimatic aspects in the design.

Climate change could cause worsening of current issues of high performance buildings such as overheating even in non-traditionally cooling dominated countries, coupled with a large increase in power generation needs for cooling. Moreover, this aspect could also lead to an increase in the buildings embodied energy, due to a greater use of new systems and solutions to counteract overheating. Therefore, future research should not only focus on studying the effects of climate change on the buildings energy use, but extend these boundaries and investigate the relationships between climate change and the entire building life cycle. Thus, it becomes of fundamental importance to integrate, as well as the effects of climate change, the life cycle perspective in an integrated and multidisciplinary design approach of buildings, through the use of the Life Cycle Assessment method, a well-established methodology for assessing the environmental impacts along the building life cycle from extraction, manufacturing, transportation, operation, maintenance and end of life.

LCA is an important instrument to help reduce the overall environmental burden of buildings and provide insights into their overall energy and environmental performance. Since LCA approaches cover the whole lifespan of a building, the assessment of its long-term performances and its related impacts are challenging, especially so if climate change is considered.
As such, approach Life Cycle Assessment using merely one average year means neglecting the variability of the impact an evolving climate might have on the building, which was shown to be significant in previous

chapters. For these reasons, the impact of future climate change on the energy performance of buildings, according to projections of future weather data, is relevant and shall be considered in building LCA.

It is thus crucial to develop corresponding official scenarios and datasets for future climate evolution. Datasets should be based on future climate scenarios aiming at achieving the resilience of buildings to climate change.
This will have a significant impact on the results and might lead towards a shifting towards cooling for heating dominated countries and a reduction in heating energy use which may have additional repercussions also on the Life Cycle performances of the building (e.g. increase in use of cooling equipment).

To conclude, the methodologies proposed are in all cases valid and efficient with slightly different strengths and applicability suggestions: it is however necessary for the future of building energy simulation, either practitioners or in research, to adopt one. Results can vary slightly according to the modeling choices performed, however global warming will vastly impact also the energy uses of the building sector in the close future: not fully addressing it from the early stage of the building design will not solve the problem and could potentially – as already mentioned – worsen it.

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Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results

A Contribution to IEA EBC Annex 72

February 2023

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Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023)
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023)
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023)
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023)
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023)
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023).
- Basics and Recommendations on Discounting in LCA and Consideration of External Cost of GHG Emissions (Szalay et al. 2023)
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023)
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023)

It is important to mention that parts of the analysis of service lives of building components in this report is based on a survey among experts which was realized during the first half of 2019. The authors would like to acknowledge the following survey contributors: Greg Foliente (Australia), Alexander Passer (Austria), Damien Trigaux (Belgium), Vanessa Gomes (Brazil), Antonin Lupisek (Czech Republic), Harpa Birgisdottir (Denmark), Bruno Peuportier (France), Thomas Lutzkendorf & Maria Baloutski (Germany), Chi Kwan Chau (Hong Kong), Eri Alsema (Netherlands), Dave Dowell (New Zealand), José Silvestre (Portugal), Tajda Potrc Obrecht (Slovenia), Antonio Garcia & Bernadette Soust-Verdaguer (Spain), Alice Moncaster (United Kingdom) and Manish Dixit (United States of America).

Summary

The operational and embodied GHG emissions are recorded and evaluated in a life cycle analysis of buildings. The embodied emissions are composed of the modules A1-A5 (upfront), B2-B5 and C1-C4. For reasons of simplification, concrete calculations usually focus on A1-A3, B4, C3-C4.

Module B4 makes a significant contribution to the results of a building LCA. Components and systems that are either replaced very frequently or cause high environmental impacts (initially and when replaced) are important. For the modelling of B4, there are different methodological questions for which methods need to provide answers. This is the aim of this report. It particularly discusses the service lives definitions, the service life values of building components/elements and their related uncertainties and variabilities based on values found in literature as well as default values used in A72 countries. The latter values were collected based on a survey among A72 experts. This report also illustrates the consequences/ influence on the result of the variability of service life values of building components, the replacement rate calculation method and the reference study period on the basis of a case study. Finally, recommendations are provided.

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Abbreviations

Abbreviations	Meaning
BITS	building integrated technical systems
CEN	European Committee for Standardization
CRB	Kompetenzzentrum für Standards in der Bau- und Immobilienwirtschaft
DHW	domestic hot water
eBKP	der elementbasierte Baukostenplan
ESL	estimated service life
EPD	environmental product declaration
GHGe	greenhouse gas emissions
ISO	International Organization for Standardization
LCA	life cycle assessment
LCC	life cycle costing
PDF	probability density functions
RSL	reference service life
RSP	reference study period of the building
SIA	The Swiss Society of Engineers and Architects
SL	service life of the material

Definitions

Component: item manufactured as a distinct unit to serve a specific function or functions. A **building component** is a part of a building, fulfilling specific requirements/functions (e.g. a window or a heating system). The service life of a building component can be shorter than the full service life of the building. Building components are sometimes referred to as “building elements” (ISO 21931-1:2022).

Environmental Product Declaration (EPD): claim which indicates the environmental impacts and aspects of a product, providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information (prEN 15978-1:2021).

Life cycle Assessment (LCA): LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a building, infrastructure, product or material throughout its lifecycle (ISO, 2006).

1. Context

Buildings are a combination of a variety of different components/elements with different reference service lifetimes. While the load bearing structure can generally be designed for a lifetime of 50 to 100 years, there are building elements that are likely to be replaced sooner, for example at 30 years for the windows. The service life of a building element also determines the number of replacements during the reference study period (RSP) of the building. These replacements are accounted for in the so-called module B4 replacement and generally covers the replacement(s) of building element, including the deconstruction and end of life of existing elements (materials, technical systems) as well as the production and installation of a new (and identical) element. Due to the different application context and in-use conditions, the service life and the related replacement rate of building elements remain uncertain parameters of the building LCA model. The uncertainty of the available service lives' data in literature affects the reliability of the building LCA results and more specifically the assessment of the replacements (Module B4 according to EN 15978). **Error! Reference source not found.**.1 presents the building life cycle stages according to SN EN 15978 highlighting the replacement module B4 object of analysis of this report.

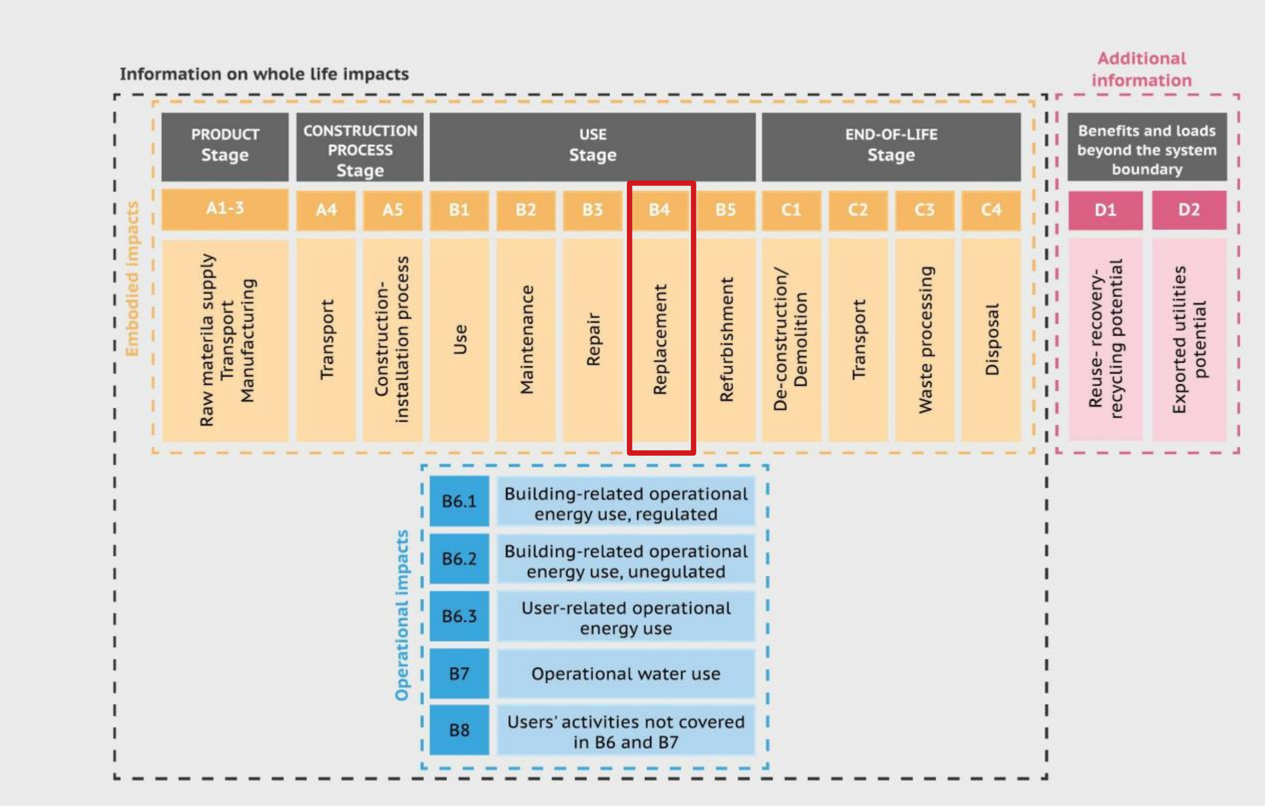

Figure 1.1: Building life cycle stages according to SN EN 15978 (CEN/TC 350, 2011) including the replacement stage

As far as the LCA of the replacement stage is concerned, it can be calculated, using Eq. 1,

$$LCA_{replacement} = \left(LCA_{\,Product\ and\ Construction\ Process} + LCA_{\,End\ of\ life}\right) * k \qquad (1)$$

where:
k is the replacement rate that occurs during the RSP of the building. It can be calculated for a given building element as shown in Eq. 2,

$$k = \frac{RSP}{SL} - 1 \qquad (2)$$

where:

RSP is the reference study period of the building according to SN EN 15978 (CEN/TC 350, 2011) (years);

SL service life[1] of the element (years).

This current methodological background report discusses 4 methodological assumptions:

- the service lives (SL) of building elements (background definition, current values and their inherent variabilities/uncertainties),
- the different levels of details to define the service lives in an LCA, depending on the level of decomposition of the building model,
- the different building lifetime (or RSP in EN 15978) used to calculate the replacement rate,
- the calculation of the replacement rate k.

In order to quantify the effect of the service lives' uncertainty on the total LCA, building case studies are used in different countries to illustrate the current practice and the influence of these assumptions on the replacement stage calculation in building LCAs.

Remark: In this methodological report, the "*service life*" term is used for referring to all the different available terms such as lifetime / service life / duration of use for a building element (as presented in the next sub-section). For the temporal system boundaries in the life cycle of buildings, a distinction is made between the technical or economic service life on the one hand, and the reference study period (RSP) on the other. All statements in this background report relate to an assumed RSP.

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[1] In the normative context e.g., following SN EN 15804 and SN EN 15978, this term is called "Reference Service Live" (RSL)

2. Status of Discussion

At present, different methodological assumptions are used to assess the replacement stage in a building LCA i.e.,

- The service lives definitions and values of building elements and their related uncertainties and variabilities
- The level of details for fixing the service life of a building element (cf. the different level of details for the building decomposition in the A72 report by Passer et al. 2023)
- The value for the RSP of the building
- The calculation method for the replacement rate

The following sections present a brief introduction of these different topics.

2.1 Service Lives Definitions, Service Life Values of Building Elements and their Related Uncertainties and Variabilities

This section reports the different definitions and values for the service life of building elements. It also presents some empirical evidence of the current variabilities in values used in LCA methodologies and in other contexts of use.

2.1.1 Different definitions of the 'service life'

Different service life values are defined in the literature for the building elements and technical systems. The term *'service life'* (or lifetime) can be defined in various ways, depending on the scope of the final user e.g. building designer, owner, LCA or LCC expert, (Lasvaux et al, 2020). According to Thiebat (2019), the service life of a building (and by extrapolation, the service life of building component and material, as well) can be classified into physical (service life that corresponds to the lifetime allowed by physical degradation procedures), functional (that takes additionally into account the *'performance/requirements ratio'*) or economic service life (service life that corresponds to the residual economic value). Furthermore, the international standard ISO 15686 (ISO, 2011, p.31), distinguishes among the service life, the reference service life, the estimated service life, the predicted service life and the service life assumption during the design (planned service life). In the Swiss context, the Swiss Society of Architects and Engineers (SIA) differentiates the technical service life (SIA, 2016), (SIA, 2015), from the useful life (SIA, 2016), (SIA, 2015) & (SIA, 2003) or the amortization period (SIA, 2010), used for LCA calculations. Furthermore, other terms related to service life exist[2] such as:

- Defined service life (based on conventions)
- Defined service life for calculations (*Rechenwert*)
- Guarantied service life
- (expected) Lifetime under defined conditions of use and maintenance
- Average length of stay (*mittlere Verweildauer*)

Table .1 presents some of the definitions, found in different CEN, ISO and SIA standards.

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[2] Personal communication with T. Lutzkendorf, (26.03.2019)

Table 2.1: Example of definitions of the “lifetime” of building elements (not exhaustive)

Existing terminology	Source	Definition / Explanation
Lifetime	SIA 480 (SIA, 2016)	*"The technical lifetime is the period between the commissioning of a component and its subsequent replacement with a decrease in reliability or an increase in maintenance and replacement costs of its components"*
Technical lifetime *Technische lebensdauer (de)*	SIA 480 (SIA, 2016)	*"period between the commissioning of a component and its subsequent replacement with a decrease in reliability or an increase in maintenance and replacement costs of its components"*
Duration of use *Wirtschaft Nutzungsdauer (de)*	SIA 480 (SIA, 2016)	*"Prescribed time interval elapsed between startup and replacement of a component or installation. The usage time is limited either by technical lifetime or by a possible replacement to meet new needs (comfort, aesthetics, new assignment, etc.) or to improve the technical performance (e.g. the balance sheet improvement energy)”*
Amortisation lifetime *Amortisationszeit (de)*	SIA 2032 (SIA, 2010)	*"The amortization period is the period during which the embodied energy (or other environmental impacts) for the manufacturing and disposal is amortized. With the exception of the foundation excavation and the supporting structure, the depreciation period corresponds to the duration of use (see definition above).* *For the foundation excavation and the support structure, the fixed amortization period is less than what would be the duration of use, so as not to load future generations with depreciation corresponding to the current investments in embodied energy"*
Predicted service life	ISO 15686-1 (ISO, 2011, p.31)	*"service life predicted from performance recorded over time in accordance with the procedure described in ISO 15686-2"*
Reference Service Life (RSL)	ISO 15686-1 (ISO, 2011, p.31)	*"service life of a product, component, assembly or system which is known to be expected under a particular set, i.e. a reference set, of in-use conditions and which can form the basis for estimating the service life under other in-use conditions"*
Service live	(Dulling, 2006)	*"period of time after installation during which a facility or its component parts meet or exceed the performance requirement"*
Estimated service life (ESL)	ISO 15686-1 (ISO, 2011, p.31)	*"service life that a building or parts of a building would be expected to have in a set of specific in-use conditions, determined from reference service life data after taking into account any differences from the reference in-use conditions"*
Expected life when designing	ISO 15686-1 (ISO, 2011, p.31)	*"Life as the designer has indicated to the Client specification to support decisions"*

Multiple studies, as stated by Silvestre, Silva & de Brito (2015), have identified the deterministic (Factor Method as defined in ISO 15686 standard), the probabilistic and the engineering method (combination of the previous two), as possible ways to determine and predict the service life. In practice, the service life constitutes a quite complex material parameter, which is affected by a variety of different factors, not necessarily technical. Dulling (2006) mentioned that the service life is affected by the design level, the material and the workmanship quality, the maintenance level and cleaning (affecting the durability), the external and internal climate and the operational environment (affecting the degradation). Furthermore, as summarized by Cooper (2004), multiple scientific research suggested that among the parameters that influence the service life are ‘the design, the technological change, the cost of repair and the availability of parts, the household affluence, the residual and resale values, the aesthetic and the functional quality, fashion, advertising and social pressure'. In the PI BAT project (Office fédéral des questions conjoncturelles, 1993), other parameters are mentioned, like the new legal requirements or the cost-effectiveness, among other external factors influencing the obsolescence of the materials. In addition, Jakob (2007) and Wilson, Crane & Chryssochoidis (2015) identified a variety of different parameters (socio-economic, etc.) behind material replacement for energy-efficient renovation in buildings.

Example of the Factor Method:
To obtain a prediction of the estimated service life (ESL), the factor method is used. It is defined in the ISO Standard 15686 (ISO, 2011), (ISO, 2012). It estimates ESL by weighting RSL values using on-site (expected) conditions of the element for seven factors known to influence service life (Bahr & Lennerts, 2010; Moser & Edvardsen, 2002).[3] For each of these seven factors, ISO standards suggest weights ranging from 0.8 for conditions that heavily accelerate element deterioration to 1.2 for conditions that greatly prolong the service life of an element. Under perfect conditions, ESL values can therefore exceed RSL values by a factor of almost 3.6, while under the worst possible conditions ESL is about 80% shorter than corresponding RSL.

The Factor Method, according to which the reference service life is corrected by seven factors, to account for the different non-technical parameters that affect the service life, has been criticized for its reliability, as stated in Straub (2015). Straub presented the main objections, concerning this method, of an expert committee gathered to examine the problematic of the service life of building products. Some of these objections of the committee concerned whether the factors should be multiplied, quantified or expressed in numbers. In addition, Straub summarizes further studies (Bahr & Lennerts, 2010; Nireki et al., 2002; Re Cecconi & Iacono, 2005) that proposed ways to optimize the Factor Method.

2.1.2 Different values of the service life

There are many sources and documentations providing service lives values for building elements. Some were recently reported in the Swiss DUREE research project (Lasvaux et al, 2020), funded by the Swiss Federal Office of Energy. This project started in 2017 an international, European and Swiss literature review to collect service lives data of building elements and technical systems. The data were then reported in a database with a decomposition of the building which started from the eBKP classification on construction cost. The database includes the five main categories of the functional nomenclature of the SN 506511 standard. These main categories where further decomposed into two-subcategories, according to SN 506511 and five more sub-categories were added in the DUREE database, in order to cover more detailed building components.

Service life data were collected from the following types of sources:

a. in the LCA literature (service lives values as conventional or recommended data to national LCA methodologies),
b. in the LCC literature (service lives support to LCC analyses)
c. in other sources grouped as "management" to depict different contexts of use:
    - building portfolio and real estate management,
    - professional owners,
    - experts from the bank & insurance sectors,
    - experts from the building energy management,
    - association of tenants & owners,
    - other expert groups,
    - specialised websites,
    - other.

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[3] These factors include: (A) element's quality that accounts for the quality of materials but also potential damages occurring during transport and storage (B) design level that accounts for the integration of the element in the building structure hence its protection from erosive forces, (C) on-site implementation quality that assesses if the element has been correctly installed, (D) the internal physical environment that takes into account the erosive forces affecting the element from the inside (e.g. a window installed in a kitchen or bathroom), (E) external physical environment capturing the exposure to external corrosive forces, (F) use conditions that measures the element's usage intensity, and (G) maintenance conditions.

Other sources for service lives exist, such as the service lives data, provided in the IEA EBC Annex 72 (Subtask 1) during the Activity 1.1, based on surveys in order to define national methodologies, conducted in early 2019 (data from SB tool CZ (Czech Republic), Dutch program (The Netherlands), TOTEM LCA tool (Belgium), Denmark LCA method (Denmark), Pleaides ACV (France), University of Sevilla (Spain) based on Mithrarathe et al (2004), BRANZ estimate (New Zealand), BBSR Tables (Germany), etc.). The Annex 72 partners filled an Excel template with an extraction of the DUREE database building decomposition with national data of building elements' service lives. By doing so, the calculations of descriptive statistics for the Annex 72 can be based on the DUREE database.

2.1.3 Empirical variability of data provided by Annex 72 partners

Within this project, all partners were asked to reply to a survey as part of the subtask 1 related to the LCA methodology. Within this survey, a subsection was dedicated to the survey on building reference service lives as implemented in every country within their LCA methodologies (or tools) for buildings. Table 1.2 presents the countries that gave their data, but not all of them were subsequently used. When this happens, the reason is reported in the table below in the "comments" section.

Table 1.2: List of Annex 72 partners who provide the service lives used in their national LCA methodologies

A72 participating countries from which data were collected	Taken into account for the descriptive statistics	Comments
Australia	No	Service lives provided using a former building decomposition
Belgium	Yes	
Brazil	No	Only a few data were reported as Brazil has no measured service life database.
Czech Republic	Yes	-
Denmark	Yes	-
France	Yes	-
Germany	Yes	-
Hong Kong	No	Service lives provided using a different building decomposition
Netherlands	Yes	-
New Zealand	Yes	-
Portugal	Yes	-
Slovenia	Yes	-
Spain	No	Service lives were provided which come from literature sources from other countries
Switzerland	Yes	-
United Kingdom	No	Service lives provided using a different building decomposition
USA	Yes	Literature data were taken as individual data in the descriptive statistics calculation

Figure 2.1 shows the descriptive statistics of eight building elements, using the data provided by the Annex 72 partners. These building elements correspond to some building elements usually assessed during the LCA of a new building or for an energy-related building renovation. The values are represented using boxplots; the box representing 50% of the observed values (interquartile range), the whiskers the first and ninth percentile and the median is represented by the horizontal plain black line inside the box.

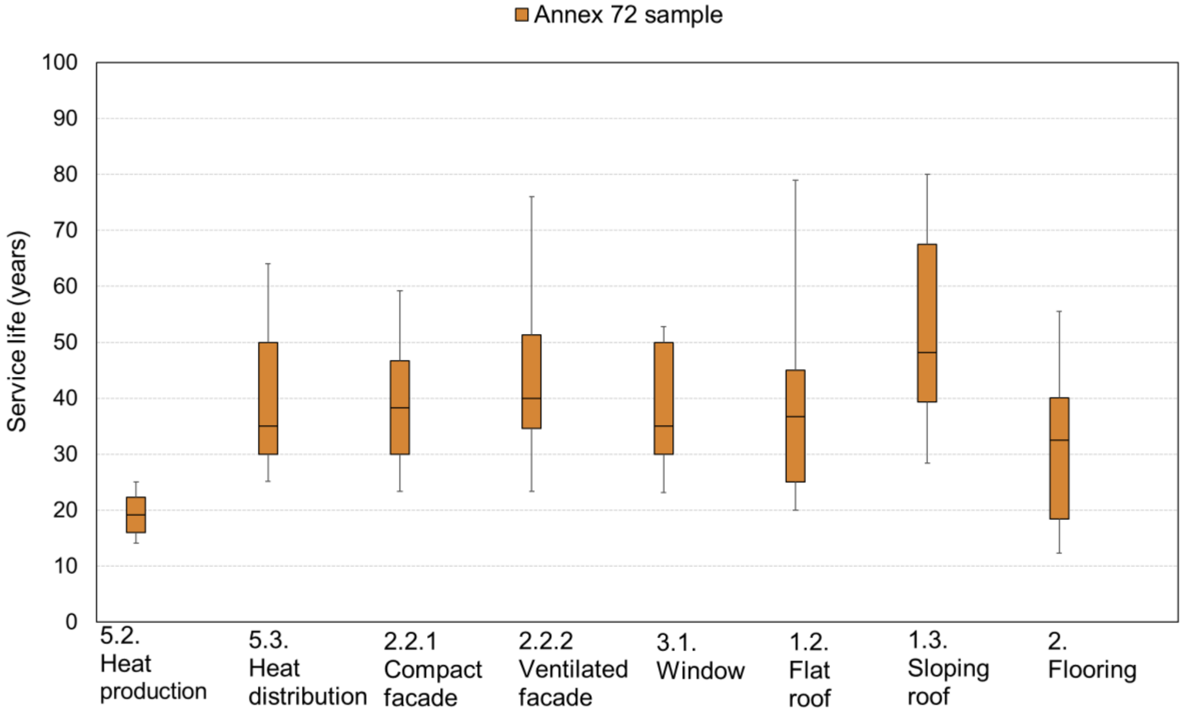
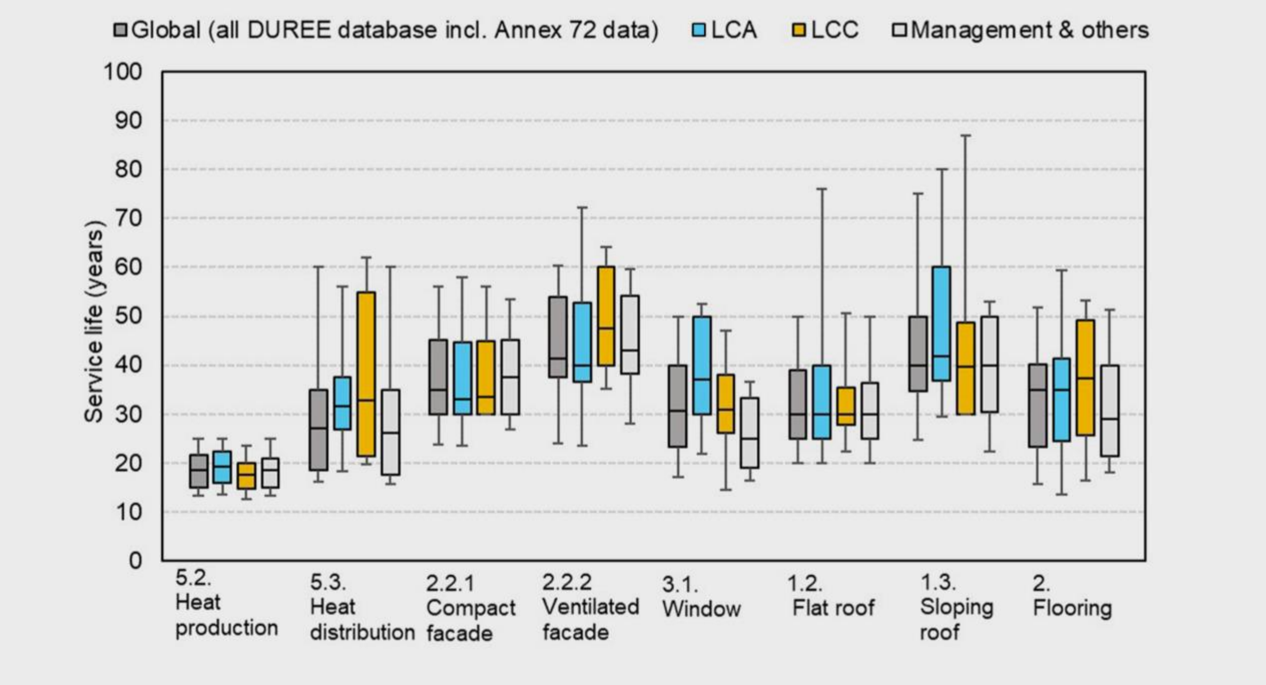


Figure 2.1: Descriptive statistics for eight building elements, from data reported by the Annex 72 partners as part of Activity 1.1. Survey on national LCA methodologies[4].

2.1.4 Empirical variability depending on the context of use of the data

As different definitions and contexts of use are identified in the literature (cf. Table 2.1), it is interesting to separate the service life data according to their context of use. As an illustration, Figure 2.2 shows the descriptive statistics for the same building elements, using all the data gathered in the DUREE database during the Swiss DUREE project. The sample was separated in three source types, i.e.



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[4] A compact facade is a plain facade (excl. structural element) that comprise an external covering, the thermal insulation (e.g., an EPS) and a mortar to glue the complex onto the structural wall.
A ventilated façade is a façade comprising an air tightness and the insulation inside a frame in wood or metal and a covering on the exterior.

service lives used for LCA[5] calculations, the ones used for LCC and the other ones used by building owners among others (called “management”). In the next result, the Annex 72 data are filling the different samples (mostly the LCA one and sometimes the LCC one if the service lives are also used for LCC calculations).

A quick look at the results confirms the inherent variability in the collected values. A substantial spread of service lives’ can be observed for the eight building elements while it is possible to rank the elements by median service lives values from the heat producer with about 15-20 years to the ventilated façade with about (45-50 years). Median SL values for the other elements fall in-between. It can be concluded that there is no source type that presents systematically lower or higher service life data. More information can be retrieved from the DUREE report[6] and in the Data in Brief paper and Excel table gathering the descriptive statistics[7].

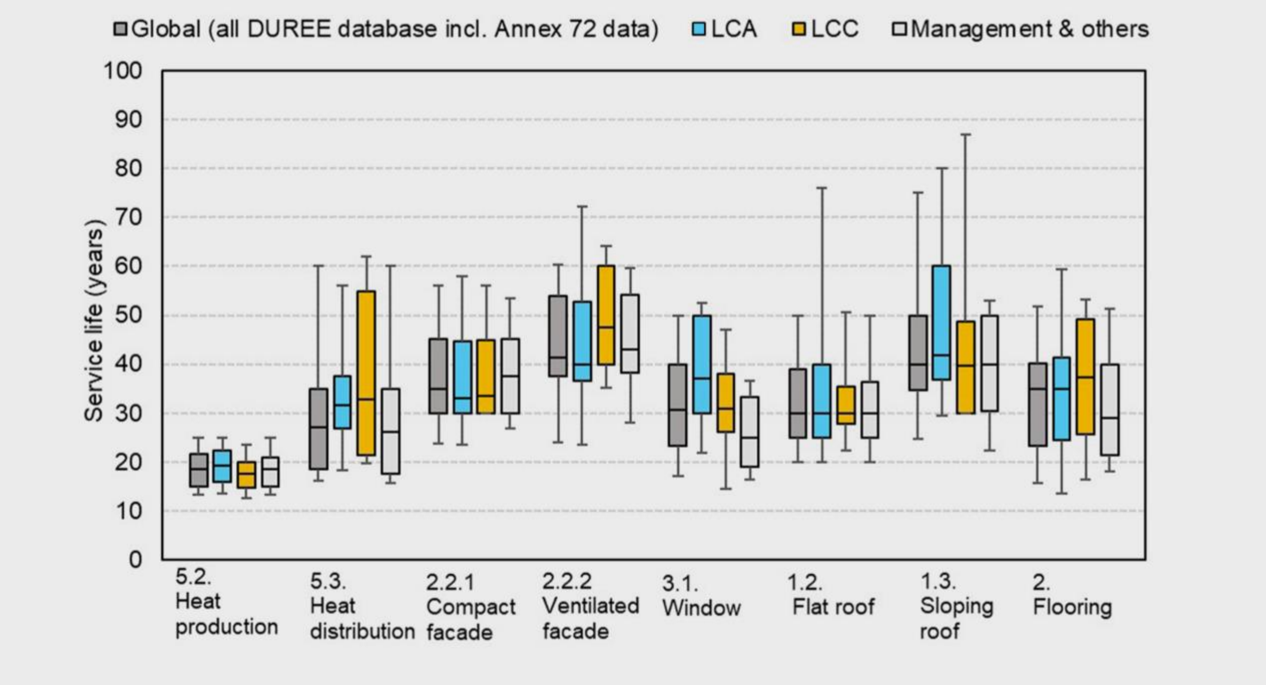

Figure 2.2: Example of reported values in the literature used for different purposes (LCA calculations, LCC calculations and other sources like professional building owners) based on the studies by Lasvaux et al (2020).

2.2 Level of Details for Fixing the Service Live of a Building Element

Figure 2.3 presents a general description of a building and its decomposition in different levels. Each building element (e.g., Roof) consists of several building components (e.g., C4.4 roof, F1 roof covering, G4 interior roof covering), which have different functions and belong to different construction categories. The classification system marks individual building components, based on the Swiss code of construction costs (e-BKP). Other decomposition systems exist and are further described in the A72 report by Passer et al. (2023) as well as by Soust-Verdaguer et al. (2020).

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[5] And energy calculations

[6] Lasvaux S. et al 2019. ”DUREE Project: Analysis of lifetimes of building elements in the literature and in the renovation practices and sensitivity analyses on building LCA & LCC case studies”, Swiss Federal Office for Energy (SFOE), Final report, June 2019, available online: https://www.aramis.admin.ch/Texte/?ProjectID=38626 .

[7] K. Goulouti, P. Padey, A. Galimshina, G. Habert, S. Lasvaux 2019. “Dataset of service life data for 100 building elements and technical systems including their descriptive statistics and fitting to lognormal distribution”, Data in Brief, Volume 36, June 2021, available online (Open Access): https://www.sciencedirect.com/science/article/pii/S2352340921003462

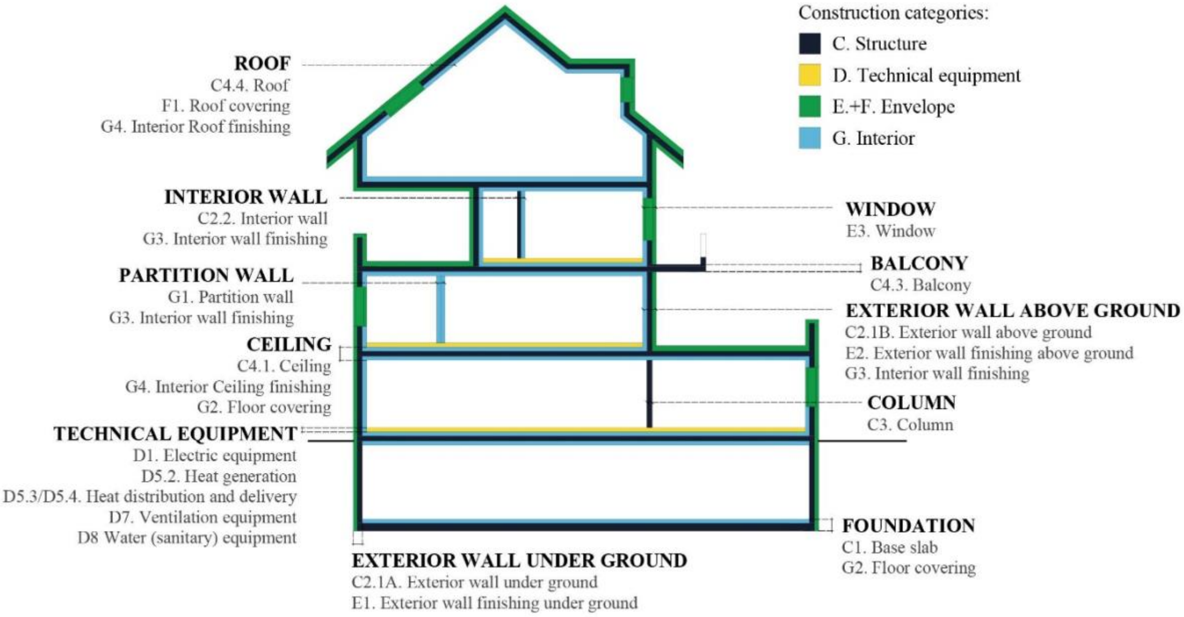

Figure 2.3: General description of the building, building element, building component and construction categories according to Cavalliere et al. (2019).

As shown in Figure 2.3, the service life of a building element can be defined at different levels of details. However, as a building element gather different components with different functions, it is not appropriate to define a single service life for a multi-layered element. The service life is thus defined for each component (or layer). For instance, depending on the scope of the assessment, the service life can be attributed for 2 levels of details according to Figure 2.3:

1. construction categories (structure, technical equipment, envelope (wall and roof external coatings as well as windows and doors), interior (i.e., non-load-bearing walls and interior finishing))
2. detailed components & layers (e.g., roof covering, interior roof finishing etc.)

If more product-specific data are available, the service life can also be defined even further for specific product using the information of reference service live (RSL) in the Environmental Product Declaration (EPD).

Indeed, the definition of the service live in practice will be a function of two “limiting” criteria:

- First, representative renovation practices[8] should be considered in order to avoid misleading service lives definition. For example, in practice, if the rendering and the external insulation are replaced at the same time, the two components should not be distinguished in the view of their service lives even if literature sources provide a service live for the rendering and the insulation. At least, the lowest service life should be used for both materials (layers). The same problem exists with the windows (glazing and framing). They are generally replaced as a single component and thus define different service lives does not correspond to reality.
- Second, possible lack of service lives data for very specific elements or for innovative products may not allow attributing service lives in a lower level of details.

2.3 RSP Values for Buildings

The RSP period can vary depending on the national LCA methodology and the context of use of the assessment results. The national LCA methods generally uses conventional values for this parameter. In Switzerland, the LCA national method (Cahier Technique SIA 2032, 2010), (Cahier Technique SIA 2040, 2011) proposes 60 years. The SIA 480 standard does not define an RSP but the service life of the building

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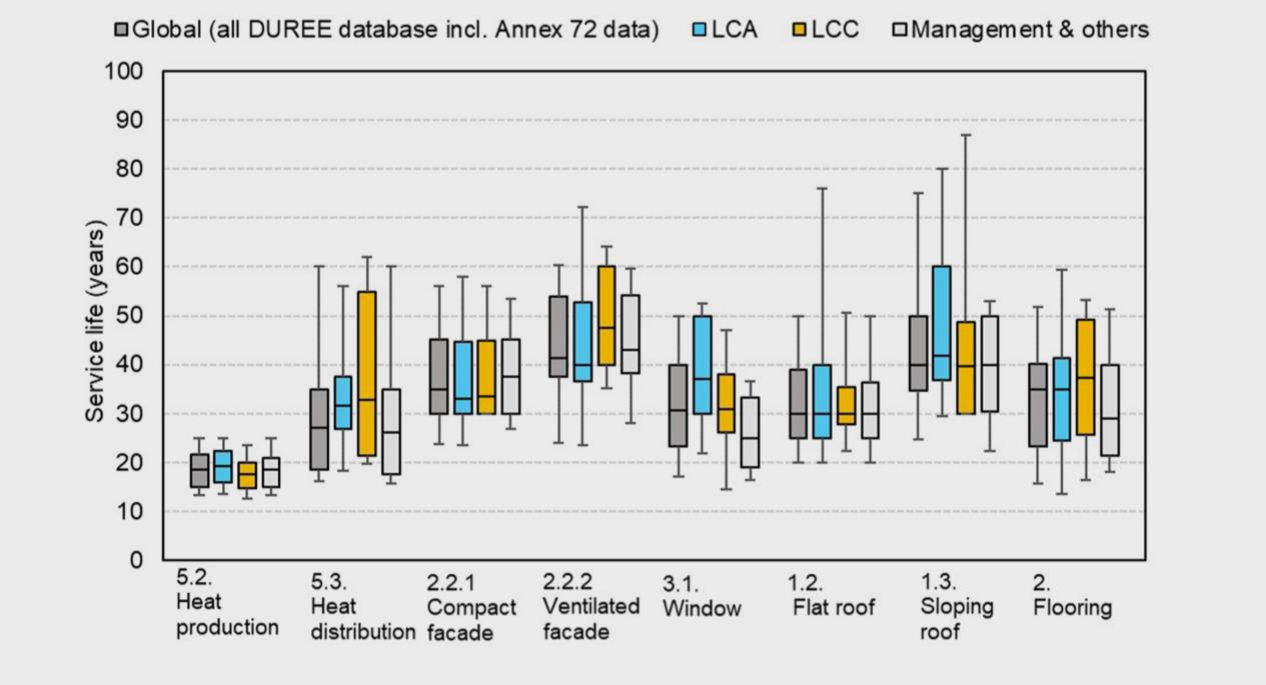
[8] And representative of the reference context of use as mentioned in EN 15804 and EN 15978.

structure instead. The SIA 480:2004 standard considers from 80 to 100 years (SIA, 2004) while the revised 2016 version considers from 40 to 120 years with an intermediate value at 75 years (SIA, 2016). In addition, the SNARC method, used in early design stages, considers 30 years (SIA, 2004). Other LCA methods in Europe consider 50 years (BBSR, 2011), 80 years (Izuba-Energies, 2019) or even 120 years (IEA - Annex 72, 2019).
Using 30 years can be appropriate in order to amortize the LCA of the construction over a short period (e.g. to comply with environmental / public policies goals such as the carbon neutrality by 2050) or for building typologies with shorter lifetime, while using 100 years allows to account for a longer life cycle, which may represent better the reality. In general, many national LCA methodologies consider 50 to 60 years to calculate the LCA[9].

In general, the service lives of structural building elements correspond/coincide to the RSP in a building LCA. The underlined assumption for the RSP will affect the number of times a building element needs to be replaced. As the service lives found in the literature (see Figure 2) present substantial variations, the replacement rate will be a function of the elements' service lives and the RSP values.



2.4 Replacement Rate Calculation

Currently there are mainly two different approaches on how to deal with replacements in the life cycle inventory of a building:

- Approach A: Annualised impacts per building element;
- Approach R: Rounded up number of replacements of building elements;
- Approach S: Simulation of the building life cycle.

The three approaches are described in the following.

Approach A, Annualised impacts per building element

The annualised environmental impacts of a building element are calculated taking into account the service life (or the reference service life (RSL) or the adjusted expected service life) of the element. First, the

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[9] Cf. SBE Graz paper from Rolf Frischknecht and the current Activity 1.1 on survey of national LCA methodologies

environmental impacts of manufacturing a particular building element (e.g. a window) are determined. Secondly, the environmental impacts are divided by the reference service life (RSL) of this building element (e.g. 30 years). These two steps are repeated for all the building elements, which compose the building under assessment. Finally, all resulting values, per year, are added up, a sum which corresponds to the annual environmental impacts of the building under consideration. This approach is applied in Switzerland in the technical bulletins SIA 2032 (SIA 2020) and SIA 2040 (SIA 2017), in which the distinction between initial efforts and efforts due to replacements are of little interest and the residual values are simply neglected.

Approach R1, Rounded up number of replacements

First, the number of replacements of a particular build-ing element (e.g. a window) is determined by dividing the reference service life (reference study period) of the building (e.g. 60 years) by its reference service life time (e.g. 30 years) minus 1. In this example, the windows will be replaced only once during the service life of the building. In case that the RSP of the building is 50 years, the exact number of replacements would be 0.67. Since fractional replacements are not possible, these values are rounded up to the next integral number (in the example: 1). Secondly, the environmental impacts of manufacturing a particular building element (e.g. a window) are determined. Thirdly, the environ-mental impacts of manufacturing all building elements of a building are added up to get the environmental impacts of the product stage (Modules A1-A3). Fourthly, the environmental impacts of manufacturing all building elements of a building are multiplied by the number of replacements and then added up to get the environmental impacts of replacements during the use stage (Module B4). Fifthly, the total environmental impacts of the product and the use stage are divided by the RSP of the building under assessment. This approach is required by the CEN standard on the assessment of the environmental performance of buildings.

Approach R2, rounded up number of replacements with a certain condition

This approach distinguishes the obtained values for the calculated number of replacements depending on a threshold. If the replacement rate is higher than a percentage (e.g., 20%) of its integer value it is rounded up, otherwise it is rounded down[10]. Like that, overestimation of the replacement rate can be avoided, in case is the number of replacements is very small, e.g. 1.05 times. Practically, this means that if the end of life of a building element is close to the end of the building RSP, this is no replacement.

However, even if Approach R1 and R2 reflect better the reality of the replacement rate, the use of the fractional one presents a negligible influence on the building LCA results, especially compared to the choice of the RSP value (cf. Case studies results' section of this report).

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[10] Such calculation rule is currently implemented in existing building LCA tools

Approach R3, component-specific rounded up

The analysis of the aging process of real buildings shows that the replacement rate in the case of components is often overestimated[11]. Most of building components often turn out to be more robust than expected, or the building owners are more tolerant of an aged state. An approach can be that for such building components, the calculated number of replacements is always rounded down and no replacement is assumed in the last 5-10 years of the life cycle model. However, the situation is different with technical equipment that is critical for safety and efficient operation. In these cases, since a planned replacement must always be carried out, and often is mandatory, the number of replacements can be rounded up. This leads to a component-differentiated approach which so far is not seen applied in any of the national methods, tools, but is presented as a possibility in the draft of upcoming EN 15978.

Approach S: Simulation of the building life cycle

A simulation process accounts for environmental impacts using a one-year time step[12]. Each building element has an age counter, incremented each year. When the age reaches the life span, impacts corresponding to the replacement processes are added. Replacement is not considered anymore after 90% of the building life span.

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[11] See: Ritter, F. (2011). Lebensdauer von Bauteilen und Bauelementen-Modellierung und praxisnahe Prognose (Vol. 22). TU Darmstadt.

[12] E.g. Pleiades ACV EQUER, see Polster, B., Peuportier, B., Blanc Sommereux, I., Diaz Pedregal, P., Gobin C. and Durand, E. Evaluation of the environmental quality of buildings - a step towards a more environmentally conscious design, Solar Energy vol. 57 n°3, pp 219-230, 1996

3. Illustration of the Approaches and their Consequences based on a Case Study

3.1 Service lives definitions and values of building elements and their related uncertainties and variabilities

This section presents a case study that draws on the findings of the Swiss DUREE research project (Lasvaux et al, 2020) and the related journal paper (Goulouti, Padey, Galimshina, et al., 2020).
Service lives data, collected in the DUREE database[13] and combined with Annex 72 service lives data (collected in the survey on national LCA methodologies) present a substantial variability and uncertainty as shown in the

Figure 2.1 and 2.2. It is thus important to assess whether their empirical variabilities affect the reliability of the building LCA results and more specifically the reliability of the replacement stage calculation. The data were used, for the determination of the probability density functions (PDF) for each building component of the case studies. In this building case study, they are first used to calculate a replacement rate k (see Eq. 1) for each element type by dividing each service life with a reference study period (RSP) chosen at 60 years. Then, the service life data were transformed in replacement rates and the PDFs of the element types were defined, by fitting a lognormal distribution. The present study takes into account the uncertainty of the element types service life (input of the model) in the building LCA (output – response of the model).

Remark & Scope of the probabilistic LCA: All the other uncertainties related to the parameters of the building LCA e.g. uncertainty of the operational energy use of the building and the LCA are not within the scope of this study. By doing so, the relative importance of the service lives' uncertainties is solely evaluated, taking into consideration that a small uncertainty on the total LCA result (output), derives from an insignificant influence of the service life (input).

One way to identify the error propagation, due to the uncertainty of the input on the output, is to use the Monte Carlo method within a probabilistic framework. 40'000 Monte Carlo simulations are computed in order to probabilistically take into account the replacement of the building elements. Like that, the Probability density functions (PDF) of the LCA outputs are defined. Finally, the Sobol' Sensitivity Indices are calculated following (Saltelli et al, 2008) to determine the impact of the service lives' variability on the LCA uncertainty, for the different building elements.

This methodology is applied to one Swiss residential building case study located in Zürich and for the greenhouse gas emissions (GHGe) indicator. Table 2.1 presents the characteristics of the residential building.

Table 2.1: Characteristics of the new constructed residential building

General information	B1
Construction type	Medium weight
Materials for the structure	Wood & concrete
Type of facade	Compact & ventilated
Type of roof	Sloping roof
Energy reference area	350
Energy standard	Minergie-ECO
Accommodation units	2

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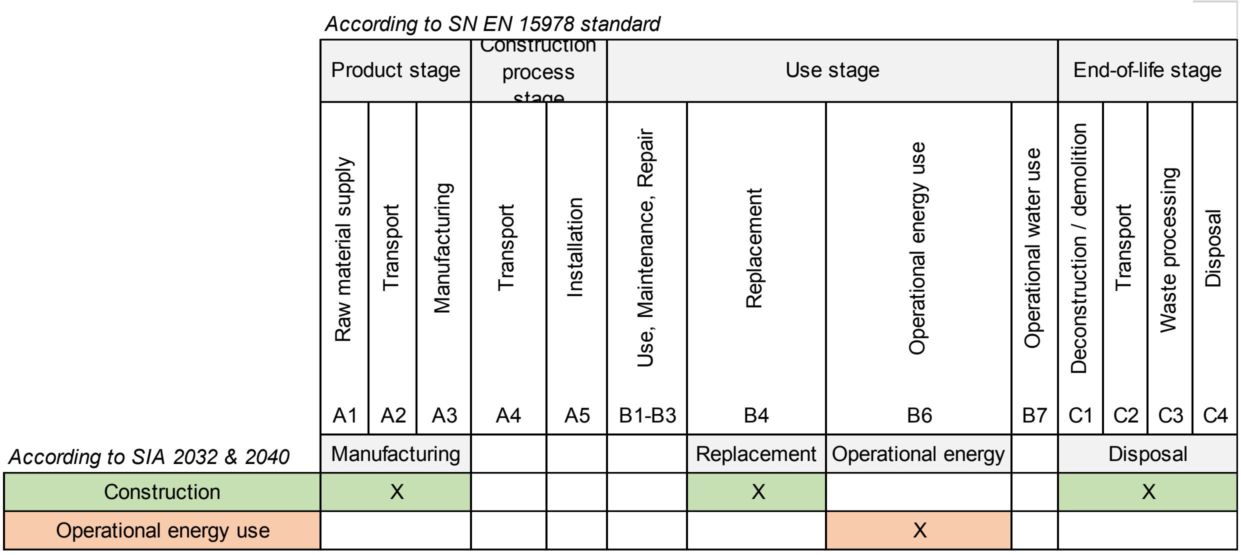
[13] Based on the Swiss DUREE research project, final report available here: https://www.aramis.admin.ch/Texte/?ProjectID=38626

Basement	Yes
Number of floors	3
Heating & ventilation systems	
Heating device	District heating
Energy source	Wood chips
Solar panels	No
Annual energy demand (MJ/m^{2}y)	
Heating	106
Domestic Hot Water (DHW)	75
Ventilation	24

The life cycle domains and phases of materials and building integrated technical systems (BITS) are defined according to SIA 2032 (SIA, 2010) and SIA 2040 (SIA, 2011) as shown in Table 3.2. The basic life cycle domains are the Construction and that of the Operational energy use. Table 3 shows the different life cycle domains and the corresponding phases taken into account, in the present study. No other environmental impacts were considered in this approach (e.g. maintenance, or environmental impact due to mobility of the users, as stated in SIA 2040).

The baseline RSP value is first defined at 60 years and the replacement rate is fractional. In the next sections, alternative assumptions will be evaluated.

Table 3.2: Life cycle stages of a building adapted from SN EN 15978; in green the included stages for the “construction” domain and in orange the “operational energy use” according to SIA 2032 and SIA 2040.



<table>
<tr><td></td><td colspan="13"><i>According to SN EN 15978 standard</i></td></tr>
<tr><td></td><td colspan="3">Product stage</td><td colspan="2">Construction process stage</td><td colspan="4">Use stage</td><td colspan="4">End-of-life stage</td></tr>
<tr><td></td><td>Raw material supply</td><td>Transport</td><td>Manufacturing</td><td>Transport</td><td>Installation</td><td>Use, Maintenance, Repair</td><td>Replacement</td><td>Operational energy use</td><td>Operational water use</td><td>Deconstruction / demolition</td><td>Transport</td><td>Waste processing</td><td>Disposal</td></tr>
<tr><td></td><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>B1-B3</td><td>B4</td><td>B6</td><td>B7</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td></tr>
<tr><td><i>According to SIA 2032 & 2040</i></td><td colspan="3">Manufacturing</td><td></td><td></td><td></td><td>Replacement</td><td>Operational energy</td><td></td><td colspan="4">Disposal</td></tr>
<tr><td>Construction</td><td colspan="3">X</td><td></td><td></td><td></td><td>X</td><td></td><td></td><td colspan="4">X</td></tr>
<tr><td>Operational energy use</td><td colspan="3"></td><td></td><td></td><td></td><td></td><td>X</td><td></td><td colspan="4"></td></tr>
</table>

(X = calculated in the LCA of the Swiss residential building according to the SIA technical books)

The Swiss building element classification scheme, for cost estimation, eCCC-Bât in French, (or eBKP-H, in German) is used to classify the building elements. The classification of eBKP-H nomenclature has already been used to report the service lives data. Each building element consists of several building components, which have different functions and belong to different construction categories.

In this case study, the service lives data are those of the second level of analysis according to the Swiss DUREE research project (Lasvaux et al, 2020). This means that 16 difference service lives data are used for the modelling of the replacement phase of the building LCA.

Figure 3.1 presents the result of the probabilistic LCA (the first part entitled the ***uncertainty analysis*** of one new construction case study (B1), for the GHG emissions) compared to two deterministic LCA suing deterministic service lives from Swiss documentations (SIA 2032 and CRB). The probabilistic LCA (right, noted “DUREE DB”) is about [μ=22 kg $CO_{2\text{-eq}}$/(m^2y), $\sigma^2=3^2$], while the deterministic LCA, from SIA 2032 reports a value of [20.4 kg $CO_{2\text{-eq}}$/(m^2y)] and CRB [mean=19 kg $CO_{2\text{-eq}}$/(m^2y)]. The results show that the uncertainty of the replacement rate can significantly affect the LCA uncertainty. The replacement stage in the probabilistic LCA, accounts for 14% to 36% of the GHG emissions for the B1 residential building.

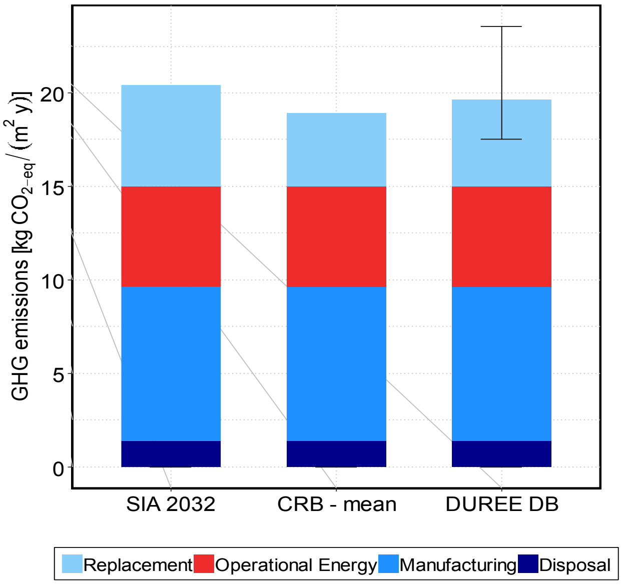
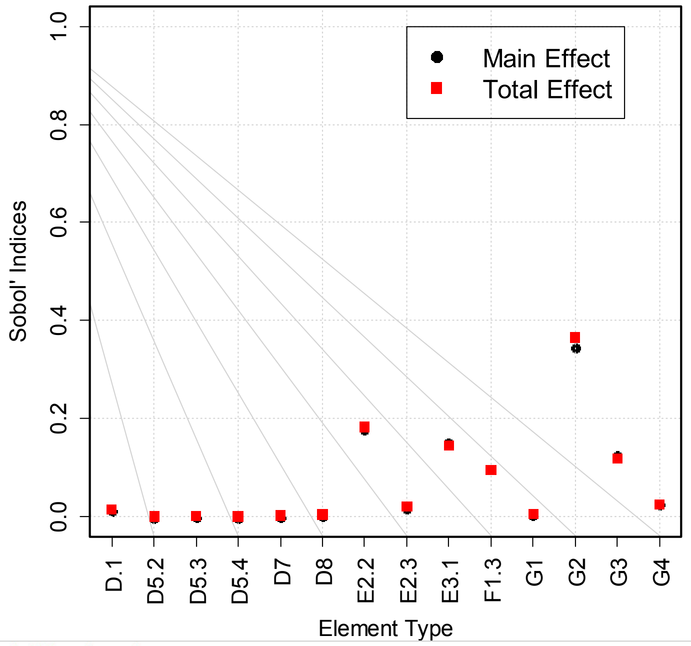


Figure 3.1: Contribution analyses for the probabilistic LCA and comparison with the deterministic LCA, using the SIA 2032 and CRB - mean service lives (taken from Lasvaux et al (2020) and Goulouti, Padey, Galimshina, Habert & Lasvaux (2020))

Figure presents the synthesis of the second part of the probabilistic LCA (i.e., the ***sensitivity analyses*** using the Global Sensitivity Analysis and Sobol Indices (Saltelli et al, 2008)) for the GHG emissions of the residential building B1.



Names of the building elements:

D1. Electrical installations
D5.2 Heat production
D5.2d Solar collector
D5.3 Heat distribution
D5.4 Heat diffusion
D7. Ventilation
D8. Sanitary equipment
E2.2 Compact facade
E2.3 Ventilated facade
E3.1 Windows
F1. Flat or slanted roof
F1.3 Slanted roof
G1. Internal partitions
G2. Flooring
G3. Wall coverings
G4. Ceiling coverings

Figure 3.2: Sobol' sensitivity Indices (main and total effect) for the GHG emissions of building B1 taken from Lasvaux et al (2020).

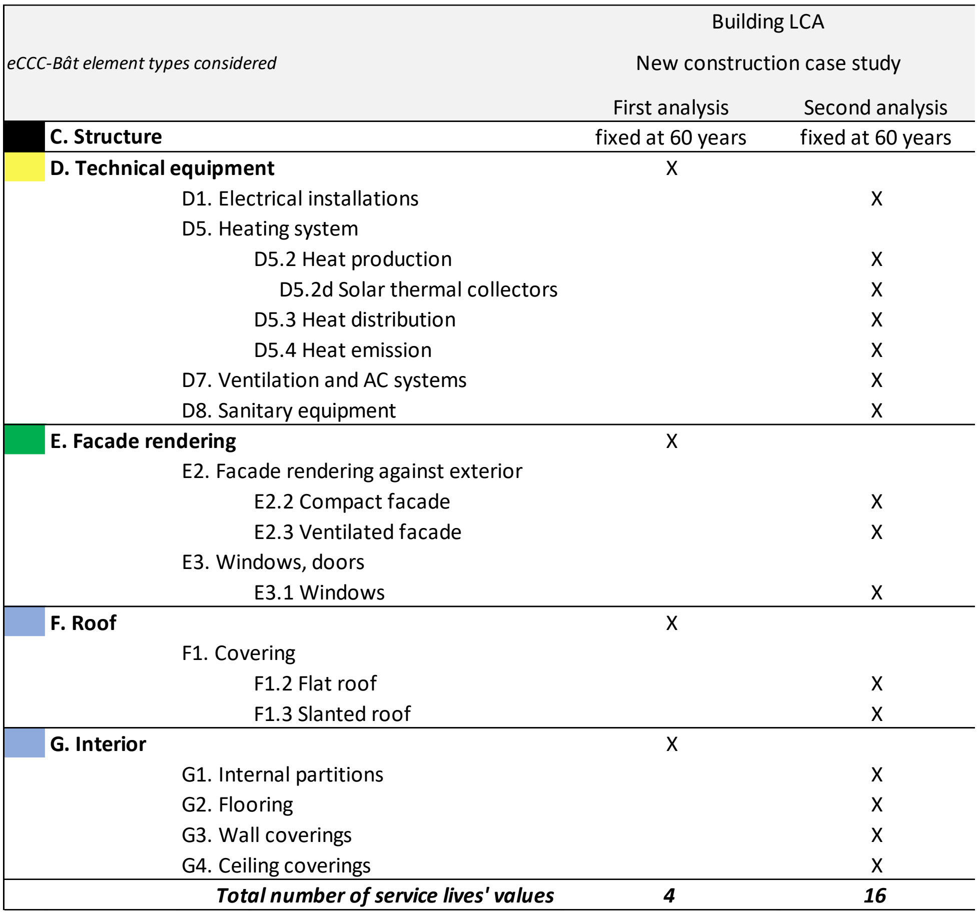
The outcomes of this building LCA case study are the following:

- If a threshold is defined at 0.10 for the sensitivity indices, only six element types out of 16 are the most influential on the LCA uncertainty, i.e. E2.2 (compact façade), the E3.1 (windows), the F1.3 (sloping roof), the G2 (flooring), G3 (internal finishing). This means that special attention should be given when defining the service lives for these element types in further LCA calculations;
- The uncertainty of the technical systems service lives (D element type) present low impact on the LCA uncertainty for the GHGe. If this finding remains valid for other case studies and LCA indicators, the LCA model could be simplified and conventional deterministic values would be sufficient to model this aspect, instead.

3.2 Level of Details for Fixing the Service Live of a Building Element

The same building case study (B1) is used as already presented in Table 3.1. In connection to the Annex 72 (Passer et al. 2023), the building LCA can follow different building decomposition (from major element to sub-elements and layers of materials). In Switzerland, the eBKP-H nomenclature form the CRB (Code for the construction costs) is used with different levels of details. It is thus possible to break down the building LCA in a sum of different elements, each one having its LCA value and its service life. In connection to the Life Cycle Cost (LCC), such approach exists and allows to define a service life for one main category (e.g., the technical equipment) but also for a sub-category (e.g., the heating system) and another more precise element (e.g., the heat producer). Table presents the number of service lives that can be for two different levels of details (taken as an example, as other configurations are possible). By doing so, it is possible to conduct building LCA with a varying level of details.

Table 3.3: eBKP-H codes and the corresponding names of the element types included in the case studies taken from Lasvaux et al. (2020).



	eCCC-Bât element types considered	Building LCA New construction case study First analysis fixed at 60 years	 Second analysis fixed at 60 years
⬛	**C. Structure**		
🟨	**D. Technical equipment**	X	
	D1. Electrical installations		X
	D5. Heating system		
	D5.2 Heat production		X
	D5.2d Solar thermal collectors		X
	D5.3 Heat distribution		X
	D5.4 Heat emission		X
	D7. Ventilation and AC systems		X
	D8. Sanitary equipment		X
🟩	**E. Facade rendering**	X	
	E2. Facade rendering against exterior		
	E2.2 Compact facade		X
	E2.3 Ventilated facade		X
	E3. Windows, doors		
	E3.1 Windows		X
🟦	**F. Roof**	X	
	F1. Covering		
	F1.2 Flat roof		X
	F1.3 Slanted roof		X
🟦	**G. Interior**	X	
	G1. Internal partitions		X
	G2. Flooring		X
	G3. Wall coverings		X
	G4. Ceiling coverings		X
	Total number of service lives' values	***4***	***16***

For example, a building LCA can be calculated in early design or in a simplified approach using the 4 main categories (structure, technical equipment, facade rendering, roof, interior) with one LCA value (based on statistics or aggregated data) and service lives for each category. It is also possible to have a more detailed analysis as show in Table . In practical application, the need for a low level of details may be justified by the need of doing a quick & simplified LCA[14] (also valid for a quick & estimated LCC) while more detailed analysis will be justified to compare more defined case building projects. Different types of screening, simplified and detailed LCA, can be done and more information is provided in the Annex 72 report by Passer et al. (2023).

As an illustration, probabilistic GHG emissions using PDF of service lives can be calculated for both levels of analysis (from Table), Figure . These results present the same values as in
Figure 3.1 by providing the complete PDF instead of the "error bar" for the probabilistic GHG emissions (noted "DUREE DB" in the graphics.

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[14] Here, the proposed building decomposition comes from the "life cycle cost" perspective & community. It can be used for building LCA and building LCC that do not aim at linking building energy simulation (BES) and building LCA as the building elements of the thermal envelope (used in BES) and those not included in the BES (such as the foundations) added for the building LCA are not differentiated.

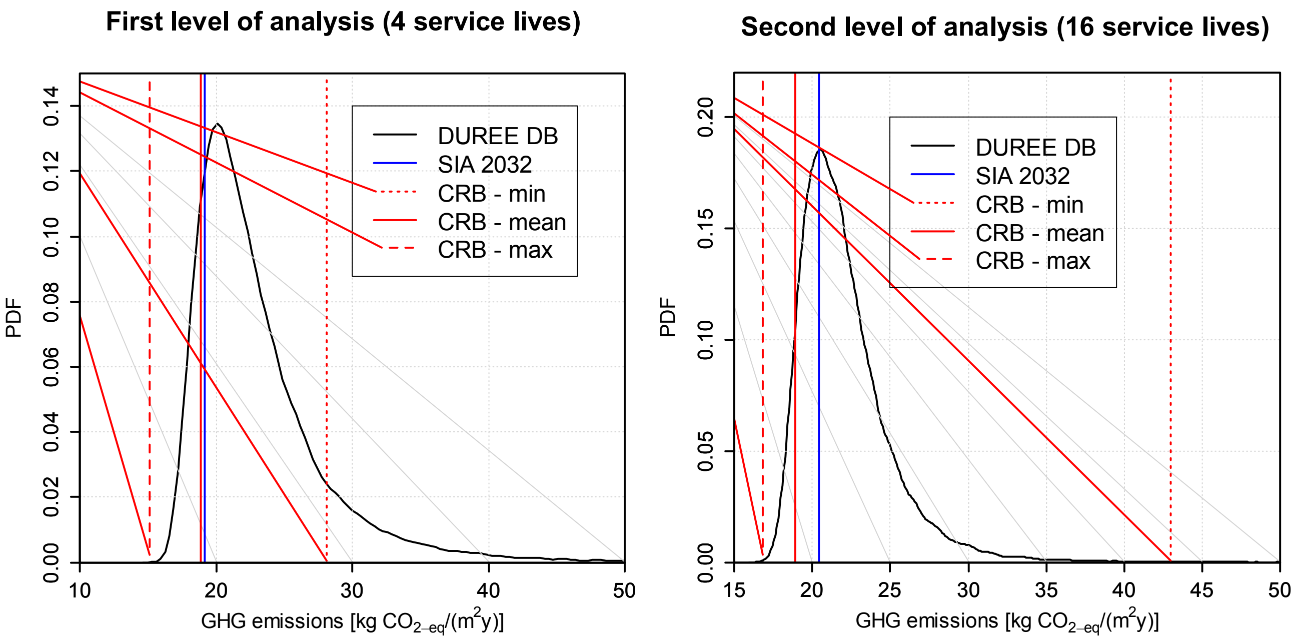

Figure 3.3: PDF of the probabilistic LCA for the B1 case study in the first level of analysis and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives (left); PDF of the probabilistic LCA for the B1 case study for the second level of analysis as presented in the previous section (right), adapted from the DUREE research project (Lasvaux et al, 2020)

In Figure (left), the probabilistic LCA in the first level of analysis is calculated [$\mu = 23.22$ kg CO_2-eq/(m^2y), $\sigma^2 = 5.5^2$] and compared with the deterministic LCA of the SIA 2032 [19.2 kg CO_2-eq/(m^2y)] and CRB [min=28.1 kg CO_2-eq/(m^2y), mean=18.9 kg CO_2-eq/(m^2y) and max= 15.1 kg CO_2-eq/(m^2y)][15]. The three CRB values (min – mean – max) correspond to the minimum, mean and maximum service lives, which mean maximum, mean and minimum replacement rates, respectively. The most probable value of the LCA, i.e., the mode of the distribution (xm=20 kg CO2-eq/m2y) is slightly higher than the deterministic SIA 2032 and CRB–mean (4% and 6% respectively). Figure (right) shows the PDF of the probabilistic LCA for the second level of analysis, along with the deterministic LCA, from SIA 2032 [20.4 kg CO_2-eq/(m^2y)] and CRB [min=43kg CO_2-eq/(m^2y), mean=19 kg CO_2-eq/(m^2y), max=17 kg CO_2-eq/(m^2y)].

This example shows the feasibility to calculate the probabilistic LCA using different levels of analysis (and building decomposition) for both the LCA and the definition of the service lives.

3.3 RSP Values for Buildings

The same building case study (B1) is used as already presented in Table 3.1. The building RSP is varied from 30 up to 120 years, with intermediate values of 50, 60, 80 and 100 years, in order to identify the influence on the LCA of this methodological convention. The intermediate values derive from the most common used RSP among the LCA methodologies, applied in different countries (Janjua et al., 2019). The calculation was conducted for the B1 building case study. The contribution analyses and the sensitivity indices were calculated for the GHG emissions indicator.

Error! Reference source not found. presents the contribution analyses of the Swiss building B1 for the different RSP, for the probabilistic LCA for the GHG emissions. The median of the replacement rate is plotted, along with the first and third quartiles. As expected, looking at the median value, the share of the manufacturing stage decreases, from 57% to 23%, while the replacement environmental impact increases,

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[15] The 95% confidence interval of the mean is narrow [$\mu = 23.22\ \mathrm{kg\,CO_{2-eq}}\ /(\mathrm{m^2y}) \pm 0.05$], revealing the accuracy of the simulations.

from 15% to 42%, when shifting from 30 years to 120 years. This is due to the shift in the life cycle stages, when the RSP is extended: the share of the replacement phase increases, since replacement occurs more times, during 120 years, while the impact of the initial construction (manufacturing stage) decreases, since it is apportioned to much more years.

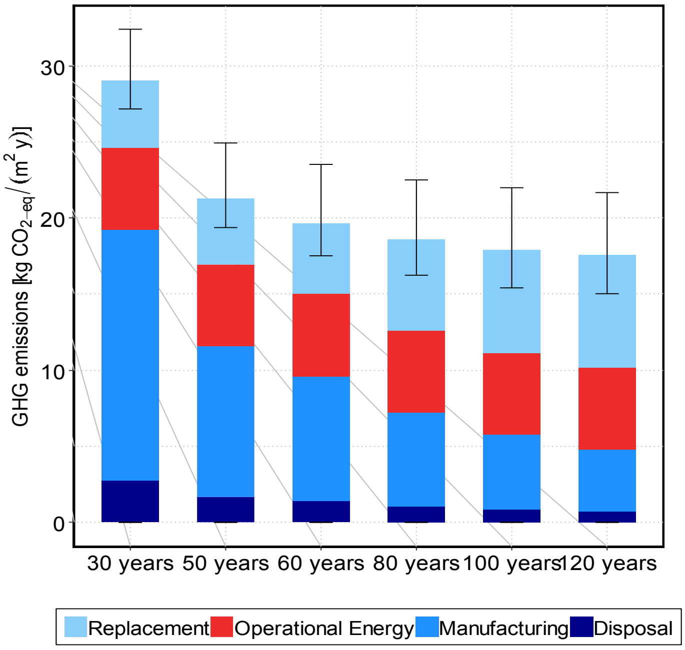

Figure 3.4: Contribution analyses for the probabilistic GHG emissions using the DUREE database for different building lifetimes of 30, 50, 60 80, 100 and 120 years, taken from Lasvaux et al (2020) and Goulouti, Padey, Galimshina, Habert & Lasvaux (2020)

Figure presents the results of the ***scenario analysis*** for the 6 different RSP values using the Sensitivity Analysis and Sobol' Indices of the probabilistic LCAs. The outcomes of the sensitvity analyses for different RSP for one building (B1) are the following:

- The same influential building elements can be identified as presented in the Swiss case study in Section 3.1
- Varying the reference study period (RSP) of the building from 30 to 120 years leads to a significant variation of the sensitivity indices of the most influential element types. Thus, the RSP is an influential parameter on the LCA and LCC uncertainty.

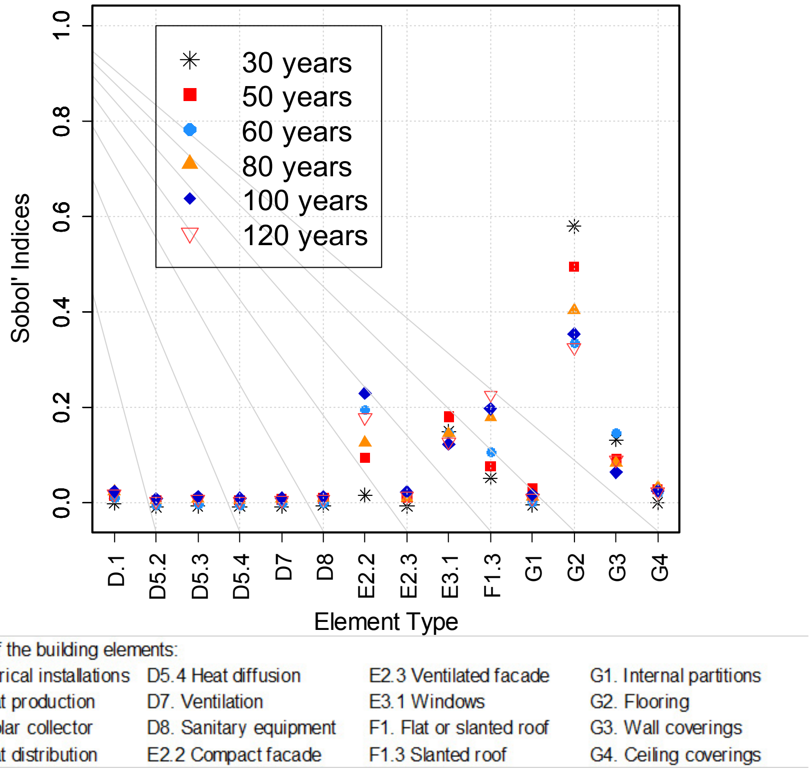

Figure 3.5: Sobol' Indices for the GHG emissions and the B1 case study for different building lifetimes of 30, 50, 60, 80, 100 and 120 years, taken from Lasvaux et al (2020) and Goulouti, Padey, Galimshina, Habert & Lasvaux (2020)

3.4 Replacement Rate Calculation

The same building case study (B1) is used as already presented in Table 3.1. The baseline scenario for reporting the LCA results in above sections considers the fractional mode, as defined in SIA 2032 and SIA 2040. In the current section, the fractional mode is compared with the rounded mode, according to SN EN 15978 (CEN/TC 350, 2011). In addition, the "rounded - 20%" mode is included. According to this mode the replacement rate is rounded up, in case that it is higher than 20% of its integer value, otherwise it is rounded down. Such a calculation mode may be implemented in some of the building LCA calculation software, as for example in Logiciel Pleaides ACV (Izuba-Energies, 2019). Like that, overestimation is avoided in case that the replacement rate is very small, e.g. k = 1.05.

Figure presents the PDF of the B1 case study for the GHG emissions. The three different ways of calculating the replacement rate result to slightly different PDFs (differences approximately 14%, for the mean), with the following properties, i.e. $[\mu = 24.5\ \mathrm{kg\ CO_{2-eq}}\ /(\mathrm{m^2 y}),\ (\sigma^2 = 2.7^2)]$, $[\mu = 25.5\ \mathrm{kg\ CO_{2-eq}}\ /(\mathrm{m^2 y}),\ (\sigma^2 = 3^2)]$, $[\mu = 22.0\ \mathrm{kg\ CO_{2-eq}}\ /(\mathrm{m^2 y}),\ (\sigma^2 = 3^2)]$, for the rounded 20%, rounded up and fractional mode, respectively.

Figure presents the Sobol' Indices for the three different calculation modes for the replacement rate. The results show that the tendency of the sensitivity indices remains the same, independently of the calculation type. As a result, even if rounded up, or rounded - 20% may better reflect the reality of the replacement rates, the use of the fractional replacement rate does not change the order of the sensitivity indices and their impact on the LCA uncertainty.

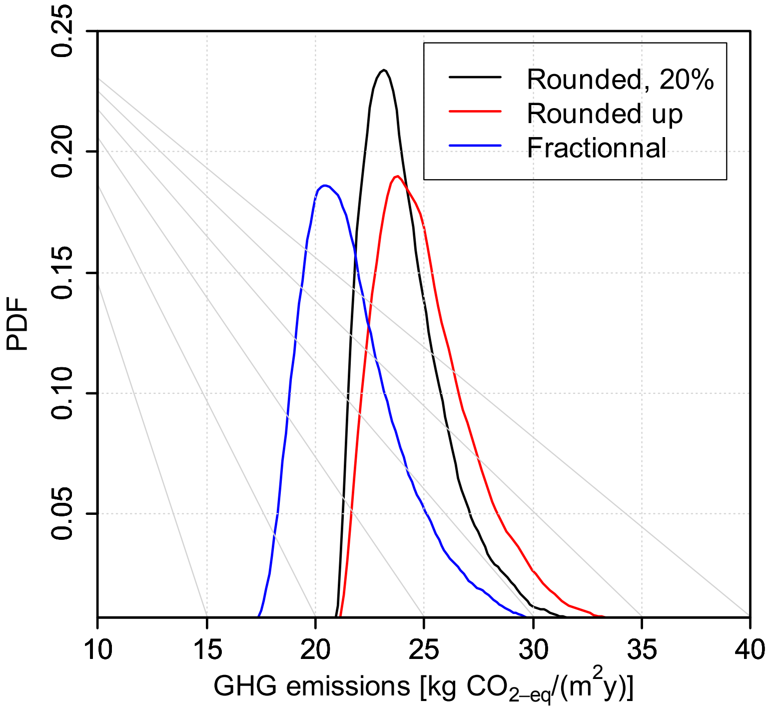

Figure 3.6: PDFs of the probabilistic LCA of the B1 case study, using the three calculation modes taken from Goulouti, Padey, Galimshina, Habert & Lasvaux (2020)

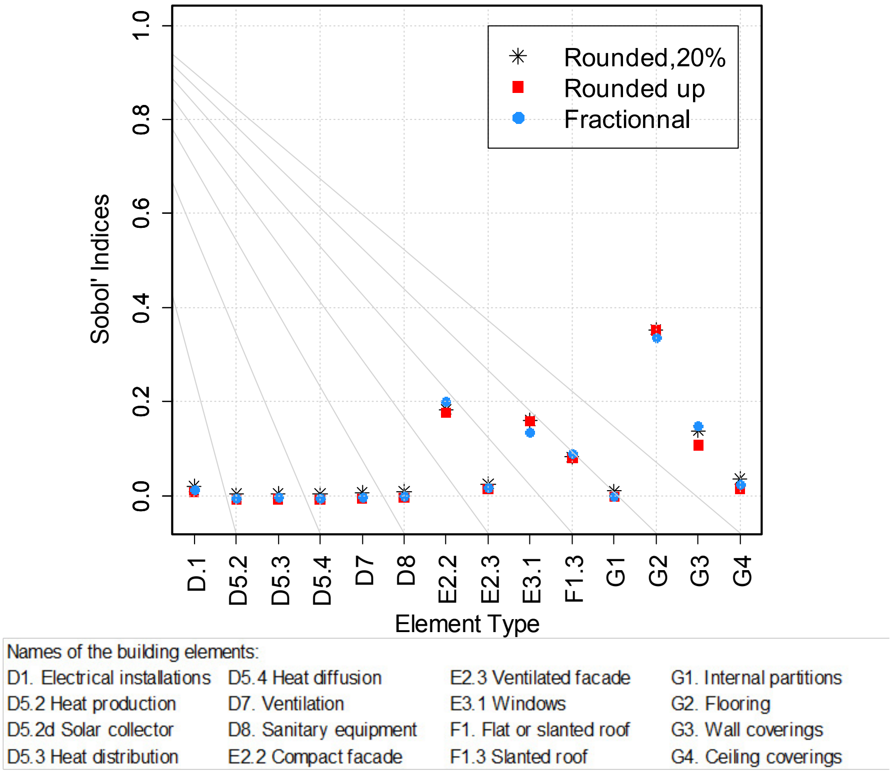

Figure 3.7: Fractional, rounded up, rounded 20% influence on the Sobol' Indices for the GHG emissions and the B1 case study, taken from Lasvaux et al (2020) and Goulouti, Padey, Galimshina, Habert & Lasvaux (2020)

The outcomes of the sensitvity analyses for different RSP for one building (B1) are the following:

- The same element types can be identified as presented in the Swiss case study in Section 3.1.
- The LCA uncertainty is not influenced by the calculation mode of the replacement rate, i.e. fractional according to Swiss SIA 2032 / SIA 2040 standard or rounded up according to SN EN 15978 standard. Hence, both modes could be used in further LCA analysis.
- The results show that the tendency of the sensitivity indices remains the same, independently of the chosen calculation method. As a result, even if rounded up and rounded (20%) may better reflect the physical reality of replacement rates, the use of a fractional rate does not change the sensitivity of the LCA.

3.5 Case Study's Limitation and Conclusions

This case study concerns only one LCA indicator (GHG emissions), tested for one system boundaries (Swiss LCA method from SIA 2032 & SIA 2040 technical books), and for one building case study. The complete research study supporting this project's report can be found in the DUREE project final report[16] and associated papers[17,18].

Last but not least, this case study helps to better understand the consequences of uncertain service lives values, uncertain reference study period for buildings but does not contain yet rules and guidance for a better modelling of module B4. The next chapter presents the rules and guidance.

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[16] Lasvaux S. et al 2019. "DUREE Project: Analysis of lifetimes of building elements in the literature and in the renovation practices and sensitivity analyses on building LCA & LCC case studies", Swiss Federal Office for Energy (SFOE), Final report, June 2019, available online: https://www.aramis.admin.ch/Dokument.aspx?DocumentID=50999.

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[18] K. Goulouti, P. Padey, A. Galimshina, G. Habert, S. Lasvaux 2019. "Dataset of service life data for 100 building elements and technical systems including their descriptive statistics and fitting to lognormal distribution", Data in Brief, Volume 36, June 2021, available online (Open Access): https://www.sciencedirect.com/science/article/pii/S2352340921003462

4. Conclusions and Guidance on How to Handle Replacements (Module B4)

The following conclusions, rules and recommendations come from the main A72 report by Lützkendorf, Balouktsi and Frischknecht et al. (2023).

Module B4 makes a significant contribution to the results of a building LCA. Components and systems that are either replaced very frequently or cause high environmental impacts (initially and when replaced) are important. For the modelling of B4, there are different methodological questions for which methods need to provide answers. First, the definition of the service lives for different types of building elements is unavoidable. Special attention should be given to building elements whose uncertainty may have an important impact on the final LCA result. Second, there are several approaches to calculate the replacement rate based on components' service lives. Third, a matter of question is at what level of detail the service life of a component comprised of several layers of varied service lives must be fixed. Rules and recommendations for action are provided below to support the handling of such calculations in building LCAs (Table 4.1 and gray box below).

Table 4.1: Rules on how to model replacements

ISSUE(S)		RULE(S)
How to deal with the uncertainty of building elements' service lives?	1.	Default values for the service lives of all possible construction products and technical equipment shall be provided
	2.	For fixing the default values for the most influential service lives of building elements on the total LCA result, uncertainties shall be handled, robustness of results shall be checked (through ranges)
How to calculate the replacement rate of building elements?	3.	It shall be clearly stated whether Approach A (Annualised impacts per building element), approaches R1, R2 or R3 (rounded up approaches) or S (simulation) shall be followed when calculating the replacement rate. Particularly, for approach R3, it shall be made clear for which components, products and equipment the number shall be always rounded up (never rounded down) including a justification.
At which level of detail shall the service life of a building element be defined?	4.	If two products/layers are typically replaced at the same time, the two components shall not be distinguished in the view of their service lives even if literature sources provide different service live for these two products. At least, the lowest service life shall be used for both materials (layers).

Recommendations for action

National standardisation bodies (application / use case: C, see Table 1.2)

a. Develop and provide tables with default service life values for building elements and construction products

b. Provide service life ranges for influential building elements based on empirical evidence to assist designers to examine the robustness of the LCA results following a probabilistic approach

Developers / providers of sustainability assessment systems (application / use case: C, see Table 1.2)

c. use the default service life values for building elements provided by your national standards.

Researchers (application / use case: B, see Table 1.2)

d. run sensitivity analyses to investigate the significance of effects of various service life ranges for different components on the final LCA outcome

e. provide empirical evidence on the actual service life of building components under different conditions of use

Construction product manufacturers (application / use case: F, see Table 1.2)

f. provide different default values for service life according to different conditions of use

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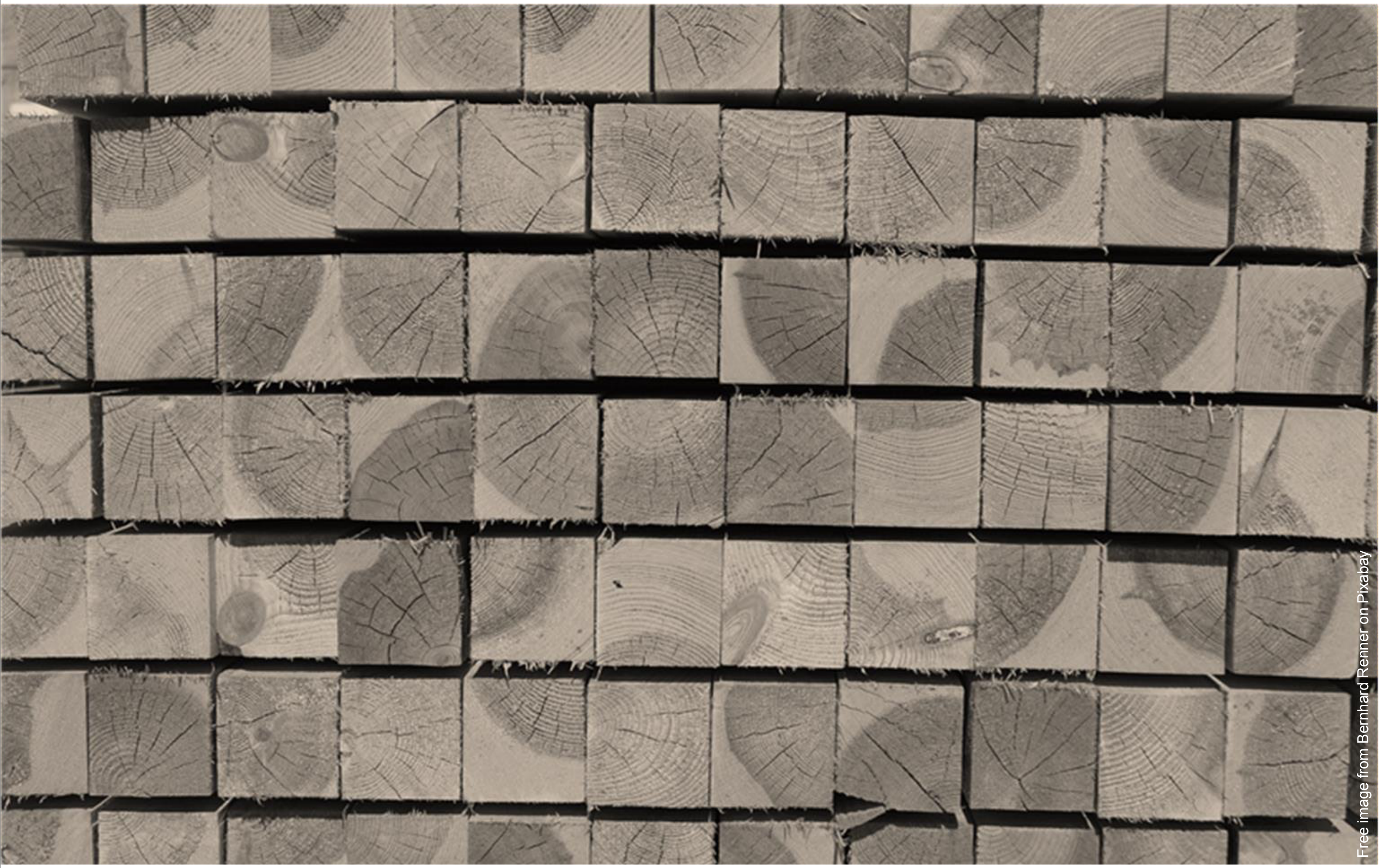
Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon

A Contribution to IEA EBC Annex 72

February 2023



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Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” ” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and Recommendations on Influence of Future Electricity Supplies on LCA-based Building Assessments (Zhang 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

There is a general consensus that CO2 emissions contribute significantly to climate change and that mitigation is one of the most important challenges of the current generation. At least since the new EN 15804+ A2:2019, which distinguishes between emissions from fossil and biogenic sources, there has been discussion on how to address emissions from biogenic sources. The current report discusses the different approaches to assessing biogenic carbon. The approaches have different methods to allocate emissions within the observed system.

The report provides an overview and explanation of the most common approaches to assessing biogenic carbon. In LCAs for buildings, biogenic CO2 is typically accounted for using two different approaches: the 0/0 approach (or carbon-neutral approach) and the -1/+1 approach. The 0/0 approach considers only the contribution of greenhouse gases from fossil sources, while the -1/+1approach considers the uptake of CO2 emissions during the growth of biogenic materials and their release at the end of the life cycle. The overall results at the end of the life cycle should be the same, the only difference being that the -1/+1 takes into account fluxes of biogenic carbon. There are also approaches that use time-dependent characterization factors and propose two different possible scenarios: (i) assuming that uptake occurs before the building is constructed, i.e., before the material is harvested, thus following the natural carbon cycle, or (ii) assuming that uptake occurs after the bio-based material is harvested, taking into account the regrowth of trees, thus compensating for exactly the amount of material that was harvested.

The report evaluates biogenic carbon fluxes using the various approaches discussed and provides recommendations for (a) the inventory level and (b) the impact assessment level. The use of wood/biomass materials is desirable, but it is important that the whole life cycle is considered to avoid misinterpretation of results. Requirements should be formulated not only for A1-A3, but should also include the associated disposal modules C3-C4. As an alternative, requirements for A1-A3 should be formulated separately for GWPfossil and GWPbiogen. Due to limited consensus, dynamic modelling of biogenic carbon should be used with caution, while that standards shall be relying on static characterization factors and a net-zero life-cycle balance for biogenic CO2 (Modules A1-C4), unless the biogenic carbon is permanently and safely stored in dedicated underground storage or permanently stored in carbonated cement used in concrete.

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Abbreviations

Abbreviations	Meaning
A72	IEA EBC Annex 72
CF	Characterisation Factors
DOCf	Degradable Organic Carbon Fraction
EoL	End-of-Life
EPD	Environmental Product Declaration
GABC	Global Alliance for Buildings and Construction
GWP	Global Warming Potential
GTP	Global Temperature Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
NZ	New Zealand
RSL	Reference Service Life

Definitions

Global Warming Potential (GWP): Impact category (or characterization factor for climate change) describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time. A time frame of 100 years is currently most commonly used and accepted. [kg-CO2eq] (adapted from ISO 14067:2018)

Carbon content: refers to the amount of carbon stored in (physically contained in) a product or building. This physical carbon is contained in biogenic products such as timber (called biogenic carbon) as well as fossil-based products such as plastics.

Energy source: source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

Energy carrier: substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes.

1. Introduction

The contribution of buildings to global greenhouse gas emissions (GHG) is widely acknowledged (IEA GABC 2018). Many strategies to lower resource consumption and emission intensity during buildings' life cycle have been proposed during the last decades, with varying reduction potentials. Using so-called 'bio-based' products, i.e. materials based on renewable feedstocks that absorb CO_2 during their growth, has been increasingly proposed as a climate change mitigation measure (Ministère de la transition écologique, 2020; Pomponi & Moncaster, 2016; Moschetti et al., 2019; Peñaloza et al., 2016, Carcassi et al., 2022). Among the realm of bio-based products used in buildings, wood stands out as a historically adopted structural choice, mostly in light-framed construction or low-rise residential buildings (Churkina et al. 2020) and in recent years, with cross-laminated timber (CLT), in multi-storey apartment and office buildings (Hoxha et al 2020). With the increasing acknowledgement of steel and concrete as energy or GHG emission-intensive products, design decision makers in general gradually opt for using wood as a replacement of the latter traditionally employed structural materials.

Nonetheless, the potential reduction in GHG emissions from replacing minerals or metal-based materials with wood (or other bio-based products) must be properly estimated. Through a range of indicators, the international standardized method of life cycle assessment (LCA) has been used to calculate the impacts of new solutions and projects. The LCA method has four main steps: goal and scope definition, life cycle inventory, impact assessment and interpretation.

Global warming potential (GWP) is the indicator used to translate the effects of emissions of GHG generated during a building's life cycle into their contribution to increased radiative forcing. The most common gases contributing to the GWP indicator are the CO_2, CH_4, N_2O and CO. CO_2 emissions should be distinguished between fossil and biogenic sources. Biogenic CO_2 is absorbed during the growth of biobased materials (Carcassi et al. 2022).

In the 6th assessment report of IPCC, it is stated that every tonne of CO_2 emission adds to global warming resulting in a near linear relationship between cumulative CO_2 emissions and the increase in global surface temperature, irrespective of the time when the emission takes place (Figure 1, IPCC 2021). This is a fact which is important to keep in mind when reading this report.

The modelling of biogenic carbon in life cycle assessments of buildings still lacks methodological consensus (Hoxha et al. 2020). Typically, in building LCAs, biogenic CO_2 is accounted for using two different approaches: the 0/0 (or carbon neutral) approach and the -1/+1 approach. The first considers by default that the uptake of CO_2 during the growth of the bio-based material is compensated by its release at the end of its service life (Hoxha et al 2020). Consequently, the 0/0 approach considers only the contribution of gases from fossil sources to the GWP calculation. The -1/+1, on the other hand, considers both the uptake during growth and the release at the end of life (Hoxha et al. 2020). Standards (EN 15804:2019) highlight that if the uptake is accounted for, the release must also be considered in end-of-life recycling, landfilling and incineration. The life cycle-based greenhouse gas emissions arising from the two approaches should be equal, the only difference being that with the -1/+1 approach one can track the biogenic carbon flows throughout the full life cycle.

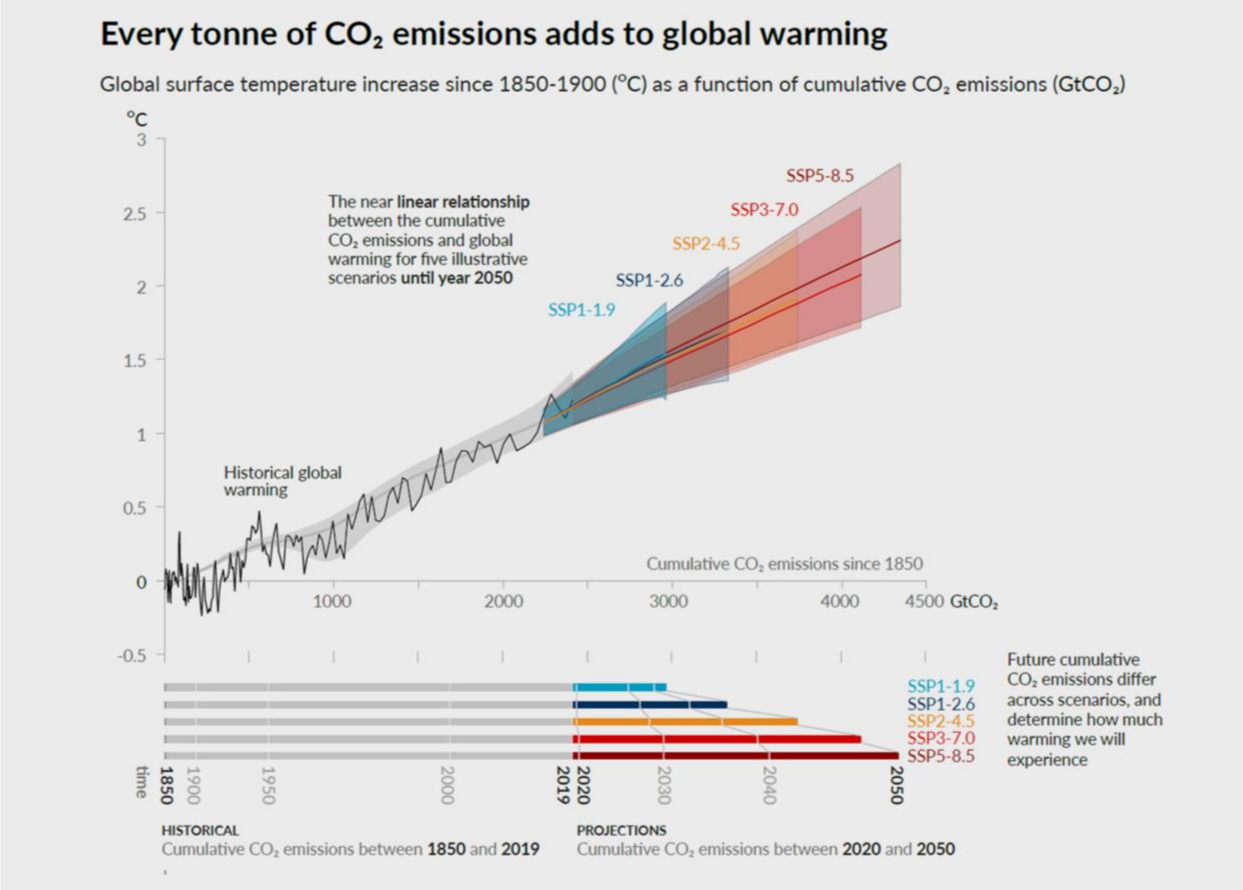

Figure 1: Near-linear relationship between cumulative CO_2 emissions and the increase in global surface temperature (IPCC 2021).

Aiming at solving the abovementioned issues, the so-called ‘dynamic’ or ‘time dependent’ approaches for biogenic carbon accounting have been developed with focus on carbonation of recycled concrete with biogenic CO_2 and bio-based materials modelling (Guest et al., 2013; Cherubini et al., 2011; Arehart et al., 2021) and others which can be applied to any context, product or system (Levasseur et al., 2010). The definition of time-dependent characterization factors proposed by Levasseur et al., (2010) is based on some key value-based choices when it comes to calculating biogenic carbon uptake in bio-based products used in buildings. Two different scenarios have been addressed in literature: (i) assuming that the uptake happens before the building is constructed, i.e., before the harvesting of the material, following the natural carbon cycle or (ii) assuming that the uptake happens after the bio-based material is harvested, considering regrowth of trees, compensating for the exact amount of material that was harvested (Peñaloza et al., 2016). The dynamic calculation approach has been portrayed as a pertinent way to account for biogenic CO_2 uptake and release in buildings LCA (Hoxha et al., 2020), and it has harnessed the attention and interest of policymakers who aim to define rules for wood products modelling in LCAs (Ministère de la transition écologique, 2020; Zibell et al. 2021).

Considering the lack of consensus on the appropriateness of the different currently available methods to account for biogenic carbon in buildings, this chapter aims to discuss the opposing views and derive recommendations based on the calculation guidelines published by the Intergovernmental Panel on Climate Change (IPCC, 2021) and the increasing knowledge on carbon sources, sinks and deriving budgets.

The report is structured in two main parts: discussion and recommendations for biogenic carbon accounting at (a) **the inventory level,** and (b) **the impact assessment level**. The final section of the report presents a brief discussion on the development of non-binding orientation values or binding secondary requirements for greenhouse gases in building products, more specifically wood and biomass-based products.

2. The Inventory Level

2.1 The 0/0 Approach

The modular structure proposed in the European standard EN-15978 (2019) is used to subdivide the building system, including the product and construction stage (module A), use stage (module B) and end-of-life stage (module C). The subsequent product system is referred to as module D beyond the system boundary. Figure 2, extracted from Hoxha et al (2020), illustrates the 0/0 approach for a wooden product used in a building. A distinction is made between the forest system, the building system and a potential subsequent product system, in case of wood recycling. As can be seen in the figure, biogenic CO_2 is not considered in any of the modules. In the cases where wood is landfilled after reaching the end of its service life, the release of biogenic methane (CH_4) is modelled in module C, due to its higher impact on global warming compared to biogenic CO_2. Because biogenic CH_4 emissions shall be and are taken into account this approach is not to be considered nor called a "climate neutral" approach. Data collection for building LCAs following this approach therefore does not require any consideration of the amount of CO_2 absorbed during forest growth, nor released during end of life.

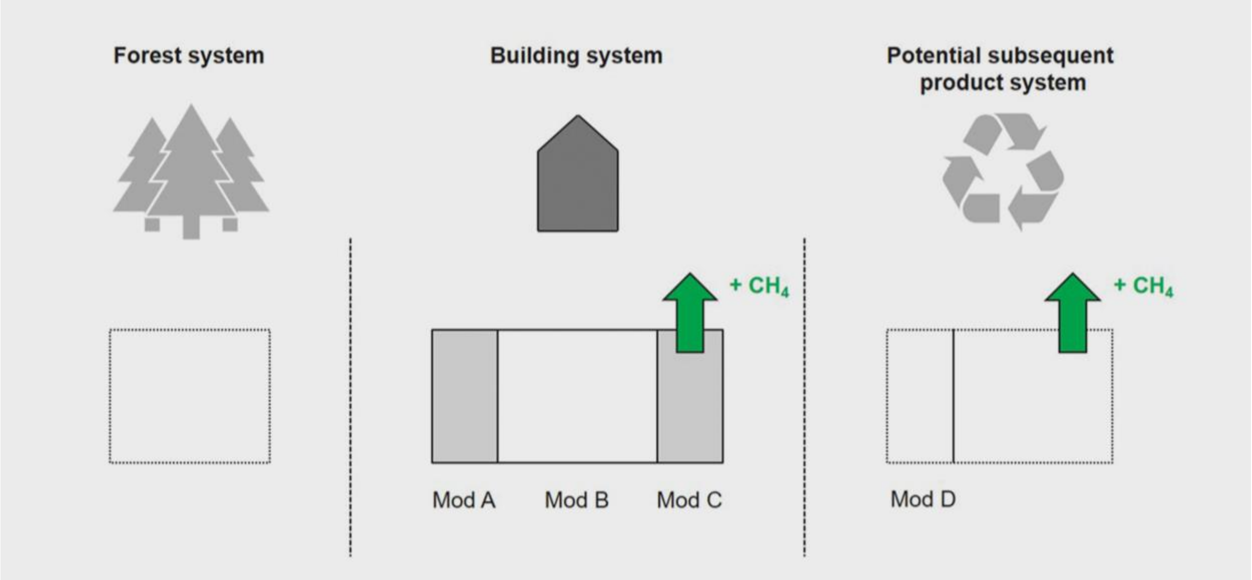

Figure 2: The 0/0 approach to model biogenic carbon uptake and release. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

2.2 The -1/+1 Approach

2.2.1 General

Figure 3 (Hoxha et al. 2020) illustrates the -1/+1 approach, in which both biogenic CO_2 uptake (-1) and release (+1) are considered, as well as the transfers of biogenic carbon between the different systems. The uptake of biogenic CO_2 during the forest growth is transferred to the building system and reported as a negative emission in module A, whereas at the end-of-life of the building, biogenic CO_2 (or CO or CH_4) is released or the carbon content is further transferred to a subsequent product system (in case of recycling). In both situations a positive emission is reported in module C. It must be noted that the biogenic CO_2 balance should be zero for all product systems. Also, because biogenic CH_4 emissions shall be and are taken into account this approach is not to be considered nor called a "climate neutral" approach.

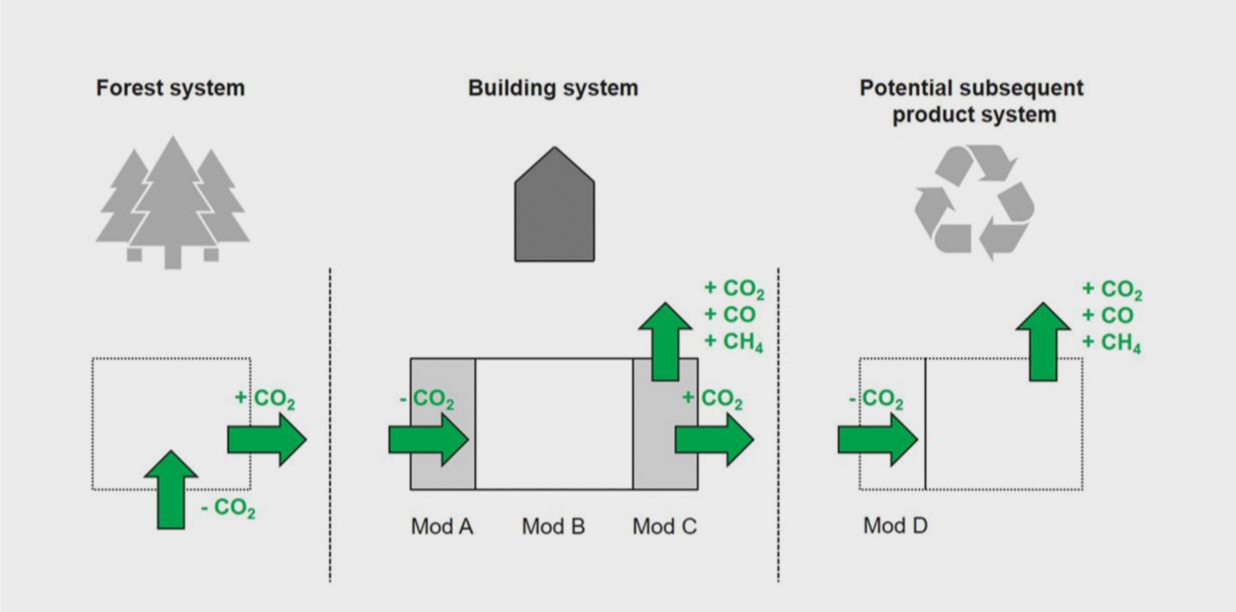

Figure 3: The -1/+1approach to model biogenic carbon uptake and release. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

Building LCAs conducted with the -1/+1 approach therefore require the calculation of the amount of CO_2 absorbed by the wooden product(s) used in the building, which – at the end of life – will be considered as released in its entirety. It is noteworthy, however, that typical life cycle databases currently do not include detailed, mass-balanced information on the biogenic CO_2 content absorbed by biobased materials during their growth. In fact, when encountering biogenic CO_2 information in life cycle databases, practitioners must ensure that the carbon balance is maintained, which might entail in some efforts regarding data adaptation.

2.2.2 The -1/+1* approach

In some countries, variations of the -1/+1 approach are observed, which are not allowed in others. A noteworthy variant is the -1/+1* approach, in which the right-hand-side depends on the end-of-life fate case of the product and on whether or not landfills are considered a permanent sequestration, or specifically whether it is recycled, sent to landfill (>0) or incinerated (+1) (Figure 4). The -1/+1* means that the fixation of biogenic carbon is considered, but no or not all biogenic carbon is modelled as an emission at the end of life. In Australia, Canada, France and New Zealand, wood sent to landfill gets a GWP factor close to zero but substantially lower than +1. Wood that exits the system boundary, e.g. for reuse, recycling gets a “+1” in NZ, and then the potential benefit of its reuse, recycling is calculated in module D. The interpretation of landfills as a permanent or temporary sequestration varies among countries. In Australia and New Zealand, two values of degradable organic carbon fraction (DOCf) for softwood timber are allowed: NZ applies the lower value of 0.1% while AU could use either 0.1% or applies the higher value of 10% (Australian Government, 2016; Wood Solutions, 2020), which results in 99.9% and 90 % assumed permanent sequestration in NZ and AU, respectively. The comparison between New Zealand and Australia shows the impact of applying two different DOCf scenarios in landfilling, because the share of biogenic carbon released at end-of-life by incineration and degraded carbon in landfills is nearly the same (AU: 10.5%, NZ: 10.1%). Both countries use the same EPD datasets, which supply two different DOCf values for landfilled softwood timber: one option is a DOCf value of 10% estimated from Australia’s National Greenhouse Accounts (Australian Government 2016), and the other option is a DOCf value of 0.1% based on the bioreactor laboratory research on Australian Radiata Pine (Wang et al., 2011).

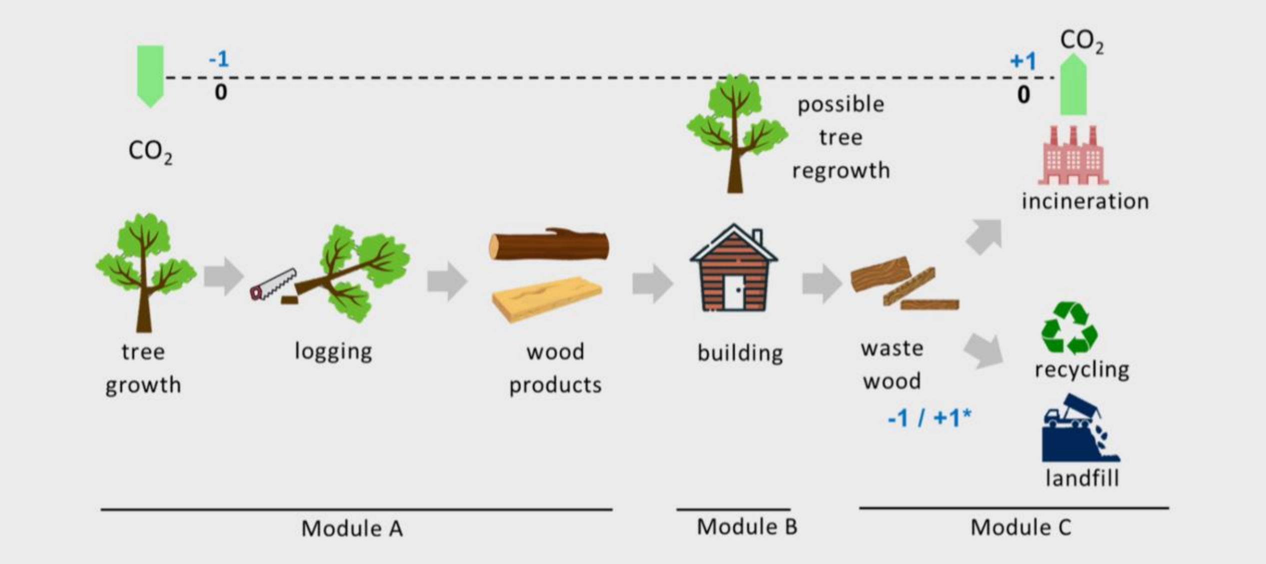

Figure 4: Methods applied on modelling biogenic carbon in the LCA bio-based products. Carbon fixation is assumed to happen either before the construction stage or carbon fixation during the use stage of the building life cycle.

It should be noted that extensive research in Australia over many years involving both bioreactor laboratory research and actual landfill studies of several softwood timber species and various types of engineered wood products (Ximenes et al., 2019) have largely supported the earlier results of (Wang et al., 2011). Summing up numerous studies and accounting for uncertainties, Ximenes at al. (2019) recommended a 1.4% carbon loss for wood in landfills in Australia and noted that "disposal of wood in landfills in Australia results in long-term storage of carbon, with only minimal conversion of carbon to gaseous end products".

In the French EQUER method (Table 1), negative biogenic CO$_2$ emissions are accounted for in the production stage if a new tree is growing which is the case for wood from certified forests. If the wood stems from non-certified forests, the same amount of carbon is stored in the building as if it were stored in the forest. Therefore, no carbon fixation is considered ("0" instead of "-1"). At the end of life, the quantity of biogenic CO$_2$ is emitted if the wood is incinerated, but not if the wood is landfilled or recycled (see Table 1). In France a 0/+1 approach is used if no tree is regrowing (i.e. the forest is transformed to agricultural or built-up land) or if the wood stems from native forests (EN 15804+A2) and the wood is incinerated at the end of life (meaning that no fixation of biogenic carbon is considered, but emissions do happen at the end of life).

Table 1: Biogenic carbon accounting according to the French Equer method

Timber harvesting	Production/ EoL-Incineration	Production/ Eol-Landfill, recycling or reuse
Sustainable forest management (a new tree is growing)	-1 / +1	-1 / >0
Other case (non-certified forest)	0 / +1	0 / >0

2.3 The Time-dependent Approach

The time-dependent approach is most frequently adopted by using the calculation procedure proposed by Levasseur et al. (2010). The following figures illustrate the two scenarios that can be considered related to the timing of biogenic carbon sequestration in the forest: (a) assuming that trees grow before the use of the harvested wood product, following the natural carbon cycle (Figure 5), or (b) accounting for the so-called "regrowth" after harvesting, assuming an equal amount of the harvested trees would start growing right after the production process (Figure 6) (Peñaloza et al., 2016; Pittau et al., 2018). Results may vary considerably between the two approaches (Peñaloza et al., 2016) - this issue is further detailed in the next section, related to the impact assessment level.

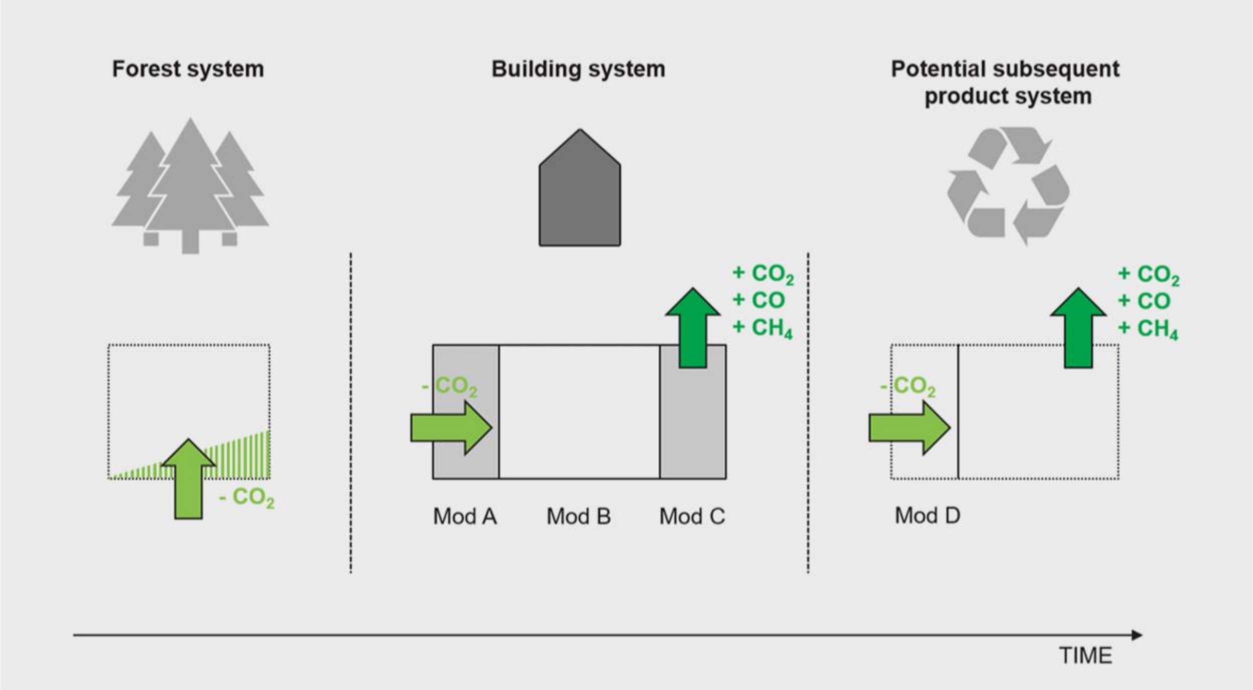

Figure 5: The time dependent approach, considering that trees grow before the use of the harvested wood product. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

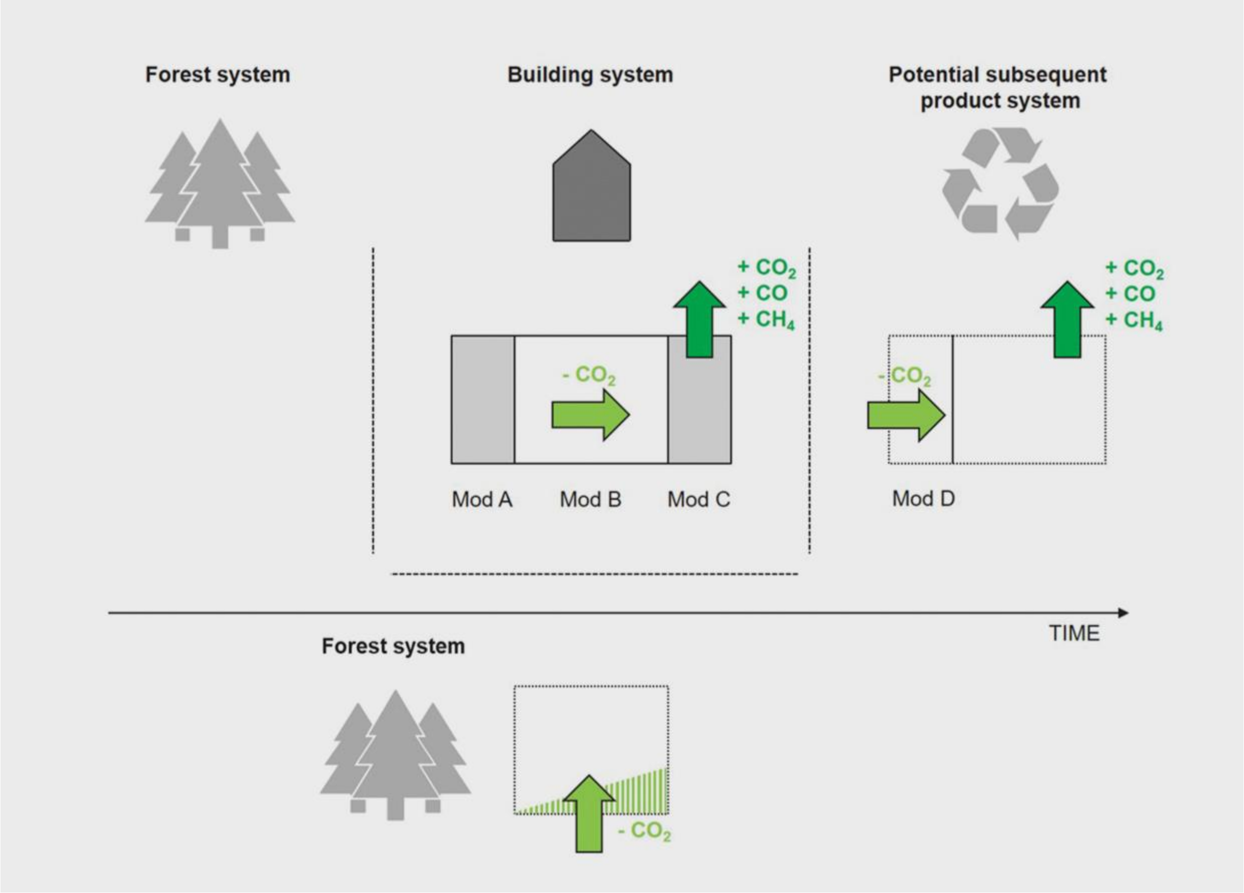

Figure 6: The time dependent approach, considering that trees regrow after harvesting. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

Analogously to the -1/+1 approach, the time-dependent approach requires that all biogenic CO_2 considered to be absorbed during trees' growth is released at the end of life. The data requirements in this approach, however, are more complex than in the previous one, because the practitioner would need to determine (i) a yearly amount of CO_2 being absorbed during material growth, instead of the full content of CO_2 in the wooden product, and (ii) the rotation period of the forest, i.e. the time it takes for the trees to reach maturity and be felled. It is not uncommon to find building LCA studies relying on detailed forestry models to determine the latter parameters (Hoxha et al. 2020, Pittau et al. 2020, Carcassi et al. 2022). In these cases, care must be taken to account only for the CO_2 that is actually transferred to the building system, i.e. "stored" within the mass of wooden product.

2.4 Key Messages and Recommendations at the Inventory Level

Considering the data and inventory modelling needs of these approaches, we hereby draw recommendations that should be considered regardless of the biogenic carbon accounting approach adopted:

a. The physical, life cycle-based balance of biogenic carbon contained in construction products, building elements and buildings shall be net zero. This may require significant adjustments in currently available life cycle inventories of materials based on renewable feedstocks such as wood. In particular, the allocation of raw material inputs shall reflect the physical flows irrespective of the allocation approach chosen. (Both 1 kg of wood beam and 1 kg of sawdust require an input of at least 1 kg of wood each.)
b. When construction materials containing biogenic carbon are either expected to be recycled or landfilled at the end of life of the building or the building element, an amount of biogenic CO_2 emissions equivalent to the biogenic carbon content shall be accounted for. Biogenic CO_2 safely and permanently removed and stored in dedicated underground facilities shall be treated differently.
c. If an existing building is replaced by a new one, the biogenic carbon stored in the existing building and the subsequent release of biogenic CO_2 shall be taken into account.
d. Natural flows of biogenic carbon in forests and on agricultural land (i.e. biogenic carbon not transferred into harvested products) left in forests such as branches, leaves and other residues shall be disregarded and not allocated to the products harvested.
e. The absorption of CO_2 shall not be accounted for, if the wood stems from forests which sold CO_2-emission certificates based on CO_2 absorption to third parties.

3. The impact assessment level

3.1 The 0/0 Approach

The calculation of the global warming potential (GWP) for the 0/0 approach follows Equation 1, which depicts the sum of the products of each greenhouse gas emission and their respective characterization factor, as defined by the IPCC. For simplification purposes, only CO_2, CO, N_2O and CH_4 emissions are considered in the equation. Since no biogenic CO_2 is accounted for in this approach, only fossil CO_2 emissions take part in the GWP calculation.

$$GWP_{0/0} = \sum_t g_{CO2,fossil}(t) * GWP_{CO2} + \sum_t g_{CH4,fossil+biogenic}(t) * GWP_{CH4} + \sum_t g_{CO,fossil}(t) * GWP_{CO} + \sum_t g_{N2O,fossil}(t) * GWP_{N2O} \qquad (1)$$

With:

$g_{CO2,fossil}(t) = \mathit{emissions\ of\ fossil\ CO_2\ at\ time\ t}$
$g_{CH4,fossil+biogenic}(t) = \mathit{emissions\ of\ fossil\ and\ biogenic\ CH_4\ (methane)\ at\ time\ t}$
$g_{CO,fossil}(t) = \mathit{emissions\ of\ fossil\ CO\ at\ time\ t}$
$g_{N2O,fossil}(t) = \mathit{emissions\ of\ fossil\ N_2O\ at\ time\ t}$
$GWP_{CO2} = \mathit{IPCC\ characterization\ factor\ of\ CO_2}$
$GWP_{CH4} = \mathit{IPCC\ characterization\ factor\ of\ CH_4}$
$GWP_{CO} = \mathit{IPCC\ characterization\ factor\ of\ CO}$
$GWP_{N2O} = \mathit{IPCC\ characterization\ factor\ N_2O}$

3.2 The -1/+1 Approach

3.2.1 General

The calculation of GWP when adopting the -1/+1 approach must also consider the uptake and emissions of biogenic CO_2, along with other greenhouse gas emissions (Equation 2). The sign used for the uptake of CO_2 shall be negative.

$$GWP_{-1/+1} = \sum_t g_{CO2,fossil+biogenic}(t) * DOCf_{CO2} * GWP_{CO2} + \sum_t g_{CH4,fossil+biogenic}(t) * DOCf_{CH4} * GWP_{CH4} + \sum_t g_{CO,fossil+biogenic}(t) * DOCf_{CO} * GWP_{CO} + \sum_t g_{N2O,fossil+biogenic}(t) * DOCf_{N2o} * GWP_{N2O} \qquad (2)$$

With:

$g_{CO2,fossil+biogenic}(t)$ = emissions and removals of fossil and biogenic CO_2 at time t
$g_{CH4,fossil+biogenic}(t)$= emissions of fossil and biogenic CH_4 (methane) at time t
$g_{CO,fossil+biogenic}(t)$= emissions of fossil and biogenic CO at time t
$g_{N2O,fossil+biogenic}(t)$= emissions of fossil and biogenic N_2O at time t

GWP_{CO2} = IPCC characterization factor of CO_2
GWP_{CH4} = IPCC characterization factor of CH_4
GWP_{CO} = IPCC characterization factor of CO
GWP_{N2O} = IPCC characterization factor of N_2O

$DOCf_{CO2}$ = degradable organic carbon fraction of CO_2 (for the -1/+1 approach the value is 1)
$DOCf_{CH4}$ = degradable organic carbon fraction of CH_4 (for the -1/+1 approach the value is 1)
$DOCf_{CO}$ = degradable organic carbon fraction of CO (for the -1/+1 approach the value is 1)
$DOCf_{N2O}$ = degradable organic carbon fraction of N_2O (for the -1/+1 approach the value is 1)

3.2.2 The -1/+1* approach

The calculation of GWP when adopting the -1/+1* approach must also consider the uptake and emissions of biogenic CO_2, along with other greenhouse gas emissions (Equation 4). The sign used for the uptake of CO_2 shall be negative. The formula for the -1/+1* approach is the same as the formula for the -1/+1 approach expect that the emissions and removals of the greenhouse gasses are multiplied by the degradable organic carbon fraction (DOCf) that is not equal 1. For further information about the DOCf used for the -1/+1* approach see also 2.2.2.

3.3 The Time-dependent Approach

To properly comprehend the dynamic characterization factors proposed by Levasseur et al. (2010), one must understand how the traditionally employed characterization factors are calculated. Two main factors have to be considered: (a) the radiative efficiency of the gas (Hartmann et al. 2013), or, in very simple terms, its capability to absorb solar radiation; and (b) the decay pattern of the gas, which indicates how the concentration of a certain gas in the atmosphere changes with time after an emission pulse. The calculation approach consists in multiplying the decay equation (time-dependent) of each GHG by their specific radiative forcing per unit of mass, which is represented by the division of the radiative efficiency (assumed to be constant) by the GHG concentration. The resulting equation (Equation 3) – still a function of time – coupled with the amount of GHG emitted, governs the instantaneous radiative forcing curve, indicating how much an emission of a certain quantity of that GHG can increase the radiative forcing in the atmosphere.

$$IRF = A_i \cdot C_i(t) \qquad (3)$$

Where Ai is the radiative forcing per unit mass. For the CO_2, CH_4 and N_2O the values are respectively: $A_{CO_2} = 1.76 \cdot 10^{-15}$Wm-2kg-1; $A_{CH_4} = 1.28 \cdot 10^{-13}$Wm-2kg-1; $A_{N_2O} = 3.9 \cdot 10^{-13}$Wm-2kg-1.

Ci is the decay equation of each GHG (represented by i). For CO_2 emissions and assuming a background concentration of 378 ppm, the Bern carbon cycle-climate model is used. It presents the decay in time of the initial unitary impulse at t = 0 (Joos et al. 2001):

$$C_{CO_2}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot e^{\frac{-t}{\tau_i}} \qquad (4)$$

$C_{CO_2}(t)$ is the decay pattern of a CO2 pulse emission.

a_i are the coefficients for the calculation of CO2 fractions remaining in the atmosphere. They have the values: $a_0 = 0.217$; $a_1 = 0.259$; $a_2 = 0.338$ and $a_3 = 0.186$.

τ_i are the perturbation time. They have the values $\tau_1 = 172.9$; $\tau_2 = 18.5$; $\tau_3 = 1.186$ years.

For the other GHGs, the first order exponential decay function is used as described by Equation 5:

$$C_{CH_4,N_2O}(t) = e^{\frac{-t}{\tau}} \qquad (5)$$

The perturbation times for CH_4 and N_2O gases are respectively $\tau = 12$ years and 114 years (Shine et al., 2007).

Then, one must calculate the cumulative effect in radiative forcing, by integrating the instantaneous radiative forcing curve (described by Equation 6) for a certain period of time. The definition of the time in which the curve is integrated is called the 'time horizon' of the GWP calculation, and equals the moment in which the warming effect is observed. Typically, a 100-year time horizon is adopted as this is the time horizon applied in the Kyoto protocol and all international negotiations.

$$CRF = \int_0^t A_i \cdot C_i(t) \qquad (6)$$

To quantify the cumulative radiative forcing of the emission of 1 kg of a greenhouse gas in relation to that of 1 kg of CO_2, the result for the cumulative radiative forcing of a certain amount of GHG is divided by the cumulative radiative forcing effect of a same amount of CO_2 (Equation 7).

$$GWP_{TH} = \frac{\int_0^{TH} A_i \cdot C_i(t)}{\int_0^{TH} A_{CO_2} \cdot C_{CO_2}(t)} \qquad (7)$$

In typical GWP calculations, the IPCC determines the cumulative effect of 1kg of each GHG, in relation to that of CO_2, for a set of fixed time horizons (20 and 100 years for the GWP and 20,50 and 100 for GTP- while the GWP is a measure of the heat absorbed over a given time period due to emissions of a gas, the GTP is a measure of the temperature change at the end of that time period relative to CO_2), obtaining the so-called characterization factors (CF). That allows an LCA practitioner to obtain an aggregated value of the GHGs emitted during the life cycle of a product or system by using these official CFs. This is the exact approach used in Equations 2, 3 and 4, for 0/0, -1/+1 and -1/+1* approaches, respectively.

The proposal of time-dependent CFs by Levasseur and colleagues (2010) was based on these authors' judgement that when applying the fixed CFs to emissions happening at different times, one would get the cumulative effect of global warming at different moments in the future. Adding up these values to represent the full life cycle GWP is perceived by the cited authors as an inconsistency and a breach of the LCA's time horizon. Claiming to adjust this, Levasseur et al (2010) proposal consists on integrating the instantaneous radiative forcing function (Equation 3) in yearly time steps instead of applying a fixed time horizon – therefore getting a CF for each year in an analysis. These yearly CFs are multiplied by the emission (or uptake) happening in that respective year, and eventually added up to represent the total global warming effect at a certain (arbitrarily fixed) time horizon. The cause and source of emissions (reference study period (RSP) of building) and impacts of those emissions are independent of each other and thus (may) have different time periods.

This latter time horizon is a choice to be made by the LCA practitioner. The results will vary quite significantly depending on this arbitrary choice. If calculating the overall warming effect 100 years after the building was built, the effect of emissions associated to the end of life of the building (say 75 years after it was built) is significantly underestimated – because 25 years later there is a "cut-off" of that effect due to the time horizon adopted.

Since the time-dependent approach moves away from the agreed upon reasoning behind the calculation of CFs by the IPCC, valid questions can be raised as to its robustness and/or relevancy:

a. there are no recommendations for time dependent CFs in any official IPCC documents, despite the proposal having been published over ten years ago;

b. the concept of time zero for GWP calculation is different than time zero for a specific LCA: the IPCC assumes that time zero for GWP calculation is the time of emission, regardless of whether it is happening today or a few decades from now;

c. the setting of the time horizon for time-dependent LCAs seems to carry a political weight: a short TH decreases the relevance of emissions happening at a later stage, pointing to a stimulus on short-term solutions to control climate change, whereas a very long TH allows for the perception that delaying emissions for a few decades has a negligible effect on the overall warming of the atmosphere.

3.4 Key Messages and Recommendations at the Impact Assessment Level

Considering the opposing views on the calculation of GWP in so-called “static” (0/0 and -1/+1) and time-dependent approaches, we hereby draw important messages to be considered in building LCAs containing wood products:

a. If opting for a time-dependent assessment of biogenic carbon flows, the time horizon at least be set to 100 years plus the final year of the reference study period (let’s say, 50 or 60 years after the construction). With this time horizon, the results of the dynamic assessment and of the -1/+1 approach (if the carbon balance mentioned in section 2 is assured) are identical.

b. Renewable materials used in building elements and buildings store biogenic carbon temporarily1. The temporary biogenic carbon storage has hardly any effects on the overall cumulative radiative forcing nor on the overall temperature increase. However, it offers a few decades of time to develop technologies to separate biogenic carbon and store it permanently after the end of life, either in buildings or in dedicated final carbon repositories.

Considering the need for clear practical guidelines in building LCAs that shall allow for harmonization and benchmark creation, the recommendations of the authors are:

c. Since the publication of Levasseur et al. (2013) scientific knowledge regarding climate change and CO_2 emissions progressed. While annual budgets were discussed in the past, global total budgets are considered relevant today (IPCC 2021). Hence, the time of release of a ton of CO_2 does not matter and has hardly an influence on its ultimate effect on the longterm rise of global mean surface temperature (which should not exceed 1.5°C). Hence, the GWP of an emission of CO_2 shall be independent of time and equal 1 kg CO_2-eq per kg.

d. The integration time (usually 100 years) used to determine the global warming potential (GWP) and the global temperature increase potential (GTP) applies independently of the time of release of CO_2 and other greenhouse gases. The integration time on one hand and the reference study period and the lifetime of a building on the other are fully independent. A fixed time horizon (of e.g. 100 years) shall not be reasoned with the (fixed) integration time used to determine GWP and GTP.

e. Still, acknowledging the importance of benchmarks and of increasing CO_2 uptake and storage, it is recommended to introduce legally binding benchmarks on biogenic carbon content (minimum biogenic carbon content in a building, >XX kg $C_{biogenic}/m^2$), since it is justified to believe that during the period of temporal carbon storages new technologies will be developed that will provide the possibility of permanent storage. Such a benchmark shall be kept separate from a carbon footprint benchmark (maximum fossil greenhouse gas emissions, <XX kg CO_2-eq/m^2 and/or < xx kg CO_2-eq/m^2a). The next section further discusses binding benchmarks and recommendations thereof.

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[1] Considering the fact that landfilling is forbidden. Since there are also special cases, like the -1/+1* notes herein and in the submitted journal paper (i.e., esp. the conclusions and recommendations therein), this report recommends that jurisdictions about landfill practice and measure/present DOCf values are developed. As an international guideline, this report should recognize that some (or many) countries use landfills primarily (or where incineration is not the main or only practice, etc. and should also provide recommendation how to handle these cases.

4. GWP as a Requirement in Legislation

In connection with funding conditions and legislative initiatives to limit greenhouse gas emissions in the life cycle of buildings, represented as GWP, the question arises as to whether and to what extent GHG emissions as a result of the production (and construction) of the building (i.e. embodied emissions) can and should be introduced in the form of non-binding orientation values or binding secondary requirements for modules A1-A3 or A1-A5.

According to EN 15804 A2 and EN 16643, the information on GWP should be additionally subdivided into GWP_{fossil}, $GWP_{biogenic}$ and GWP_{luluc}. This makes it possible to distinguish between fossil and biogenic greenhouse gas emissions. The -1/+1 approach is part of $GWP_{biogenic}$. Emissions of biogenic methane are also accounted for in the latter indicator. Shares caused by land use or land use change (luluc = land use and land use change) are usually neglected. In addition, the content of biogenic carbon in the material, product and structure shall be reported in "kg C", as briefly mentioned in the previous section.

If partial characteristic values for A1-A3 are taken from life cycle assessments for buildings, this part corresponds to the -1 approach for A1-A3. Shares according to +1, to be assigned to module C, are then not visible. In the case of above-average use of products made of wood or biomass in the production and construction of the building, the sub-value A1-A3 for GWP_{total} can assume very small or even negative values. Larger amounts of fossil GHG emissions are supposedly compensated by negative $GWP_{biogenic}$ contributions. The question arises as to the steering effect of corresponding effects.

Annex 72 experts identify three separate positions on how to handle the issue:

Position A:
Low or negative values for A1-A3 with above-average use of wood/biomass are desirable and are intended to have a steering effect in the direction of increased use of renewable raw materials.
In a national view of greenhouse gas emissions in annual slices, they show that CO_2 is removed from the environment in the growth phase. However, assigning this to the time of construction of the building is a gross simplification and does not apply to wood in particular. The situation is different for fast-growing biomass, where there is approximately a temporal correspondence. However, the time of storage of CO_2 (as well as its release) is not decisive for the overall global temperature increase.
When considering annual emissions in annual slices at the national level, two additional considerations would have to be made: (1) How many GHG emissions will be released this year by the end-of-life of dismantled products? (2) How many GHG emissions will be released at what point in time by the end of life of products now in use and can this point in time be delayed by further use/cascade use? Again, it is pointed out that this is not important with regard to global warming effects as a whole.
There is a (small) risk of using wood/biomass beyond necessity in the interest of low values at A1-A3. There is also a risk of false incentives. In particular, negative values would suggest that more extensive construction measures benefit the environment. This can only be put into perspective by including other indicators and makes it clear once again that an isolated consideration of greenhouse gas emissions is not a solution.

Position B:
The use of values according to -1/+1 for sub-values (as orientation values, secondary requirements or as main requirements) to A1-A3 is considered methodologically not permissible. In particular, the lack of visibility of emissions at the end of the life cycle is met with criticism. The use of the 0/0-approach for an isolated presentation of A1-A3 is discussed. In this way, corresponding products are included in the consideration as "greenhouse gas neutral" in the area of biogenic GWP.

On the other hand, however, this can be interpreted as a methodological break and produces problems of presentation when dividing an LCA into phases A, B and C.

Position C1:

Requirements should not be formulated for A1-A3 alone, but mandatorily take into account the associated disposal modules C3-C4.

Position C2:

As an alternative to C1, requirements for A1-A3 should be formulated separately for GWP_{fossil} and $GWP_{biogenic.}$ In addition, land register entries must be made to ensure that the quantities of biogenic and fossil carbon used in buildings are separated and permanently sequestered during demolition.

5. Conclusions

Considering the current state of knowledge on dynamic modelling of biogenic carbon in buildings, the scientifically questionable application of a fixed time horizon and the derivation of time dependent GWP factors, the variability and uncertainty due to choices of important (newly introduced) parameters, and the lack of consensus on the latter, standards and regulations for LCAs of buildings shall rely on static characterisation factors and on a net zero biogenic CO_2 balance over the full life cycle (modules A1-C4) unless the biogenic carbon is permanently and safely stored in dedicated underground storage facilities[2] or permanently stored in carbonated cement used in concrete.

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[2] Certain jurisdictions and national authorities have published documented/measured values on the degradable organic carbon fraction in landfills, which allows to determine the share of landfilled biogenic carbon released back to the atmosphere. Some countries such as Australia and New Zealand use this information to determine the net sequestration of biogenic carbon in the life cycle of buildings.

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Level of knowledge and application of LCA in design practice: results and recommendations based on surveys

A Contribution to IEA EBC Annex 72

February 2023

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Level of knowledge and application of LCA in design practice: results and recommendations based on surveys

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of the project IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

In the context of IEA EBC Annex 72, several surveys were carried out and evaluated. In a survey, the level of knowledge of designers around assessing the environmental performance of buildings and using life cycle assessment (LCA) in the design process to support decisions, as well as the need for further development of principles and tools for a wider use of LCA, were analyzed.

This background report focuses on the topic of applied LCA in the design process. In most cases, the surveys were carried out with the support of the national and regional architects' associations in the following countries: Australia (AU), Austria (AU), Canada (CA), China (CN), Czech Republic (CZ), Denmark (DK), Finland (FI), France (FR), Germany (DE), Hungary (HU), India (IN), Italy (IT), The Netherlands (NL), New Zealand (NZ), Norway (NO), Portugal (PT), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), United Kingdom (UK), United States (US). The response rate among the participating countries varies a lot.

Together with this background report, several papers have been published. A list is part of introduction on page 11.

Summary

The progress in dealing with the basics of an applied life cycle assessment (LCA) as a prerequisite for quantitative assessments of the environmental performance of buildings and its direct application in the design process is very dynamic on the one hand and shows major differences on the other hand. While some designers already have knowledge of the basics and experience with LCA application, others are taking a wait-and-see attitude for thew moment but are planning to deal with the topic more intensively in the mid-term future. It became clear that the following prerequisites must be met for a wider use of LCA as a tool for assessing environmental performance:

- Demand and reward of such services by clients
- Legal requirements including clear methodological bases
- Quality-assured data and public available data basis
- Quality-assured assessment tools
- Offers for training and further education.

In countries where these conditions exist or are just being created, the use of LCA is increasing significantly. Some of the designers in these regions perform LCA themselves during design (preferred way of working) or commission specialized service providers.

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Abbreviations

Abbreviations	Meaning
BIM	Building Information Modelling
EPBD	Environmental Performance of Buildings Directive
GHG	Greenhouse Gas Emission
IEA	International Energy Agency
LCA	Life Cycle Assessment

1. Introduction

The achievement of goals to reduce operational and embodied environmental impacts in the life cycle of buildings as a contribution to sustainable development is linked to various prerequisites. One of them is the integration of calculation processes, design comparisons and evidence of achievement of the corresponding goals in the design and decision-making processes for new construction and refurbishment projects. This in turn is linked to the fact that the actors involved are aware of the problem and are motivated to devote themselves to this task, as well as are sufficiently qualified and have the necessary means and opportunities.

Developments in recent years and decades have led to the provision of various design and assessment principles, methods and tools. In particular, the use of LCA as an instrument for quantifying and assessing life cycle-based environmental impacts of buildings enables to determine and assess the operational and embodied impacts in context and to influence them in a targeted manner during the design process. In addition, there is the further development of:

- corresponding methods for calculation and assessment, including their harmonization through standardization activities with specific application reference for building products and buildings,
- the provision of data and databases with environmentally relevant information on products and processes on a uniform basis,
- the development of calculation and assessment tools from simple component catalogs to complex software solutions (including BIM).

Reliable databases, clear methods and practical tools are also prerequisites for the introduction of binding life cycle-based environmental requirements for buildings.

Several groups of actors are directly and indirectly involved in the development of goals and requirements of an individual, institutional or legislative nature as well as in the corresponding design and decision-making processes. Thus, it is the task of the state to preserve the natural basis of life in terms of safeguarding future generations. The real estate industry combines securing the future viability of its companies with assuming responsibility for the environment and society, which has corresponding consequences for the formulation of the task for new construction and refurbishment projects and the management of building stocks. Increasingly, environmentally relevant features and properties are included in the valuation and the determination of financing conditions (e.g. TAXONOMY in Europe), which leads to a demand for corresponding information. According to the ideas of the European Commission (draft for the EPBD, 2021), the life cycle GHG emissions should be included as information in the mandatory energy certificate. On the other hand, the industry is increasingly willing to provide the required LCA data for building products of all kinds on a harmonized basis. The need for the exchange of information between actors along the value chain becomes clear.

Ultimately, the first goal is to influence the design of new construction and refurbishment projects in terms of resource conservation and climate protection - as additional requirements in an already complex target system. Calculations using the applied LCA are required, in which information from the quantity determination is linked to lifecycle-based environmental data of building products, services and processes. It is currently being discussed which groups of actors can fulfill these tasks. Sustainability auditors, energy consultants, cost surveyors and other service providers who can take on these tasks are under discussion. They would then have to prepare their results for the designers and be in close contact with them. But which tasks can the designers take on directly and are they adequately prepared for them and are the necessary framework conditions in place? What is the status of preparation for tasks that require the creation of an LCA and to what extent are such tasks already performed?

Answering these questions was the subject of a specific part of a survey prepared by IEA EBC Annex 72 that was carried out in several A72 participating countries and then assessed. Important results are presented here; otherwise, reference is made to the published results and conference papers:

– *Survey results on acceptance and use of Life Cycle Assessment among designers in world regions: IEA EBC Annex 72* (Balouktsi et al., 2022) – conference paper summarizing selected results of the survey
– *Drivers, barriers and development needs for LCA in the Nordic building sector: a survey among professionals* (Rasmussen et al. 2020) - conference paper summarizing selected Danish and Swedish results of the survey
– *Attitude Towards LCA in Hungary and Czechia: Results of a Survey among Building Design Professionals* (Szalay & Lupísek, 2022) - conference paper summarizing selected Hungarian and Czech results of the survey
– *The level of knowledge, use and acceptance of LCA among designers in Germany: A contribution to IEA EBC Annex 72* (Lützkendorf & Balouktsi, 2022) – conference paper summarizing selected results of the full report below
– *Integration of environmental aspects in the design process of buildings - state of knowledge, degree of implementation, proposals for action* (Integration von Umweltaspekten in den Planungsprozess von Gebäuden – Kenntnisstand, Umsetzungsgrad, Handlungsvorschläge) (Lützkendorf et al. 2020) – national report

The results of this survey can be combined with the results of other previous surveys on this topic, also in terms of tracking the progress made in some particular regions (e.g. see Table 1).

Table 1: Overview of selected previous surveys concerning the use of LCA in the building sector (Adapted from: Balouktsi et al., 2022)

Author	Topic	Target group	Geographic scope	No. of respondents
Klingele et al. (2007)	Environmental aspects and life cycle data in the building design	Architects & planners	Germany	305
Sibiude et al. (2014)	LCA-related needs of building stakeholders to feed back LCA tool developers	AEC community & public policy experts	France	121
Han & Srebric (2015)	Role of LCA in building system design process	Building system designers	US	96
Olinzock et al. (2015)	LCA use in the North American building community	AEC community	US	250
Schlanbusch et al. (2016)	Knowledge gaps and issues in building LCA and the role of BIM, need for collaboration between the Nordic countries	Wide range of stakeholders in the building industry	Nordic countries	57
WBCSD (2016)	Use of life cycle metrics	AEC community	World	69
Jusselme et al. (2020)	LCA at early building design stages	Architects & engineers	Europe	495
A72 survey	Dissemination and status of application of LCA	Architects & engineers	World	1166 (Europe: 956)

2. Method and Survey Design

This report focuses on the level of acceptance of LCA as useful tools/processes and the status of current application in the daily practice, as well as the identification of barriers/problems/gaps from the practitioner's point of view. To collect the viewpoint of building design professionals and consultants on these aspects in an effective and economical way, Annex 72 conducted an online questionnaire survey using Lime Survey software. The survey was disseminated in 23 countries using different instruments to increase visibility (e.g. mailing lists of association of architects, social networks and newsletters). The survey was also translated in 9 languages. Since the survey was web-based and adapted to the local language where necessary, responses could be effectively collected from a large number of design professionals. A total of 1166 answers were gathered after at least two successive reminders per country from 11/15/2018 and 12/15/2019.

The questionnaire was primarily composed of three types of questions: (a) single-selection multiple-choice questions (b) multiple-selection multiple-choice questions, (c) free textbox questions. Most of the multiple-choice questions also included a textbox where respondents could provide information beyond the pre-defined response categories. The whole survey had four parts, as illustrated in Figure 1, and it started with a welcome page that briefly explains the purpose, structure and duration of the survey, the procedures to be followed as well as that the survey is voluntary and confidential. In overall, the questionnaire survey was comprised of 48 questions. Acknowledging its significant length as a potential reason for abandoning it before its completion, the survey was designed in a flexible way so that participants can choose between a long and a short version.

Once individuals have chosen whether to continue with the short or long version, the first question concerns whether participants consider environmental performance requirements and assessment results in their design decisions. This first branching separates those respondents who are currently applying such assessments (regularly or occasionally) from those who are not. These two groups follow different questions in part A of the survey up to the first questions of part B where a second branching occurs that separates those respondents who also apply LCA from the basic "green designers". Then, all "branches" occurring are directly guided toward the questions in the second half of part B of the survey dealing with the application of BIM. After the completion of Part B of the survey, respondents can clearly be grouped into six groups (see Figure 1), with the most advanced being "BIM-LCA frontrunners", i.e. designers who are currently integrating both LCA and BIM into their decision-making process. The last four parts of the survey (C, D, E & F) are followed by all respondents.

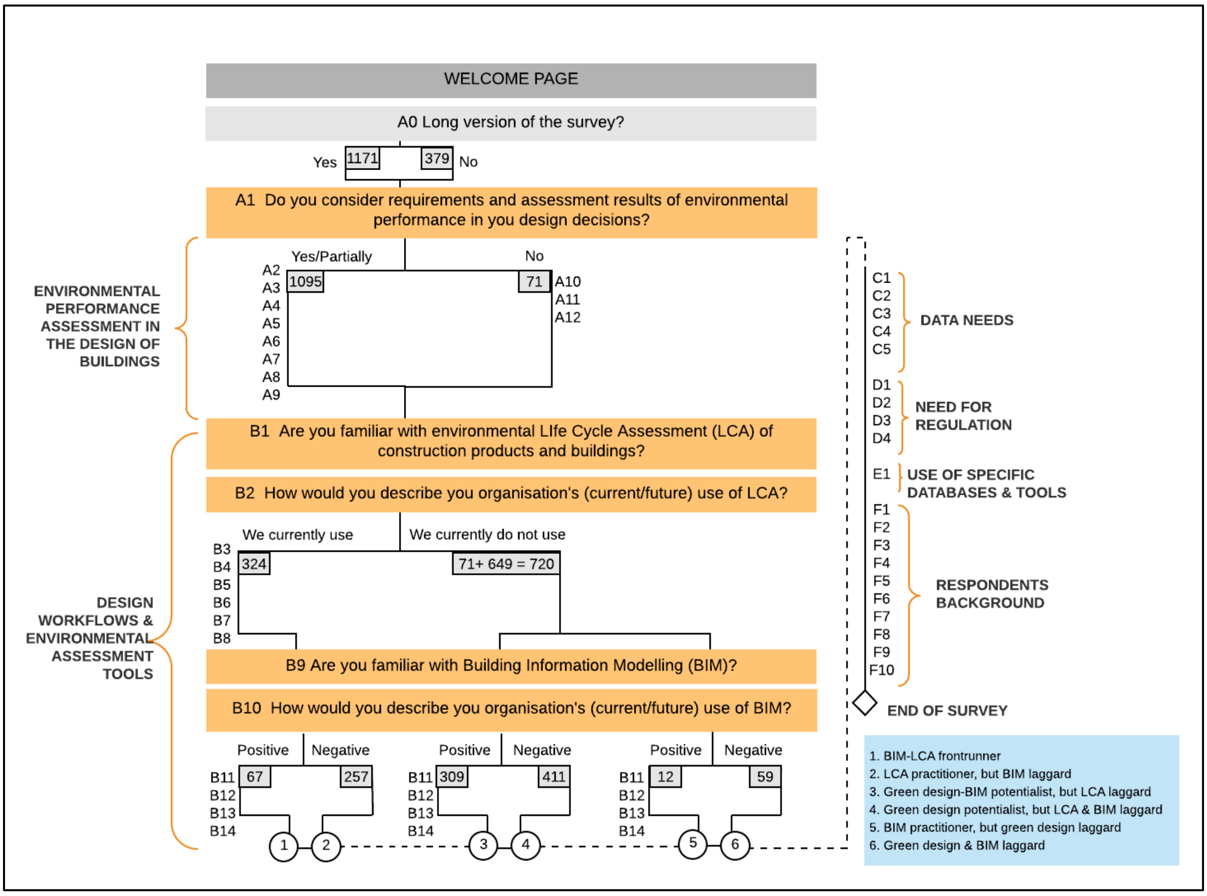

Figure 1: Schematic overview of the overall survey. The numbers in the rectangular grey boxes correspond to the number of respondents that followed each critical point of the survey. (Source: Balouktsi et al., 2022)

3. Key Results and Recommendations

First of all, it should be stated that the development of projects to reduce or avoid undesired effects on the global environment and the conservation of natural resources is a task of the government in its role as a legislator. In the case of a specific construction project, compliance and implementation is the responsibility of the clients, for whom the law stipulates the minimum requirements, but who also must live up to their responsibility towards the environment and society. Usually, clients are supported by designers. This results in close cooperation, which leads to the determination of design goals in early project phases. In addition to the requirements for technical and functional performance, goals for environmental, social and economic performance should also be defined and agreed upon – the principles for this are already part of the European standards. Environmental impact and resource use reduction thus becomes a design goal. It is therefore natural that these goals must be considered and achieved during design. This results in specific tasks for specific phases or steps of building design - see also report by Passer et al. (2022).

The situation in the individual countries, as well as in a country comparison, proved to be extremely heterogeneous, at least up to the date of responses to the survey. Dealing with life cycle assessment (LCA) tasks in the design was dependent on, among other things (from most important to least important on overage):

- level of demand by client
- the size of the design office/ in-house expertise
- the availability of information/data
- the existing regulations and incentives
- amount of time effort
- the previous training and further education on the subject

Looking at regions individually the significance of each factor changes based on the conditions in place. For example, the answers of DACH region are dominated by participants from Germany, where the availability of information is freely accessible (therefore less participants indicated this as a barrier).

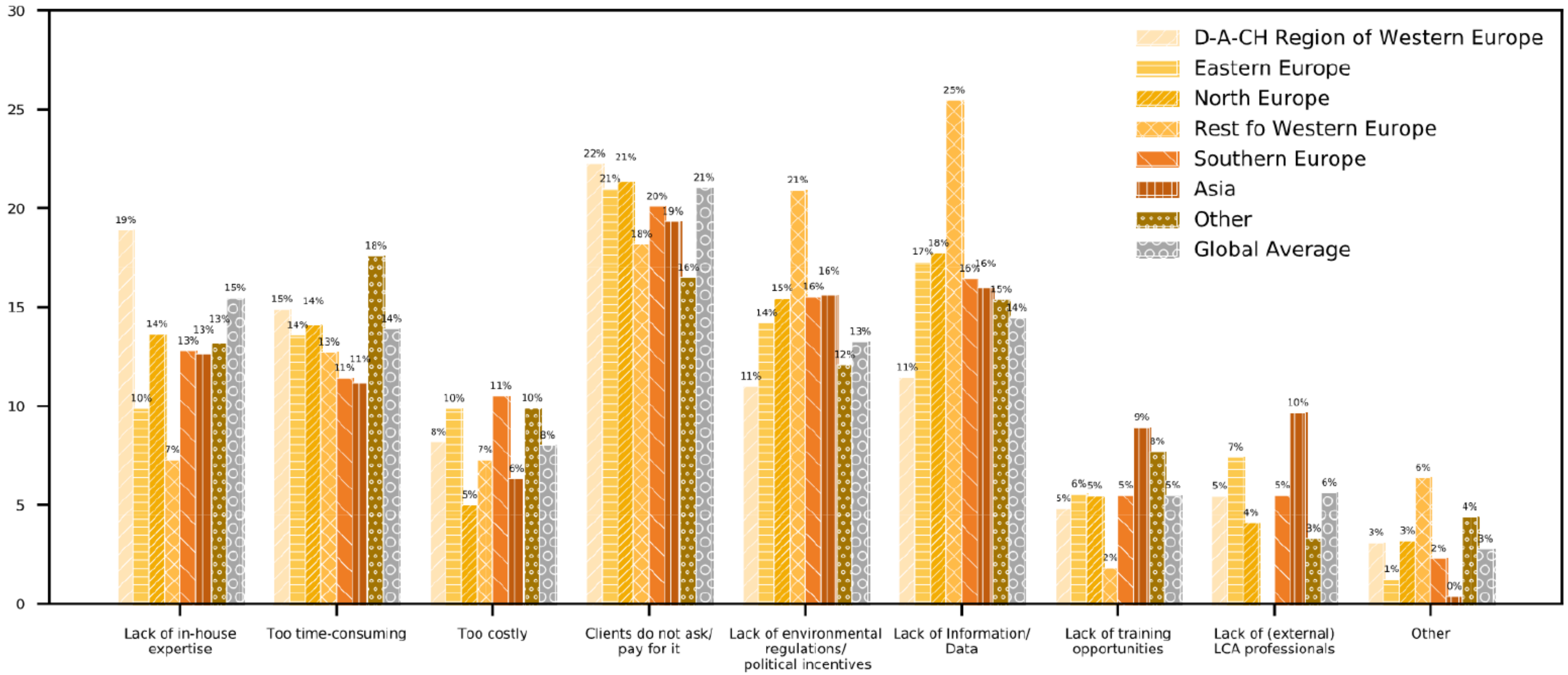

Figure 2: Answers to the question “What do you consider the main barriers to using LCA?”, including a division into regions. Note 1: based on 1044 respondents; multiple answers allowed; Note 2: The countries representing each region are (order starting with the higher number of respondents): DACH Region = DE + AT + CH, Asia = CN + IN, Southern Europe = ES + PT + IT + SI, Northern Europe = DK + SE + NO + FI, Eastern Europe = HU + CZ, Rest of Western Europe = FR + NL + UK, Other = CA + US + AU + NZ (Source: Balouktsi et al., 2022)

It became clear that there are big differences in:

- **the level of knowledge of the basics and details of an LCA**: The survey showed that many respondents are familiar with the basics of LCA but there is important lack of knowledge about its detailed application (about one third of respondents, see Figure 3).
- **the level of knowledge and application of relevant standards:** although over the last decade, strong support for LCA has been given by both international and European standardization activities, an impressively high number of respondents indicated that, not only they do not refer to international standards in their daily practice (which was expected), but they have not even heard of them (almost 60% of respondents).
- **the level of knowledge and use of existing tools:** Most respondents are not familiar with the different LCA databases and tools. As an average, less than one fourth applies such tools in the daily practice. When it comes to BIM as certain type of instrument gaining in importance in architectural practice, only a small share of respondents reported to currently apply BIM for integrating LCA data, while already one third of respondents use BIM for quantities extraction (see: Balouktsi et al., 2022).
- **the type and scope of personal experience with LCA**: although less than one third of the respondents are currently using LCA in their decision-making on average (Figure 4)[1], this share ranges from more 10% (Asia: CN + IN) to more than 70% (Western Europe: FR + NL + UK). The latter percentage is assumed to be high due to the legal requirements in place in France and the Netherlands (Lützkendorf, & Balouktsi, 2022). Positively, more than half of respondents are planning to use LCA in the medium-term future, on average.

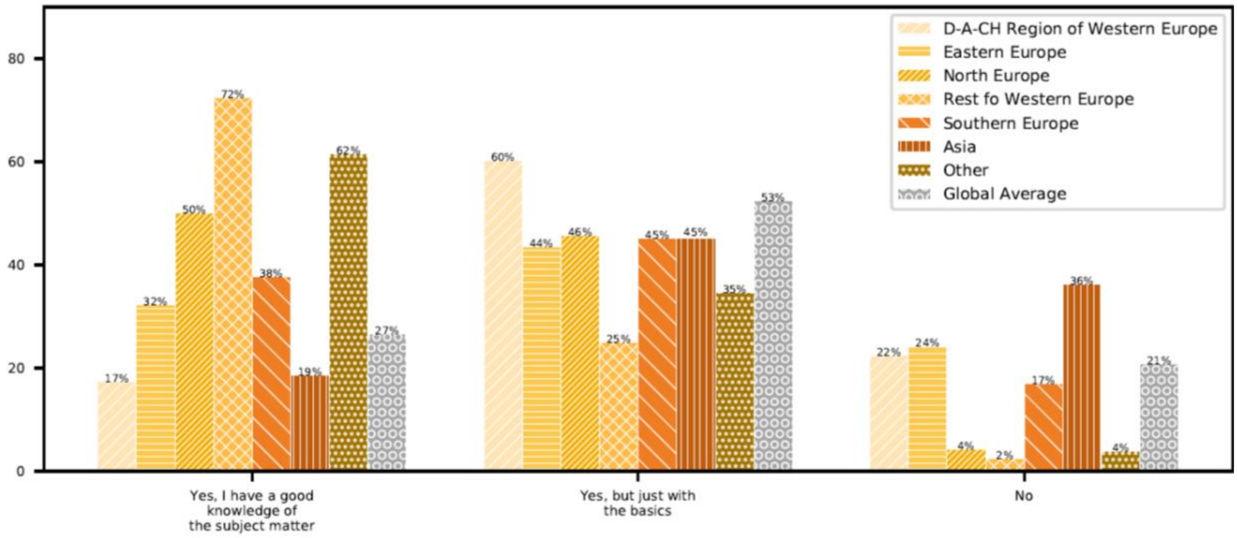

Figure 3: Answers to the question "Are you familiar with environmental Life Cycle Assessment (LCA) of construction products and buildings?", including a division into regions. Note 1: based on 720 respondents; Note 2: The countries representing each region are (order starting with the higher number of respondents): DACH Region = DE + AT + CH, Asia = CN + IN, Southern Europe = ES + PT + IT + SI, Northern Europe = DK + SE + NO + FI, Eastern Europe = HU + CZ, Rest of Western Europe = FR + NL + UK, Other = CA + US + AU + NZ (Source: Balouktsi et al., 2022)

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[1] It should be noted that the average share of designers regularly using LCA is influenced by the sample: DACH has by far the most respondents and a larger share of designers (after Asia) with no or little knowledge on LCA.

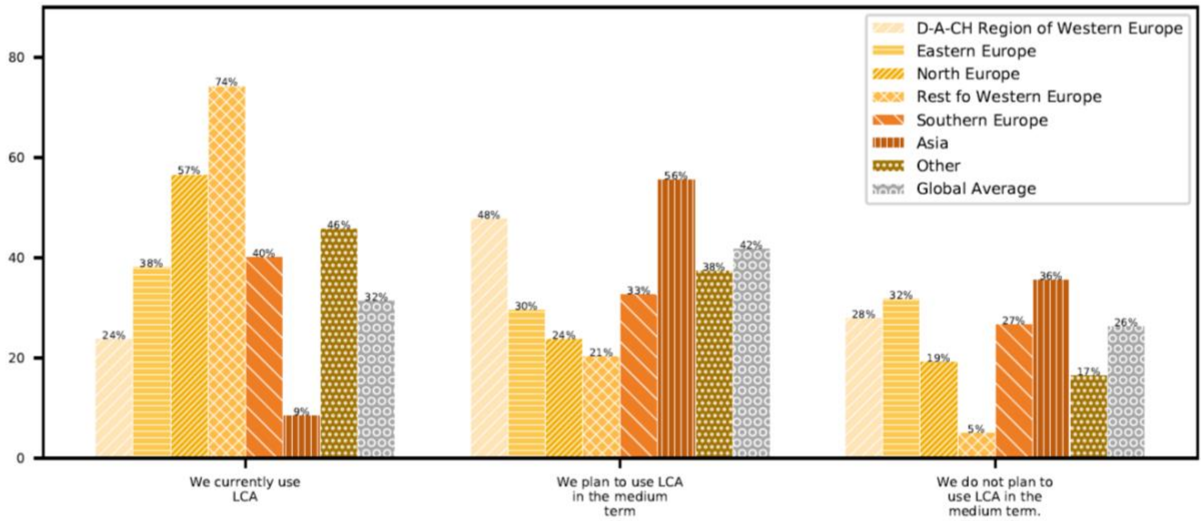

Figure 4: Answers to the question “How would you describe your organisation's (future) use of LCA?”, including a division into regions. Note 1: based on 720 respondents; Note 2: The countries representing each region are (order starting with the higher number of respondents): DACH Region = DE + AT + CH, Asia = CN + IN, Southern Europe = ES + PT + IT + SI, Northern Europe = DK + SE + NO + FI, Eastern Europe = HU + CZ, Rest of Western Europe = FR + NL + UK, Other = CA + US + AU + NZ (Source: Balouktsi et al., 2022)

As a result, some of the designers are already preparing LCA and others are preparing to be able to offer this in the near future. Another part of the respondents would like to subcontract such tasks. Only a small proportion of designers do not want to get involved in this area of responsibility in the medium term.

In particular, the - planned or already implemented - introduction of relevant funding programs and/or legal requirements means that the demand for corresponding expertise and authorization is growing rapidly. Requirement values will be tightened to such an extent that subsequent calculations by experts will not suffice. The need for design-accompanying use is therefore once again pointed out.

The situation will improve in the medium term. Comparable to the tasks involved in determining costs, reference values and experiences emerge that will make the designer's work easier until they can fall back on knowledge they have gained themselves.

The tasks of the designers are seen, among other things, in:

- If assessment of existing buildings with regard to energy consumption, emissions, convertibility, refurbishability
- Advising clients on finding and setting goals, advising on legal requirements and funding programs
- Creation of LCAs as part of design in the context of building and component optimization and to support variant comparisons
- Creation of evidence that the client makes available to third parties (including building supervision, bank, valuation professionals)

The following recommendations can be given for the expansion of possibilities for the design-accompanying use of the applied LCA:

- Integration of the determination, assessment and targeted influencing of the environmental impacts of buildings as well as the provision of the required evidence in the service profile of the building design with instructions for individual work phases - see the related work by Royal Institute of British Architects (RIBA)[2], among others.
- Assignment by the client and appropriate remuneration including the provision of time and fee funds for variant comparisons
- Legal requirements to limit the use of resources and the undesirable effects on the environment in the life cycle of buildings; if necessary, it is recommended to start by including binding requirements in funding programs (package of methods, databases, calculation and verification rules) – e.g. this has been the most recent approach in Germany[3].
- Provision of easily accessible and generally recognised/tested calculation values/databases for the creation of life cycle assessments, such as the German database Ökobau.dat and the Swiss databases KBOB.
- Provision of practical design and assessment tools of varying complexity (software, component catalogues)
- Offers for training and further education
- Expansion of the range of services offered by specialist designers, consultants and life cycle assessment experts

Note: This summary includes insights that were gained up to early 2020. Attention is drawn to the high dynamics of the development of this topic.

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[2] For details, see: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work, as well as, https://riba-prd-assets.azureedge.net/-/media/GatherContent/Test-resources-page/Additional-Documents/RIBASustainableOutcomesGuide2019pdf.pdf?rev=5013ea18b10949f1af0a14cb439fcb32

[3] E.g. see information on the QNG label (only in German): https://www.nachhaltigesbauen.de/austausch/beg/

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Survey on the use of national LCA-based assessment methods for buildings in selected countries

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al. 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023)
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023)

It is important to mention that parts of the analysis of in this report is based on a survey among experts via a questionnaire which was realized during 2020. The authors would like to acknowledge the following survey contributors in addition to the ones already identified in the author list: Laetitia Delem (Belgium), Julie Železná (Czech Republic), Paul Mittermeier & Anna Braune (Germany) Erik Alsema (Netherlands), Ricardo Mateus (Portugal), Groupe AGECO (Canada) and Manish Dixit (USA).

Summary

This background report examines existing mandatory or voluntary national assessment methods for the life cycle related environmental impacts caused by buildings (LCA-based methods for environmental performance assessment) with the aim to provide an overview of their major variations. Part of this overview also explores the type and extent of awareness and application of these methods in each country covered. The descriptions of the methods and the situation in different countries are based on a survey among the A72 experts.

This forms a first basis to develop rules and recommendations for national authorities and private organisations on how to create or improve such methods which was one of the main objectives of Annex 72.

Particularly, this report first provides a concise overview of the situation in 17 participating countries in Annex 72, covering Europe, Oceania, North America and Asia, and addressing the following topics:
- Historical background/ Beginning of the application of LCA in the construction sector
- Situation in the field of LCA application /Application context
- Methodological bases
- Databases
- Number of applications and users
- Integration into the design process
- Acceptance and dissemination

The overviews cover the situation up to early 2021. In a second step, this analysis was also combined with a structured multi-part questionnaire to acquire more details of the methods, especially in relation to their differences in:
- System description
- Modelling aspects
- Environmental indicators
- Assessment standards, data, tools and benchmarks
- Market Conditions and driving forces

With the help of the questionnaire the details of 25 methods from 19 countries were reported and analysed. The analysis showed great variations among the methods in use. Each country has a different starting point and is at a different stage of development in this field. Nevertheless, to enable comparability and usability of lifecycle-based results, the provision of a consistent and transparent basis for a methodology and reporting structure for environmental performance assessment of buildings in line with international and regional standards is needed. The present background report intends to contribute to this.

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Abbreviations

Abbreviations	Meaning
AP	Acidification Potential
ADP	Abiotic Depletion Potential
A72	IEA EBC Annex 72
BIPV	Building-integrated Photovoltaic
EoL	End-of-Life
EP	Eutrophication Potential
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
HFA	Heated Floor Area
HVAC	Heating, Ventilation, Air-conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KBOB	Koordinationsgremium der Bauorgane des Bundes
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEP	Mechanical, Electrical and Plumbing
NFA	Net Floor Area
ODP	Ozone Depletion Potential
PE	Primary Energy
PE,nr	Primary Energy, non-renewable
POCP	Photochemical Ozone Creation Potential
RSP	Reference Study Period
SIA	Schweizerischer ingenieur- und architektenverein
VOC	Volatile Organic Compound

Definitions

Life cycle Assessment (LCA): LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a building, infrastructure, product or material throughout its lifecycle (ISO, 2006).

Global Warming Potential (GWP): Impact category (or characterization factor for climate change) describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time. A time frame of 100 years is currently most commonly used and accepted. [kg-CO2eq] (adapted from ISO 14067:2018)

Indicator: quantitative, qualitative or descriptive measure (ISO 15392:2019).

Life cycle stage: all consecutive and interlinked stages in the life of the object under consideration. The life cycle comprises all stages, from raw material acquisition or generation from natural resources to end-of-life (ISO 21930:2017).

Information module: distinct parts for a building's life cycle for which impacts are to be declared. Each building's life cycle stage is comprised of more than one information modules.

Operational impacts: Impacts associated with energy and water consumed during a building's operation.

Embodied impacts: When an environmental impact of a product is characterized as "embodied" it does not mean that it is really embodied in the product itself. It is used in a metaphorical sense to describe the impacts caused by life cycle stages of a product other than the operation (embodied in a virtual sense).

System boundary: boundary representing what building parts and life cycle stages are included and what not in the building assessment (adapted from EN 15978:2011)

Component: item manufactured as a distinct unit to serve a specific function or functions. A building component is a part of a building, fulfilling specific requirements/functions (e.g. a window or a heating system). The service life of a building component can be shorter than the full service life of the building. Building components are sometimes referred to as "building elements" (ISO 21931-1:2022).

Benchmark: reference point against which comparisons can be made (ISO 21678:2020).

Environmental Product Declaration (EPD): claim which indicates the environmental impacts and aspects of a product, providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information (prEN 15978-1:2021)

Reference unit: Denominator of a characteristic value to which the numerator is related.

1. Introduction

To develop a well-informed guideline for national authorities and private organisations on how to create or improve context-specific methods for the assessment of life cycle-related environmental impacts caused by buildings (A72 report by Lützkendorf et al. (2023)), it is important to examine existing methods and standards first. The aim of this background report is to provide an overview and analysis of existing national methods of/approaches to life cycle assessment of buildings, which in some cases are mandatory (i.e. part of building codes and regulations), in others voluntary (i.e. part of voluntary sustainability certification systems, national standards, funding activities or research activities), and to discuss the major variations in building LCA, and therefore the challenges of harmonising it. Part of this overview is also to explore the type and extent of awareness and application of the methods in the countries.

In order to analyse the possibilities of further development and gradual alignment of the methodological foundations, it is necessary to identify areas of potential alignment and context-specific reasons behind key methodological choices. To this end, this background report presents the results of an international survey among the in Annex 72 involved experts and country representatives on the methodologies applied to assess the environmental impacts of buildings in some of the participating countries.

Regardless of whether an official mandatory or voluntary national method is in place, Section 2 provides a concise overview of the situation in some participating countries in Annex 72 in relation to:

- Historical background/ Beginning of the application of LCA in the construction sector
- Current situation in the field of LCA application /Application context
- Methodological bases
- Databases
- Number of applications and users
- Integration into the design process
- Acceptance and dissemination

This overview covers the situation up to late 2020/early 2021. For the Annex 72 participating countries with a particular method in place, details of the methods were provided by means of a multi-part questionnaire which was filled out by country representatives or national experts. A short analysis of the answers is presented in Section 3. The questionnaire survey intended to reveal the various levels of development of different methods and differences in approaching life cycle environmental assessments of buildings. Topics covered were:

- System description
- Modelling aspects
- Environmental indicators
- Assessment standards, data, tools and benchmarks
- Market conditions and driving forces

2. Short Overview of State-of-the-Art of Environmental Life Cycle Assessment of Buildings as a Method in Selected Countries Around the World

2.1 Situation in Europe

2.1.1 Austria

Historical background/ Beginning of the application of LCA in the construction sector

The use of building certification systems in Austria dates back to late 1990 and follows up initiatives like e.g. IISBE. One of the first systems was developed within several research projects, now launched under the umbrella of ÖGNB. In late 2000 the DGNB system was founded and adapted in Austria by ÖGNI.

Situation in the field of LCA application /Application context (as of early 2021)

The LCA methodology for the assessment of buildings' environmental performance throughout their life cycle is not mandatory in Austria. As an alternative, various building certification schemes exist, that can be applied in order to get an insight into their environmental performance.

As an example, the klimaaktiv framework (Klimaaktiv, 2021) provided by the Austrian government, has the most applications throughout the market. Yet, klimaaktiv does not require a full LCA according to EN 15978. For the embodied impacts in klimaaktiv, the so-called 'OI3-Index' (IBO, 2021), developed by the company IBO Verein und GmbH is applied. The 'OI3-Index' evaluates the ecological quality of the building materials on the basis of the environmental indicators global warming potential, acidification potential and the demand for non-renewable primary energy and represents the performance as a single number. In the calculation, the user can change between different system boundaries. Regarding the operational impacts, klimaaktiv addresses the mandatory energy certificate calculation according to EC (2010). Overall, klimaaktiv is a certification system that rates a building's quality via a scoring system. The criteria in klimaaktiv thereby are heavily focused on energy performance, yet a slight shift is observed towards a more holistic view of the building.

Other voluntary certification frameworks are the ÖGNB-Total Quality Building (TQB) (ÖGNB, 2021) framework or the 'Holistic Building Program' (HBP) (Bundesimmobiliengesellschaft, 2021) by the Austrian governmental real estate company BIG, that in general behave very similar to the klimaaktiv certification framework.

The most advanced framework applied in Austria, that includes a full life cycle LCA, is the certification system by ÖGNI (ÖGNI, 2021), which has adopted the DGNB methodology for Austria. As with DGNB, it requires a full LCA based on EN 15978:2011.

Methodological bases

The methodologies to perform an LCA in Austria are the Austrian national standards based on the EN 15978 and EN 15804. Yet, the beforehand described 'OI3-Index', used by klimaaktiv, TQB and HBP does not state the modularity principle of EN 15978 explicitly. This index includes, depending on the system boundary chosen, the environmental impacts until the refurbishment (Module B4). To the authors' knowledge, the end-of-life emissions (Module C1-C3) and benefits and loads beyond the system boundary (Module D) are not included in the ‘OI3-Index’.

As mentioned before, the ÖGNI methodology, based on the DGNB methodology, as it demands a full life cycle LCA, addresses the modularity principle according to EN 15978 and addresses the major modules throughout the life cycle.

Databases

The main database available in Austria is ‘Baubook’ (baubook, 2021), which is also developed and maintained by the company IBO Verein und GmbH. This database, in the authors’ view, gets the most recognition throughout the market, since it is used to calculate the beforehand described ‘OI3-Index’. This database is linked with various software applications for the calculation of the mandatory energy certificates for buildings.

Yet, users conducting solely LCA studies as well as environmental product declarations (EPD), also apply the Swiss Ecoinvent database (Wernet et al. 2016) in Austria. Within DGNB / ÖGNI system the ökobaudat database is being used.

Number of applications and users

We do not have any relevant data for this.

Integration into the design process

As it is not mandatory in Austria to perform a LCA of a building, the integration into the design process is currently still under development in research projects. To the authors’ knowledge, currently available software packages are performing like databases and do not allow a smooth design process.

Acceptance and dissemination

With recent developments, we see that the topic of LCA implementation gains more and more acceptance. Cities and governments increasingly set their focus on environmental issues and with that, also financial resources are set free for LCA calculations of buildings.

2.1.2 Belgium

Historical background/ Beginning of the application of LCA in the construction sector

In recent years, various steps have been taken to integrate LCA in the Belgian building practice (Trigaux, et al., 2018). Firstly, since 2010, a national LCA method, called MMG (“Environmental profile of building elements”), was developed to assess the environmental impact of building elements and buildings in a harmonized way (Allacker, et al., 2018). Secondly, a national database was established with specific data for Belgian construction products based on Environmental Product Declarations (EPDs) (Belgische Staatsblad 2014). Thirdly, a web-based calculation tool TOTEM (“Tool to Optimize the Total Environmental impact of Materials”) was launched in 2018.

Situation in the field of LCA application /Application context (as of late 2020)

The TOTEM tool can be used by architects and other building stakeholders on a voluntary basis. Furthermore, the use of TOTEM is required in the Flemish sustainability rating tool for public buildings “GRO”, more specifically for the fulfillment of the material-related assessment criteria (Flemish Government 2019).

TOTEM currently focuses on residential and office buildings, but the tool will be extended to other building typologies in future.

Methodological bases

The MMG LCA method is in line with current LCA standards and methods in Europe (CEN 2011; CEN 2013; EC 2013; EC-JRC 2011) and specifies the life cycle scenarios for the Belgian context. The whole building life cycle is considered, including the product stage (modules A1-A3), construction process stage (modules A4-A5), use stage (modules B2, B4, B5 and B6) and end-of-life stage (modules C1-C4). Module D is not included as it falls outside the system boundaries and is not compulsory (CEN 2011; CEN 2013).

Databases

In the current version of the TOTEM tool, generic environmental data from the Swiss Ecoinvent database (version 3.3) are used for the Life Cycle Inventory (LCI) (Wernet et al. 2016). Preference is given to Western European transformation processes to ensure the representativeness for the Belgian context. When generic Western European processes are lacking, Swiss data records are adapted by replacing the energy and water flows by European corresponding processes. In future, specific environmental data from the Belgian EPD database will be included in TOTEM.

Number of applications and users

As TOTEM is a relatively recent tool, the implementation in the building practice is still in its early stages. In June 2019 about 2000 users were registered on the TOTEM website.

Integration into the design process

The implementation of TOTEM in the building practice is still in its early stages. The number of architects and building stakeholders using LCA during the design process is currently rather limited.

Acceptance and dissemination

The acceptance and dissemination of LCA among Flemish architects was investigated in a survey in 2014 Meex (2018). The results showed that architects mainly focused on energy-related aspects. Less than half of the participants had heard of the term “LCA” and only a limited number used LCA in their architectural practice. When LCA was used, it was mainly in a passive way, i.e. by consulting LCA databases, rather than in an active way, i.e. by making LCA calculations. As the survey was carried out before the launch of the TOTEM tool (2018), an update would be required.

2.1.3 Czech Republic

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used in Czech Republic for applications in the construction sector since about 2010. At the beginning it was used for scientific use. The motivation was the fact that the legislation on the compulsory Energy Performance Building Declaration for all buildings came into force in the Czech Republic in that time. The environmental quality of buildings has been therefore in scientific projects enriched by other parameters, such as embodied energy of building materials. It was based on the LCA method, number of indicators was limited.

Situation in the field of LCA application /Application context (as of late 2020)

Currently, the only national LCA methodology is embedded in SBToolCZ, the Czech multi-criteria building assessment. This national method is therefore used for all buildings that seek SBToolCZ certification, but there are not many. It is also used in applications where only the environmental impacts of a building need to be evaluated, but for this purpose the method proves to be insufficiently complex and detailed. Therefore, the national LCA method is currently being prepared, which will focus specifically on the assessment of the environmental impact of buildings on the basis of the LCA method.

Methodological bases

The method in its basic outline is based on the standards EN 15987 and EN 15643-2. Only the A1-A3, B4 and B6 modules are included. To calculate B4, the method provides a table with the service lives of building materials and components. The method includes 6 indicators. Some of the other stages of the life cycle (A4, end-of-life phases) are also taken into account by SBToolCZ, but not in line with LCA method. The new method that is now being developed will include more life cycle stages and provide more detailed guidance.

Databases

According to the current method, data from the Czech database called Envimat, based on the Ecoinvent database, should be used. However, in practice, the Ecoinvent or other generic database which is available to the practitioner, is often used. In the methodology, which is now under development, the database recommendation will include the possibility of using EPD in addition to generic databases.

Number of applications and users

We do not have any relevant data for this.

Integration into the design process

The LCA method is not included in any Czech legislation. Thus, it only enters the building design process where the investor is interested in reducing the environmental impact of his building, even in other life cycle phases than the operational (environmental impacts of the operational phase are already partly regulated by EPBD, which is mandatory). In addition, LCA is used in cases where the investor seeks for a building quality certificate SBToolCZ or BREEAM.

Acceptance and dissemination

Designers, architects and investors' awareness of the environmental impact of buildings is in most cases limited to the operational phase of the life cycle. The motivation of investors to be willing to pay extra for environmental assessment and optimization of their home is still low. Designers' knowledge is increasing, but they do not currently have enough tools and data.

2.1.4 Denmark

Historical background/ Beginning of the application of LCA in the construction sector

LCA was introduced to the Danish building sector in the late 1990'ies. A research project elaborated LCIA data on common construction materials and integrated these into a software tool that was freely available, the BEAT model (Building Environmental Assessment Tool). Some 10 years later, the new established Danish Green Building Council chose an adapted version of the DGNB International certification scheme to become their 'official' scheme for operation. In this scheme, the building LCA weighs ~14% of the final score. In 2014, the Danish government put additional emphasis on LCA in the construction sector by financing a collection of research/guidance reports and the development of a new tool, the LCAbyg.

Situation in the field of LCA application /Application context (as of late 2020)

LCA is applied with the different certification schemes in use among building designers. A voluntary sustainability code is under preparation for inclusion in the building regulations and LCA will most likely form part of this.

Methodological bases

The methodological basis for LCA in Denmark is the EN 15978. Via the development of the DGNB method and the LCAbyg, a consistent method for application has been set. The method builds on existing, national research on service life of materials and buildings as well as waste handling of materials. For the operational energy, the Danish implementation of the EPBD sets the basis for calculating the operational energy demands.

Databases

Impact assessment data for construction materials are implemented in LCAbyg based on Ökobau.dat. It is mainly average product data that are integrated although the user can manually integrate product specific data. Impact assessment data for the energy mixes is developed from the politically agreed plans for a more renewable-based future energy mix.

Number of applications and users

In Denmark, as of 2019, more than 230 buildings are DGNB-certified or in the process of becoming certified. Further, more than 650 consultants have been trained in LCA through the courses held by the Danish Green Building Council. Additional LCA courses, hosted by other networks/organisations, further increase the number of stakeholders informed about and able to use LCA. LCA is also an integrated part of several university and vocational courses.

Integration into the planning process

LCA is not mentioned as part of the regulation. An appendix for the description of services by consulting architects and engineers include LCA as a potential topic for inclusion.

Acceptance and dissemination

The organizations behind the consulting architects and engineers have openly lobbied for more ambitious political targets concerning sustainable construction, including LCA targets. From case to case, consultants still see a lack of demand on environmental assessment services from the client's side.

2.1.5 France

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used in France for applications in the construction sector since 1995 (Polster, et al., 1996). Initial applications were performed in research institutions.

Situation in the field of LCA application /Application context (as of late 2020)

Since around 2008, life cycle assessment has been used within the framework of sustainability assessment systems such as BREEAM and later E+C- (2017)[1]. The application of certification schemes, and of LCA within such certification, is voluntary. It may become compulsory in the next regulation planned for end of 2021. Applying LCA is more useful at early design phases, when decisions are made which have the largest impacts on environmental performance, but this approach is still rare. Applications at a neighbourhood level are also performed since 2004 (Popovici & Peuportier, 2004).

Methodological bases

Building life cycle assessment is based upon ISO 14040 and EN 15978. But there are differences among tools, in particular regarding energy use: e.g. EQUER is linked to energy simulation and hourly electricity mix values are used, whereas constant mixes are used in E+C-. Module D is included as avoided impacts either using the 50/50 method (EQUER) or only 33% (E+C-). Furthermore, both systems differ regarding the replacement of building elements: simulation in EQUER (i.e. integer number of replacements), non-integer number of replacements in E+C- (building life span divided by the element life span). A 50 years reference study period is fixed in E+C-, which leads to overestimate the contribution of products and may lead to encourage programmed obsolescence.

Databases

The data to perform LCAs are either derived from "Ecoinvent" by contextualisation (EQUER) or obtained from INIES (E+C-). INIES includes data from industry-specific and manufacturer-specific EPDs, but accounts for a limited number of substances in inventories (e.g. dioxins are mixed with other VOCs) so that health and biodiversity related indicators cannot be precisely evaluated. Indicators of air and water pollution are based upon a critical volumes method. These EPDs are based on EN 15804. Generic data, particularly if they

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[1] Référentiel « Energie – Carbone » pour les bâtiments neufs – Méthode d'évaluation de la performance énergétique et environnementale des bâtiments neufs – Juillet 2017

address also health and biodiversity issues, are more appropriate at early design than specific EPDs, which can be used at later phases.

Number of applications and users

The share of floor area of new constructions that apply environmental LCA is not known. The number of LCA experts has increased over the last decade. More and more professionals receive training to prepare for the next regulation. Institutes for sustainable construction have been set up at some universities/schools, also offering lectures on LCA for students of architecture and civil engineering.

Integration into the planning process

In the regulation specifying the fees for architects and engineers, LCA is not explicitly mentioned. If LCA is compulsory in the next regulation, the corresponding work will be accounted for as other regulation related tasks like energy calculation.

Acceptance and dissemination

The use of LCA in design process is low and architects have still little knowledge. LCA will probably be used at the end of the design to check the compliance with the regulation, which is not the most useful application of this method.

2.1.6 Germany

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used in Germany for applications in the construction sector since about the 1970s (Gartner et al. 2018). As early as 1922, however, the quantities of coal required for the manufacturing of building products and the heating of buildings were determined and assessed (Friedrich et al. 1922). Initial applications focused on scientific issues and were reserved for universities and research institutions.

Current situation in the field of LCA application /Application context (as of early 2021)

Since around 2008, life cycle assessment has been used within the framework of sustainability assessment systems such as BNB[2] (Rietz et al., 2019), DGNB[3] (Braune & Duran 2018), BNK[4] (Essig, 2019) and NaWoh[5] (Rietz et al., 2020). The application of BNB is obligatory for federal new buildings. Therefore, LCAs have to be created for all newly built office buildings of the federal government and their results to be compared with benchmarks.

Methodological bases

The requirements for life cycle assessment are based on ISO 21929-1 and EN 15987. Despite this uniform basis, there are differences when it comes to their practical application. This applies in particular to module D. This is either included in the considerations (DGNB) or regarded as additional information and not yet determined (BNB) because of too large data gaps. Furthermore, both systems do not consider all information modules – i.e. A4 and A5. Both systems provide both a simplified short procedure and a detailed procedure for the modelling of the building and its life cycle. Other national systems in which LCA is used are BNK for new one- and two-family houses as well as multi-family houses with up to five residential units and NaWoh for new multi-family houses.

Databases

The data to perform LCAs are usually obtained from a publicly and freely available database for LCA data on construction products - ÖKOBAU.DAT, see details in the A72 report by Chae and Kim (2023). It includes

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[2] https://www.bnb-nachhaltigesbauen.de/en/assessment-system/

[3] https://www.dgnb-system.de/en/system/index.php

[4] https://www.bau-irn.com/bnk-system/was-ist-das-bnk-system

[5] https://www.nawoh.de/

data from both industry-specific and manufacturer-specific EPDs. These EPDs are based on ISO 21930 and EN 15804 (currently under revision). Once the EN 15804 revision is finished, the DGNB and BNB systems are likely to be updated following the new requirements.

Number of applications and users

The total DGNB-certified floor area is reported to be 57,5 million m^2 (unknown during which period), while for BNB gross floor area of about 211.000 m^2 for office buildings. This makes up a share of approximately 10% m^2 of floor area of new constructions during the last decade that apply environmental LCA (considering that about 45 million m^2 are added to the stock annually in Germany). The number of LCA experts has also increased over the last decade. The first reason for this is that more and more professionals receive training to become sustainability assessment auditors - often through the further education of engineers, architects and real estate experts. In addition, institutes for sustainable construction have been set up at many universities, which also offer lectures on LCA for students of architecture and civil engineering.

Integration into the planning process

In the regulation specifying the fees for architects and engineers, LCA is not explicitly mentioned. However, sub-aspects of an environmental life-cycle assessment can be agreed as a "special service" – for example see Official Scale of Fees for Services by Architects and Engineers (HOAI)[6].

Acceptance and dissemination

Early surveys on the use of LCA by architects are available from 2004 (Klingele et al., 2007). It must be assumed that, with some exceptions, the use of LCA in design process is low and architects have still strong reservations. This is confirmed by the results of the recent A72 survey from 2019 which show that less than one fifth of architects is currently using LCA (Lützkendorf & Balouktsi, 2020).

2.1.7 Hungary

Historical background/ Beginning of the application of LCA in the construction sector

Work on building LCA started in 2003 in the framework of a national research project (Tiderenczl et al., 2006). In this project, international methods, standards and databases were compiled and the first database and the first simple LCA tool was developed for scientific purposes. A large scale life cycle assessment study of new buildings was conducted (Szalay, 2008) and research on natural materials started[7].

Current situation in the field of LCA application /Application context (as of late 2020)

Two Excel-based LCA tools have been developed at the Budapest University of Technology and Economics. These are coupled with energy performance calculation according to the Hungarian regulations (KESZ_LCC_LCA and Belső Udvar-E-P-LCA-LCC). The tools are mostly used for education and research projects and for some commercial projects. The use of LCA is not mandatory. LCA is increasingly applied in projects aiming at a sustainability certification (BREEAM and LEED), however these use not the national tools but international tools and databases (e.g. OneClickLCA). A new international project, IS-SUSCON is developing a new web application based on OneClickLCA including Hungarian cases. The app will target non-expert users to spread life cycle thinking.

Methodological bases

The university tools are in accordance with the EN 15804 and EN 15978 standards. The whole life cycle of the building is assessed from product stage (modules A1-A3), construction process stage (modules A4-A5), use stage (modules B2, B4 and B6) and end-of-life stage (modules C1-C4). Module D is not included in the assessment.

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[6] https://www.nachhaltigesbauen.de/fileadmin/pdf/Leitfaden_2011/LFNB2011-Anlage.pdf

[7] Medgyasszay Péter: A FÖLDÉPÍTÉS OPTIMALIZÁLT ALKALMAZÁSI LEHETŐSÉGEI MAGYARORSZÁGON - különös tekintettel az építésökológia és az energiatudatos épülettervezés szempontjaira, PhD dissertation, 2008, Budapest University of Technology and Economics

Databases

In the KESZ_LCC_LCA and in university research projects the Swiss ecoinvent v3.6 database (Wernet et al. 2016) is applied but with adaptations to the Hungarian context. The electricity mix and natural gas have been exchanged for Hungarian datasets in case of products that are predominantly produced in Hungary. Typical transport distances are also added based on the number and location of manufacturing plants. In Hungary, the number of national EPD-s is still very low so these are not applied yet.

Number of applications and users

The number of designers using LCA is still very low, only a few designers specialised in ecological constructions apply it. The numbers are slowly increasing with the increase of high end green certified projects in the recent years. Universities offer some lectures on LCA for architectural and civil engineering students but only in specialised courses.

Integration into the planning process

In the usual architectural practice LCA is not applied. However, the few architects specialising in ecological architecture apply LCA as an integral part of their design process. Projects targeting a green certification scheme usually order the LCA study from an external specialist and LCA does not have a real influence on design decisions.

Acceptance and dissemination

There has been no survey on the use of LCA before. Architects have a general knowledge on sustainability issues and many have heard about environmental assessments but have no deeper knowledge on LCA.

2.1.8 Italy

Historical background/ Beginning of the application of LCA in the construction sector

In 2006, the Italian LCA network was created. It became the Italian LCA network Association in 2012. The goal of this Association is the diffusion of the LCA methodology in Italy and the exchange of experiences. The Association has different working groups that focus on the application of LCA to different products and services. Among them, two are of interest for buildings: the working group “Building” and the working group “Energy and sustainable technologies”.

Current situation in the field of LCA application /Application context (as of late 2020)

Focusing on buildings, mainly the operation step is taken into account at this moment by legislation and practices. LCA is used for research purposes.

LCA is applied to building materials for developing EPD. There is an Italian Program Operator called EPDItaly. In 2017, it published the PCR for building products. Currently, 54 EPDs of building products are available in the EPDItaly website.

With the law 221/2015 (art.18) and the following law D.lgs. 50/2016 “Code of procurements” (art. 34 on criteria of energy and environmental sustainability) (modified by the law D.lgs 56/2017), the Italian Governments introduced the Minimum environmental criteria of buildings in the context of the public procurements. One way to demonstrate the existence of the required Minimum environmental criteria is to have an EPD for building products.

Methodological bases

The LCA developed for research purposes is based on the international standards ISO 14040 and ISO 14044 and on the EN 15987.

Databases

The data to perform LCAs can be obtained from EPDs or from environmental databases like Ecoinvent. Until now, no Italian environmental databases except EPDs are available.

Number of applications and users
Information not available

Integration into the planning process
LCA is not mentioned in the regulations that specify the fees for architects and engineers. LCA is not integrated in the design process.

Acceptance and dissemination
Information not available

2.1.9 Slovenia

Historical background/ Beginning of the application of LCA in the construction sector
The first studies in the field of LCA have been carried out in the last decade. The initial applications of the LCA of the studies were mainly in the research sector. The first studies focused on building materials and components since producers of building materials expressed their interest for Environmental Product Declarations (EPDs) very early.

Current situation in the field of LCA application /Application context (as of)
The LCA is mostly applied in the construction research sector for assessing building materials and components. There are only a few cases of whole building assessment. Currently, some incentives are being prepared, that should increase the use of LCA in the construction sector (e.g. subsidies for EPDs, workshops about LCA, etc.)

Methodological bases
The studies are following the rules of ISO 14040, EN 15804 and EN 15978 standards (ISO, 2006; CEN, 2011). There are no national recommendations or requirements for the methodology or the data that should be used for the study. For determining the scope of the study (the reference study period, the reference service life, end-of-life scenarios, etc.) the authors are mostly referring to published literature.

Databases
The studies rely on the data published in literature or use commercial or public databases. In the research commercial databases are used (e.g. Ecoinvent, Gabi). Some studies also rely on public databases (e.g. Ökobaudat). A local database of EPDs is available (ZAG EPD[8]).

Number of applications and users
Until now 14 EPDs have been published and some are still in progress. LCA is used in most of the research project connected to buildings and building materials, but it is seldom applied practice. The number of sustainable building certifications requiring an LCA analysis is also low.

Integration into the planning process
The integration of the LCA in the design and planning process is low. The practitioners are generally not familiar with LCA. However, LCA is being increasingly included in the curriculum of the universities and therefore it is assumed that the use of the LCA will increase in the future.

Acceptance and dissemination

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[8] https://www.zag.si/en/certificates-and-approvals/service-for-technical-assessment-and-approvals/

The LCA methodology is not well-known in the building sector and therefore in is also not used in practice. The government is also developing national indicators for assessing the sustainability of building where some initiatives to use LCA are included, which may contribute to a wider use of LCA in future.

2.1.10 Spain

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used in Spain for applications in the construction sector since about 2004. Initial experiences were considering the environmental impacts in constructions products (e.g. BEDEC ITEC Instituto de Tecnología de la Construcción). Initial applications of LCA in the field of Building construction were mainly carried out by Universities and Research institutions.

Current situation in the field of LCA application /Application context

Since around 2004, life cycle assessment has been included in construction databases and, since 2010 in environmental declaration programs (e.g. DAPC) and within the framework of sustainability assessment systems such as VERDE. The application of VERDE is not obligatory in any case. Some Universities and research institutions have developed their own Buildings LCA Tools (eg. LCA-US Tool).

Methodological bases

The requirements for life cycle assessment are generally based on ISO 21929-1 and EN 15987. Despite this uniform basis, there are differences when it comes to their practical application -e.g. VERDE is focused in B6 and B7, US-LCA Tool consider A, B –except B1-,C stages and the D is took into account considering the service life of the building product in relation with the service life of the building.

Databases

BEDEC database has been commonly used by professionals and researchers. In the research field GaBi and, overall, ECOINVENT are the most usually used.

Number of applications and users

More than 50 buildings have been VERDE certified until now. This includes residential, commercial, educational, administrative, hotels, among other uses. The knowledge about sustainability certifications is increasing in the last years. This is because, among other reasons, many curricula in architecture and engineering are increasingly including the description of these methods and tools. Some Architecture Schools also includes lessons on the LCA methodology applied to buildings.

Integration into the planning process

The integration of LCA in the design and planning process in Spain is still low. Very few of architects and engineers obtain LCA results from their buildings in order to optimize them. Maybe this is because the lack of regulation in this respect.

Acceptance and dissemination

The LCA methodology is not very well-known in the building sector. The use of LCA in design process is still very low.

2.1.11 Sweden

Historical background

In the end of the 1990s and the coming decade, the basis for development of LCA methods for buildings targeting practice in Sweden was formed, with primarily the EcoEffect tool (Assefa et al., 2007) and the Environmental Load Profile (ELP) (Forsberg, 2003; Brick, 2008). Parts of the EcoEffect tool were used in practice to some extent at the time, but primarily this development was important for more simplified approaches developed after that. The ELP also had a wide scope and was used by Stockholm municipality partly in evaluating the project development of the large spearhead neigbhourhood development Hammarby Sjöstad which started in 1996[9]. However, this was done by a consultant and not by the developers in the area. In 2006, the first more commercially oriented LCA tool for buildings was developed, Anavitor[10]. It has since then been used primarily by the large contractor and developer Skanska to build internal knowledge and develop their work with LCA.

Implementation of LCA has since then been an on-going discussion in the fore-running companies in Sweden, who in various projects have cooperated with academia in successive competence-building. However, it has up to recently still not existed any clear drivers for the implementation. Apart from absence of drivers, the main barriers have been (and to some extent still are) no freely available software managing digital calculations and a lack of “consensus” data-sets to use.

Five years ago, the interest for LCA for buildings, however started to change. One important reason was the report launched and communicated by the Royal Swedish Academy of Engineering Sciences and the Swedish Construction Federation in 2014[11]. It received a lot of attention within industry and among national policymakers, and the main message was proclaiming that half of the GHG emissions of new Swedish multifamily buildings (in an LCA perspective) are associated with the product and construction stages, building on a new LCA-study performed by KTH in collaboration with the research institute IVL (Liljenström et al., 2015).

During the mid-2000s the national environmental certification tool for buildings was developed, called Miljöbyggnad (Malmqvist et al, 2009) by two joint research groups in cooperation with approx. 30 industry partners, insurance companies and authorities. To include an indicator demanding LCA calculation was discussed, but was at that time considered a too demanding choice. Embodied emissions were therefore not considered at all by this tool, but an explanation for that was that the tool from the beginning was primarily targeting certification of existing buildings rather than new. At the time when the tool was completed, there was much debate about “which” tool to go for. At that time, more stakeholders had an increasing interest for BREEAM and LEED, and the powerful contractors Skanska and NCC with international activities, each argued for LEED and BREEAM respectively. The future of Miljöbyggnad was therefore first unsecure, but after the founding of the Sweden Green Building Council (SGBC) in 2009, all three systems are now operated by SGBC in parallel, with Miljöbyggnad being the leading certification scheme in Sweden.

Situation in the field of LCA application (as of early 2021)

As said above, a broader interest for LCA application emerged in Sweden around five years ago. The government (both the political majority before and after the election in 2014) and the national authority for housing, building and planning (Boverket) have since then initiated a series of missions, resulting primarily in a proposal for a new regulation, a mandatory climate declaration for all new buildings in Sweden from 2022 (Boverket, 2018)[12], and a guideline on LCA for buildings for practitioners[13]. Already the knowledge of this forthcoming regulation has led to numerous initiatives now taken in the building industry to build up competence and capacity in the area. Boverket has also proposed a road-map for expanding this regulation later on with limit values, as well as inclusion of additional life cycle modules (Boverket, 2020). Here follows a number of important examples on initiatives during the last five years which both increase application of LCA and improve the opportunities for LCA application in the coming years:

– A new indicator requiring a calculation of embodied GHG emissions was added in the certification tool Miljöbyggnad, in 2017.

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[9] A broad aim stated that the environmental performance of buildings in a life cycle perspective should be twice as good as the present-day state of the art

[10] www.anavitor.se

[11] https://www.iva.se/publicerat/climate-impact-of-construction-processes/

[12] Law proposal in English: https://ec.europa.eu/growth/tools-databases/tris/en/index.cfm/search/?trisaction=search.detail&year=2020&num=439&mLang=en&CFID=995299&CFTOKEN=e0e52b5820b0e82e-F0A573AB-F2C2-EC14-02289396E7B15E26

[13] https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/

- The Swedish Transport administration (STA) have developed their own open tool, Klimatkalkyl[14], which is used for large infrastructure projects. STA require climate calculations as part of their procurement of large infrastructure projects since 2015
- Large strategic innovation programme, Smart Built environment has/is currently increasing the opportunities to establish digital LCA´s
- Stockholm municipality require climate calculations of all their own new building projects from 2019
- A Road-map for a fossil-free building and construction sector[15] was launched last year and is currently signed by 120 companies/organisations. One important component is to promote calculation and consideration of embodied emissions in construction projects.
- As a result of a R&D project the research institute IVL (in collaboration with KTH) launched an open, free tool (BM-tool) with open data, to promote climate calculations by practitioners.
- Sweden Green Building Council have launched a new certification system called Noll CO_2 (Zero CO_2)[16] as well as a new certification system for sustainable urban areas- post construction, Citylab (Lind et al, 2019; Lind, 2020; SGBC, 2019)[17], which include requirements on calculating GHG emissions in a life cycle perspective and linked limit values.

Methodological bases

As described above, the current situation in Sweden means that there is still (as of early 2020) not ONE national method. The methods used are however similar and follow EN 15978 (and indirectly EN 15804). The STA tool for infrastructure works is however not following the modular thinking of these standards in the same way. Regarding buildings, if the Climate declaration regulation comes into place this will essentially become the official national method. The following methodological description therefore concerns this method (Boverket, 2018). Like the name says, it only concerns assessment of GHG emissions and in the initial step only covers the modules A1-A5. The reasons for this is to reduce complexity since it is still a considerable knowledge leap that needs to be taken for involved stakeholders, that it is the part of the life cycle that can actually be verified, and that it puts focus on the most important part of the life cycle that is not already regulated (module B6 is regulated through the Energy performance directive). By including the entire A stage in the declaration, all key stakeholders in the value-chain for new construction, so to speak, also need to engage.

Databases

There is not yet a publicly and freely available database for construction products in Sweden, which up to recently has been an important barrier for practitioners who were interested in performing building LCA´s. However, with the STA tool, some country specific data are now openly available. Also, the BM-tool is including around 100 country-relevant datasets from the most up-to-date database that the research institute IVL owns. This data builds on Gabi data and quality checked EPD´s for products used in Sweden. The Swedish concrete federation is now also offering an EPD-tool for concrete producers. The national authority Boverket will launch an open, and freely available database on generic data for construction products, which is to be used when making the mandatory climate declarations according to the coming regulation. The database is developed together with the Finnish ministry and is planned to be launched in early 2021.

Number of applications and users

This is very difficult to tell. So far, LCA assessments are limited but a number of fore-running companies are now increasingly making at least climate calculations for their buildings, as a result of the new requirements in Miljöbyggnad, in light of the proposed climate declaration regulation and/or to meet procurement requirements by for example Stockholm municipality.

Acceptance and dissemination

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[14] https://www.trafikverket.se/klimatkalkyl

[15] https://fossilfrittsverige.se/fardplaner/

[16] https://www.sgbc.se/utveckling/utveckling-av-nollco2/

[17] https://www.sgbc.se/certifiering/citylab/anvandarstod-citylab/citylab-guide-och-manual/

Primarily, more and more practitioners are now learning to make and understand LCA´s. During the last year also on a much broader basis than earlier. Consultancies in the building and construction sector are building up their capacity to offer LCA´s. So far, the acceptance for the proposed climate declaration regulation is considered as high, both among policy makers and within the building and construction industry. With the proposed regulation, in the last years, a tremendous increase in a much broader competence-building concerning similar climate calculations can be observed.

2.1.12 Switzerland

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used for applications in the construction sector since the late eighties (Ems et al. 1989; Hofstetter et al. 1992; SIA 1995, 1997).

Situation in the field of LCA application /Application context (as of late 2020)

Environmental life cycle assessments of buildings are used in certification schemes Minergy-eco[18], NNBS (network of sustainable buildings Switzerland)[19] and when assessing buildings against the benchmarks defined according to the 2000-Watt-Society (SIA 2017, 2020). The assessments are performed with certified planning tools. The SIA energy efficiency path, SIA 2040 offers a free tool to assess buildings in the early design stage[20]. In late 2011 the platform Life cycle assessment data in the construction sector was founded. The platform maintains the KBOB recommendation 2009/1 "life cycle assessment data in the construction sector" (KBOB et al. 2016, 2017), a comprehensive LCA database, which was published the first time in 2006. These data form the universal basis for all certification schemes and environmental assessments in the construction sector and in 2000-Watt-society assessments.

Methodological bases

Building life cycle assessment is based on ISO 14040 and 14044 (International Organization for Standardization (ISO) 2006a, b) and SIA 2032 (SIA 2020). Building material life cycle assessment is based on the ecoinvent v2 methodology and the complementary KBOB guidelines (KBOB et al. 2017). These rules are applied uniformly on all building LCAs requested by privately run certification schemes and those commissioned by public authorities. Since decades, Swiss LCA follow the recycled content approach and potential Module D impacts are disregarded. Similarly, allocation in multifunctional processes is done based on physical or other relationships avoiding system expansion approaches. The reference study period is 60 years.

Databases

Buildings LCAs are performed using the LCA data published in the KBOB recommendation 2009/1 (KBOB et al. 2016), which provides LCA data (greenhouse gas emissions (IPCC 2013), cumulative energy demand non renewable and renewable (Frischknecht et al. 2015) and overall environmental impacts according to the ecological scarcity method (Frischknecht & Büsser Knöpfel 2013) on construction materials and building elements (doors, window frames), building technology (heating systems, ventilation systems, solar collectors and panels, sanitary and electrical equipment), transport services (goods and people), energy supply (heat, district heat and electricity) as well as waste management services. These data are updated regularly.

Number of applications and users

The share of floor area of new constructions that apply environmental LCA is not known. Until 2017 about 1'500 buildings were certified against Minergy-eco (an estimated 1.5 mio m^2 energy reference area, Faktor 2018) and the energy reference area of buildings assessed according to SIA 2040 is estimated at about 100'000 m^2 energy reference area[21].

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[18] https://www.minergie.ch/de/zertifizieren/eco/, accessed 12.11.2020

[19] https://www.nnbs.ch/standard-snbs-hochbau, accessed 12.11.2020

[20] http://www.energytools.ch/index.php/de/, accessed 12.11.2020

[21] personal communication, Katrin Pfäffli, Pfäffli Architects, 24.5.2019

Integration into the planning process

In the regulation specifying the fees for architects and engineers, LCA is not explicitly mentioned. It is part of the planning process in view of buildings that shall comply with Minergy-eco, SNBS or SIA 2040.

Acceptance and dissemination

The use of LCA in design process is low and architects have little knowledge. LCA embedded in planning tools is being used (if commissioned, see above) by companies specialised in energy modelling and calculations (building physicists) and architects dedicated to environmental issues.

2.2 Situation in Oceania

2.2.1 Australia

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment has been used in Australia for applications in the construction sector since the early 1990s (Frith et al., 1993; Fay, 1996; Alcorn and Baird, 1996; McArdle et al.,1993; Pullen, 1995; Treloar, 1994), but LCA at this time mainly focused on research on energy limited to life cycle energy or embodied energy. Most of the research was mainly conducted by universities (Frith et al., 1993; Fay, 1996; Mackley, 1998; Treloar, 1996, 1999) and national research institute (Tucker et al., 1993; Tucker et al., 1996), and practical application to construction industry was insignificant.

Situation in the field of LCA application /Application context (as of late 2020)

In the beginning of the 21st century, research on LCA and its applications to the construction industry gradually increased. Of note was the development of life cycle assessment tools such as LCAid (Eldridge, 2002) and LCADesign (Seo et al., 2008; Tucker, 2003; Tucker, 2004). The latter integrated an LCI database with 3D building models based on the early version of Building Information Model (BIM), one of the first efforts to do so. From 2014, the Green Building Council Australia (GBCA) began to give additional points to projects that apply environmental LCA in their building certification process. However, the application of LCA has been limited to the materials used, not the entire building.

Methodological bases

There is no typical building LCA methodology in Australia. Most LCA research for building or construction industry generally follow international standards, such as ISO 14044 and EN 15978. Current commercial LCA tool (e.g., eTool[22]) is also based on these two guidelines.

Databases

The Building Products Innovation Council (BPIC) developed a LCA database for key building materials in 2011 based on an Ecoinvent shadow database (ecoinvent version 2.2). Currently this database is included in the national LCI database called AusLCI[23]. The national LCI database is regularly updated by the Australian LCA Society (ALCAS[24]). In addition, EPD data of some Australian building and construction products began to be developed and are now being used. Currently, 63 Australian EPD for building products are available[25].

Separately, the EPiC (Environmental Performance in Construction) database, in development for many years using the hybrid approach (Crawford et al., 2019), was published in 2019. The database provides environmental impacts (embodied energy, carbon and water) for 250 construction materials.

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[22] See: https://etoolglobal.com/about-etoollcd/

[23] See: https://www.alcas.asn.au/auslci

[24] See: https://www.alcas.asn.au/

[25] See: https://epd-australasia.com/epd-category/construction-products/

Number of applications and users

The application of LCA for buildings is on the rise, and the use of LCA has increased significantly as GBCA introduced LCA credits into the Green Star Rating Tool since 2014. Also, the Australian LCA Society (ALCAS) is now conducting LCA CP test to train qualified LCA practitioners as the number of LCA users increases.

Integration into the planning process

Currently, LCA is not required for building code or regulatory compliance. LCA is used on a voluntary basis in the design and planning stages of construction projects. LCA is included in voluntary sustainable rating tools for building (e.g., Green Star) and civil infrastructure works (e.g., ISCA Rating).

Acceptance and dissemination

LCA is slowly being accepted by architects and some segments of the industry since it is included in voluntary sustainable rating tools (Green Star and ISCA). But more efforts are needed to improve the awareness of its benefits and value amongst the public and the broader industry.

2.2.2 New Zealand

Historical background/Beginning of the application of LCA in the construction sector

Historically, some bespoke LCAs have been carried out for specific construction materials, for example, laminated veneer lumber (Love, 2010), up to whole buildings (for example, the Waitakere NOW Home® (Drysdale & Nebel, 2009)). Not all this work has necessarily ended up in the public domain. An evaluation was also undertaken for the Ministry of Agriculture and Forestry (now the Ministry for Primary Industries) of the potential for adapting LCA data for building materials in New Zealand (Nebel et al., 2011). Alcorn (2010) additionally published embodied carbon and energy figures for a range of construction materials, as well as assessing house designs, based on a hybrid analysis method.

In 2013, the Building Research Association of New Zealand (BRANZ) published a plan for the development of environmental product declarations (EPDs) and building level LCA in New Zealand (Dowdell, 2013). This was consulted on with the New Zealand construction sector and was well supported. Research then commenced on development of the New Zealand whole-building, whole-of-life framework ('framework') which contains a growing database of generic and specific data on environmental impacts of construction materials, as well as generic activity data for other life cycle stages (for example, material wastage rates at construction sites with end-of-life routes and materials service life information for different building elements). Framework resources are freely available at www.branz.co.nz/buildinglca (and select "Data").

An EPD programme, called EPD Australasia[26] was launched in 2014, providing a platform for manufacturers to declare the environmental impacts of their materials/products.

Situation in the field of LCA application / Application context (as of late 2020)

There is currently (December 2020) no regulatory driver for developing EPDs or undertaking building LCAs in New Zealand. However, the current situation appears likely to change.

In late 2019 the Climate Change Response (Zero Carbon) Amendment Act became law in New Zealand[27]. It provides a framework for New Zealand to develop and implement policies to contribute to the global effort under the Paris Agreement to limit global average temperature rise to no more than 1.5°C above pre-industrial temperatures. The Act's four key aims are to:

- set a new domestic greenhouse gas emissions reduction target for New Zealand to:
  a. reduce net emissions of all greenhouse gases (except biogenic methane) to zero by 2050
  b. reduce emissions of biogenic methane to 24-47 per cent below 2017 levels by 2050, including to 10 per cent below 2017 levels by 2030

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[26] See: https://epd-australasia.com/epd-category/construction-products/

[27] See: https://environment.govt.nz/acts-and-regulations/acts/climate-change-response-amendment-act-2019/

- establish a system of emissions budgets to act as stepping stones towards the long-term target
- require the Government to develop and implement policies for climate change adaptation and mitigation
- establish a new, independent Climate Change Commission to provide expert advice and monitoring to help keep successive governments on track to meeting long-term goals.

In response, the Ministry of Business, Innovation & Employment (MBIE) established a Building for Climate Change Programme (www.mbie.govt.nz/building-and-energy/building/building-for-climate-change/) during 2020. The Programme recognises the part that the building and construction sector needs to play for New Zealand to achieve its climate change goals, including net zero carbon by 2050, as well as improve New Zealand's resilience to climate change. It anticipates getting New Zealand "building in a completely different way", with changes anticipated to current building laws – the Building Act and the Building Code.
The Programme is divided into two frameworks on which MBIE began a consultation in August 2020:

- Transforming operational efficiency – emissions directly and indirectly attributable to building operations, including energy and water use, and occupant health and wellbeing.
- Whole-of-life embodied carbon emissions reduction – emissions across the full supply chain of construction materials and products, construction processes, repair and maintenance, and processes at end-of-life of a building.

At the time of writing, the outcome of this consultation is awaited.

In the absence of a current regulatory driver, the main voluntary driver is the New Zealand Green Building Council's Green Star building environmental rating tool. This also recognizes selection of products with an EPD.

Methodological bases

The BRANZ-developed framework is based on EN 15978 (CEN, 2011) and EPD Australasia, which is affiliated to The International EPD System, requires that construction-related EPDs are based on EN 15804 (CEN, 2012 + A1).

Currently, resources available in the BRANZ framework facilitate calculation of environmental impacts for the Product stage (modules A1 – A3), Construction Process stage (modules A4 – A5), maintenance (module B2), replacement (module B4), operational energy use (module B6), operational water use (module B7), the End-of-Life stage (modules C1 – C4) and Benefits and loads beyond the building life cycle (module D). Office and residential buildings are evaluated for a 60 year and 90 year service life respectively using the framework. A method for constructing and testing Building Information Models (BIM) to provide material quantities suitable for building LCA has been developed by Berg (2014) and used as the basis for the framework (Berg et al., 2016).

Massey University and BRANZ research has resulted in the development of New Zealand-specific carbon budgets for residential and office buildings, using a top-down, absolute sustainability approach, and consistent with the 1.5oC warming threshold (Chandrakumar et al, 2020; McLaren et al., 2020). These carbon budgets are embedded in the LCAQuick tool (see "Databases").

Databases

BRANZ publishes an embodied carbon (modules A1–A3) dataset called BRANZ CO2NSTRUCT[28] which is largely derived from EPD data. BRANZ has a larger database of materials embedded in its free, building LCA tool called LCAQuick[29]. The database features a mix of data derived from product-specific and industry-average EPDs, as well as generic data based on modelling using EcoInvent, so varies in quality. A database also exists within E-Tool LCD, a building LCA tool developed in Australia, which is also finding application in New Zealand.

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[28] See: https://www.branz.co.nz/environment-zero-carbon-research/framework/branz-co2nstruct/

[29] See: www.branz.co.nz/lcaquick

Number of applications and users

Lack of current regulatory drivers or incentives continues to provide a barrier to uptake of building LCA. Building clients rarely require it, and design teams rarely offer it. No firm data exists on the use of building LCA in New Zealand. Some case study examples are available on the BRANZ website[30].

Integration into the planning process

Building LCA is not currently required or incentivised by the planning process. However, the MBIE whole-of-life embodied carbon emissions reduction framework consultation document featured a proposal that reporting on whole-of-life embodied carbon will become mandatory as part of the building consent process, with subsequent and progressively tightening mandatory caps being set thereafter.

Similarly, the MBIE transforming operational efficiency framework consultation document proposed the setting of a mandatory operational emissions cap and a mandatory water use cap, both of which will tighten to a final level by 2035. There will additionally be defined indoor environmental quality parameters for all new buildings.

Acceptance and dissemination

The use of building LCA by architects and designers is currently low, with a few exceptions which tend to be one-off exercises primarily driven by recognition in building environmental rating tools. BRANZ launched a "Transition to Zero Carbon Built Environment" research programme in 2020[31]. As part of this, BRANZ is engaged in an active process to help inform, educate, train and support design teams and their clients. In this capacity, BRANZ has run seminars, webinars and training events, using LCAQuick as an education tool to help the sector better understand what building LCA is, how it can be used, and its value.

2.3 Situation in North America

2.3.1 Canada

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used in Canada for applications in the construction sector since the early 1990s. Initial applications of building LCA were carried out by an academics' consortium named Athena Project (Athena Sustainable Material Institute, 2020). Professionals started doing LCA more regularly around 2010. Athena project is now known as Athena sustainable material institute and has a widely known tool among practitioners named Athena impact estimator.

Situation in the field of LCA application /Application context (as of late 2020)

Life cycle assessment is slowly getting mainstream among construction professionals (outside of architects). Despite the long history of LCA in Canada, most of the incentive until recently came from LEED standards (Singh 2017). Since it's still a voluntary process for the most part, clients and their counterparts need to be aware of the environmental problematic caused by building, and, most importantly, be willing to certify their building. Some cities and regions regulate for public owned buildings, but, thus far, LEED has been mostly used by a handful of developers, mostly for marketing purposes.

Methodological bases

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[30] See: https://www.branz.co.nz/pubs/case-studies/lcaquick/

[31] See: https://www.branz.co.nz/environment-zero-carbon-research/

The requirements for life cycle assessment within the LEED standards and the Athena impact estimator are based on EN 15 978. Despite both using the same standard, there are differences when it comes to the application. Indeed, there is no singular methodology for Canada, resulting in disparities in the scope of analysis. As an example, surveyed practitioners include detailed module calculation for most of the life cycle beside the end of life and Module D. In comparison, Athena impact estimator includes only generic modules of A1-A5, B4, C1-C4 and D.

Databases

Outside the Athena impact estimator tool, there is no specific national database. Most practitioners use the ecoinvent database with a generic software such as SimaPro.

Number of applications and users

More and more professionals are receiving training on this matter, but there is no official data. LEED has certified over 4350 certified buildings in Canada (but that does not mean that every building had completed the LCA to get their points) (CAGBC, 2020).

Integration into the planning process

The integration of LCA in the design and planning process in Canada is still very low. Most of the analysis come in the latter stages in order to obtain LEED certification.

Acceptance and dissemination

The methodology and use of LCA is widely accepted among architects working in the industry. Legal requirements and public sectors need to push the large-scale application of LCA in the construction industry.

2.4 Situation in Asia

2.4.1 China

Historical background/ Beginning of the application of LCA in the construction sector

Environmental life cycle assessment is being used in China for applications in the construction sector since 1998 (Yang, 2009). Initial experiences were considering the environmental impacts in constructions products based on the National "Ninth Five-Year" High-tech Research Program (863 Program) - Research on Environmental Coordination Evaluation of Materials, which was hosted by Beijing University of Technology.

Situation in the field of LCA application /Application context (as of late 2021)

Life cycle assessment has not been used within the framework of sustainability assessment system - Green Building Evaluation Standard (GB/T 50378-2019). Some Universities and research institutions have developed their own Buildings LCA Models/Tools, such as the BEPAS Model (Tsinghua University) (Zhang et al. 2006), BELES Program (Tsinghua University) (Gu, 2009), BESLCI Tool (TongJi University) (Xing et al., 2008) and eFootprint (IKE)[32]. To make it easier to calculate carbon emissions, tools have been developed over last two years according to Standard for Building Carbon Emission Calculation (GB/T 51366-2019), including PKPM-CES, T20-CE, AIARCH, etc. It seems that the most mature one is PKPM-CES, which can use CAD model and read the quantity data automatically while LCA data can only be assigned manually if detailed calculation is required. At early design stage, rough default data, which are sourced from a similar case in the built-in case database, can be used. The energy simulation core is IBE, which was developed in 2017 by China Academy of Building Research. Because General Specification for Building Energy Efficiency and Renewable Energy Utilization (GB55015-2021) will take effect on 1 April 2022, which requires that operational carbon emissions of all the residential and public buildings must be reduced by 7kgCO^2/m^2/a

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[32] See: https://www.efootprint.net/login#/home

compared with the emission intensity[33] of buildings that followed standards in 2006. However, the tools are still being improved to adapt to early and late design stage. It is foreseeable that carbon emission calculations will be more and more widely used, both in practice and in research.

Methodological bases

Standard for Building Carbon Emission Calculation (GB/T 51366-2019) is based upon ISO 14040 and ISO 14044. But there are differences. Firstly, only carbon emission is calculated. Secondly, fewer stages are involved compared with EN 15978, including production (A1-A3), construction (A4-A5), replacement[34] (B4), operational energy[35] (B6), and demolition (C1). Thirdly, the reference service life of buildings is 50 years.

Databases

The EPD data for Chinese building material and products are rare and not open access. CLCD (Chinese Core Life Cycle Database) [8] provides generic data for major materials and energy products. Data for specific building products (such as window frames), service system, and end of life stages are mostly not available.

Number of applications and users

Application in new construction is rare, although research on LCA is increasing. The number of LCA experts has increased over the last decade. Some universities/schools are also offering lectures on LCA for students of architecture and civil engineering.

Integration into the planning process

The integration of LCA in the design and planning process in China is still low. Very few of architects and engineers obtain LCA results from their buildings in order to optimize them. Maybe this is because the lack of regulation in this respect.

Acceptance and dissemination

The use of LCA in design process is low and architects have still little knowledge. LCA will probably be used at the end of the design for retrospective research.

2.4.2 Hong Kong

Historical background/ Beginning of the application of LCA in the construction sector

The initial applications of the LCA of the studies were mainly in the academic research sector, which focused on building materials and components. In 2006, there were initiatives from the government and the public housing sector to commission consultancy studies to develop protocols and databases to study the LCA for office and residential buildings in Hong Kong. A local LCI database comprising building materials and building services components had been developed by localizing the overseas databases. The original intention of the government was to develop an application software for facilitating building designers and contractors to apply LCA in their design and construction. However, it has never been put out to the industry practice.

Current situation in the field of LCA application /Application context (as of late 2020)

The LCA has mostly been applied in the construction research sector for assessing building materials and components, and a limited number of studies extended the LCA assessment to cover building services system components. There are only a few cases of whole building assessment. Currently, there is a credit provision within the Building Environment Assessment Method (BEAM-Plus) relating to LCA in building design. 1 credit will be awarded for demonstrating the embodied energy in the major elements of the building structure of the building has been studied and optimized through a Life Cycle Assessment (LCA). However,

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[33] There is only an experience data, about 37kg/m^2, provided by Tsinghua Energy Efficiency Center.

[34] Only the GHG emitted by refrigerant is included. The replacement of components and equipment is not considered.

[35] GHG emissions caused by HVAC, DHW, lighting and elevators, renewable energy, carbon sink on the site are included.

it is noteworthy pointing out that BEAM-Plus is only voluntary in nature and designers have an option whether to earn the specific LCA credit in their building certification.

Methodological bases

The studies generally followed the rules of ISO 14040 or other EN standards. There are no local recommendations or requirements for the methodology or the data that should be used for the study. For determining the scope of the study (the reference study period, the reference service life, end-of-life scenarios, etc.) the authors have been mostly referring to published literature.

Databases

A majority of local LCA studies has been relying on the data published in overseas literature or public databases. There was a local database being developed some years ago but unfortunately never came to full application.

Number of applications and users

LCA is used in most of the research project connected to buildings and building materials but it has seldom been applied to industry practice.

Integration into the planning process

The integration of the LCA in the design and planning process is low. The practitioners are generally not familiar with LCA. However, LCA has been increasingly included in some curricula of the universities and therefore it is assumed that the use of the LCA will increase in the future.

3. Short Overview of Method Variations

In the following, an overview of the variations in methodological choices behind 25 method approaches (as of late 2020) from 19 countries – some countries reporting more than one methodology (i.e. France, Denmark, Germany, United Kingdom and Canada) – is provided (see Table A.0 in Appendix). Particularly, similarities and differences are shown with respect to: (a) selected reference study periods (RSPs), as well as life cycle and physical system boundaries; (b) modelling of the different life cycle stages; (c) type and scope of environmental indicators; (d) Assessment standards, databases, tools and benchmarks used; (e) market conditions and driving forces.

Of course, more methods than the reported ones, sometimes also company-specific methods, may exist in a country. However, it is assumed that the reported methods set a standard for a large amounts of building LCAs performed in each considered country.

To have a better overview of the differences in methodological developments among different countries especially in Europe, the results of this survey can be combined with other literature sources, such as the comparisons of methods prevalent in the Nordic countries by the Swedish Life Cycle Centre[36], the recent report by Röck et al. (2022)[37], as well as the recent report by OneClick LCA[38] which review European methods and best practices.

It should be noted that there is a dynamic development of methods around the world, therefore, some of the responses may already be outdated at the date of publication. However, the conclusion that there is still a high variation in choices remains. This conclusion constitutes the starting point for the A72 report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf et al. (2023), among others.

3.1 System Boundaries

3.1.1 Typically considered reference study period per building type

The survey showed that the most common reference study period (RSP) indicated by the various national methods is 50 years irrespective of the type of building. What changes is the range of the RSPs considered. A detailed overview of the considered RSPs per building type in the different methods is given in Table A.1 (Appendix).

Figures 3.1a-b show that for new residential buildings (single-family and multi-family) 50 years is also the minimum RSP applied, while the max values can reach 90-120 years and have been seen in methods applied in Denmark and New Zealand, i.e. the Danish LCAbyg tool[39] and NZ LCAQuick tool. The assumption of 90 years’ service life for New Zealand houses is based on research carried out by Johnstone (1994)[40]. Only

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[36] See: https://www.lifecyclecenter.se/nordic-building-lca-comparison/ (accessed January 2023)

[37] See: https://fs.hubspotusercontent00.net/hubfs/7520151/RMC/Content/EU-ECB-1-Facing-the-data-challenge.pdf

[38] See: https://www.oneclicklca.com/construction-carbon-regulations-in-europe/

[39] Currently LCAbyg has switched to a 50-year RSP to adapt to the upcoming requirements regarding the climate impact of buildings in Denmark.

[40] In his paper, Johnstone states: “About 50% of dwellings have been lost from each dwelling cohort by the age of 90 years and the distribution of losses follows that of a bell shape skewed to the left.” (Johnstone, 1994, p. 181).

about 50% of methods go beyond a focus on residential and office buildings and consider other types of buildings such as industrial and educational buildings. Figure 3.1d shows that industrial buildings appear to have the lowest min value for RSP (i.e. 20 years) as well as the lowest max value (i.e. 60 years).

Methods usually are in place for assessing new buildings, but in cases they do consider the renovation of existing buildings, the recommended RSP is either the same as the new building or no specific RSP is recommended. Therefore, no clear method differentiations are found between new and existing buildings.

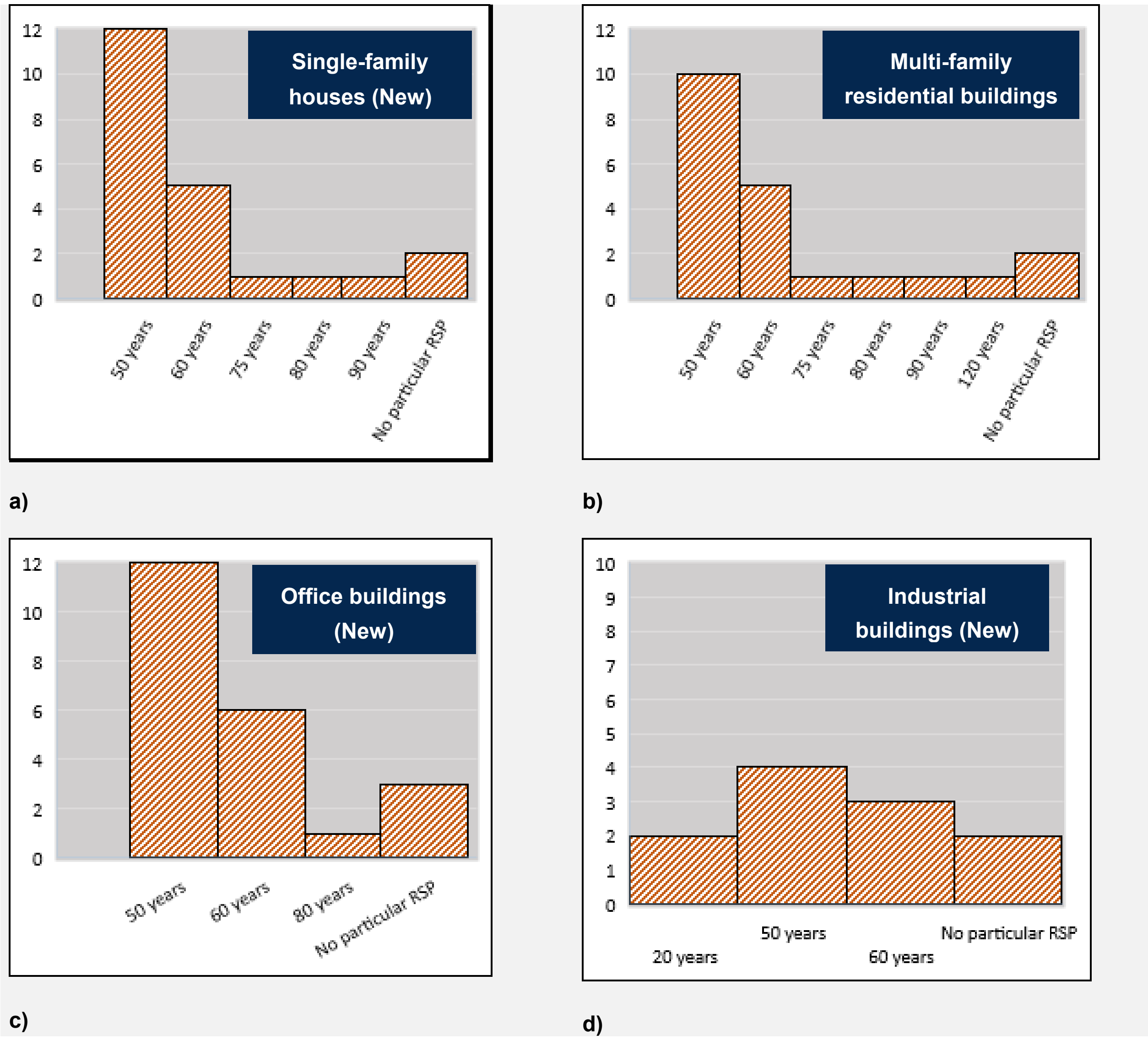

Figure 3.1: Distribution of RSPs considered for: a) single-family residential buildings; b) multi-family residential buildings; c) office buildings; d) industrial buildings. Details are given in Table A.1 (Appendix).

3.1.2 Typically considered life cycle stages and modules

Together with RSPs, a detailed overview of the considered life cycle information modules in the different methods is given in Table A.1 (Appendix). As expected, all methods consider modules A1-3 (product stage) (see Figure 3.2). Furthermore, all countries consider operational energy use in their assessments; for the ones who declared they do not, it is not that operational impacts are not accounted for in their country, but they have dedicated methods for embodied impacts, and these were the ones reported as part of the survey, such as the Dutch GWW method[41], the Swedish coming law[42] and the BRE method[43].

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[41] See: https://milieudatabase.nl/wp-content/uploads/2019/05/SBK_Assessment_method_version_2_0_TIC_versie.pdf
[42] See: https://www.boverket.se/en/start/building-in-sweden/contractor/tendering-process/climate-declaration/
[43] See: https://bregroup.com/products/impact/

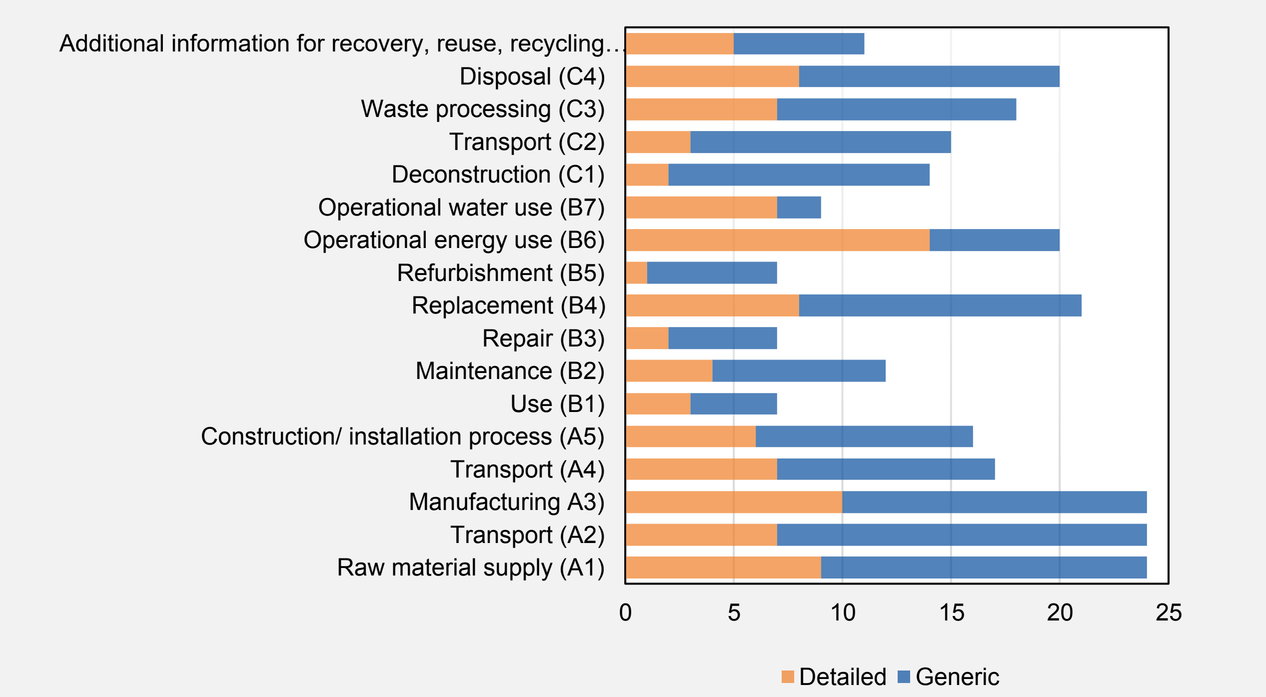

Figure 3.2: Consideration of life cycle modules in the minimum assessment scope based on generic/detailed input (based on 25 methods). Details are given in Table A.1 (Appendix).

Modules A4-5 (construction process stage) are considered by more than 2/3 of the methods. It can be observed that it is considered in (a) countries where transport distances seem to be non-negligible, such as Spain and New Zealand e.g. see Frischknecht et al. (2019; 2020); (b) countries where the methods reported are or will be part of building regulations, such as the Danish voluntary sustainability standard[44], the French E+C- method[45] and the Swedish coming law[46]. Slightly less methods consider modules C1-C2 (deconstruction and transport) than A4-5 assumingly due to their higher uncertainty.

Although replacements typically constitute the most important embodied share after product stage impacts, especially in the case of buildings with a significant share of technical equipment, some methods do not consider replacement (B4), i.e. Portugal, Sweden and Canada. In the case of the Swedish coming regulation, the intention of this omission is to put focus on:

- emissions that happen today
- emissions that can be verified at the time when the declaration is handed in
- the most impacting life cycle modules that are currently not targeted by any other regulation (which is the case for module B6)

Modules such as B1, B2, B3 and B5 are the least considered, because:

- they are still unclear to method developers, and/or
- are considered unimportant.

Figure 3.3 decomposes module B6 in more detail, following the structure of ISO carbon metric use stage ISO 16745-1 (ISO, 2017). Broadly speaking, regulated operational energy is the energy included in building regulations of a country. Typically, this is the operational energy use which a client has direct influence over, such as the energy used for space heating and cooling, domestic hot water supply and ventilation. For office buildings parts of the regulated energy use, normally, is also fixed lighting (e.g. in Austria and Germany). All other energy used in a building is referred to as unregulated energy, and can be building-related or user-related.

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[44] See: https://im.dk/Media/637602217765946554/National_Strategy_for_Sustainable_Construktion.pdf

[45] See: https://www.ecologie.gouv.fr/batiment-energie-positive-et-reduction-carbone

[46] See: https://www.boverket.se/en/start/building-in-sweden/contractor/tendering-process/climate-declaration/

It is evident that the overwhelming majority of methods focus on regulated building-related energy use. This is called B6.1 in the context of Annex 72 and recent standard updates, while the unregulated parts of energy use are called B6.2 (building-related) and B6.3 (user-related) (see Lützkendorf et al. (2023) and EN 15643:2021). Up to late 2020, only three methods included indoor transportation (B6.2) – i.e. the Austrian DGNB/ÖGNI Certification[47], the NZ whole-building whole-of-life framework/LCAQuick[48] and the method used by Groupe AGEGO in Canada (which is based on LEED standards). However, this type of energy consumption can account for 5-10% of the total operational energy consumption (Karlis 2014; De Almeida 2012). An extended scope of operational energy use including user-related energy consumption was considered in only three countries (four methods) (i.e. France, Spain and New Zealand) as shown in Figure 3.3. However, in recent developments of methods the importance of the unregulated part of operational energy use has been started being acknowledged and therefore considered in the calculation scope and benchmarks. Some examples are (a) the UK Future Homes Standard / Future Buildings Standard (2025) which provides an overall design target of 35-40 kWh/m2/yr for all energy use of new buildings from 2025; (b) the German quality label QNG[49]. One of the reasons is to deal with questions of PV systems dimensioning and the determination of the degree of self-use of solar-generated electricity in a more comprehensive way.

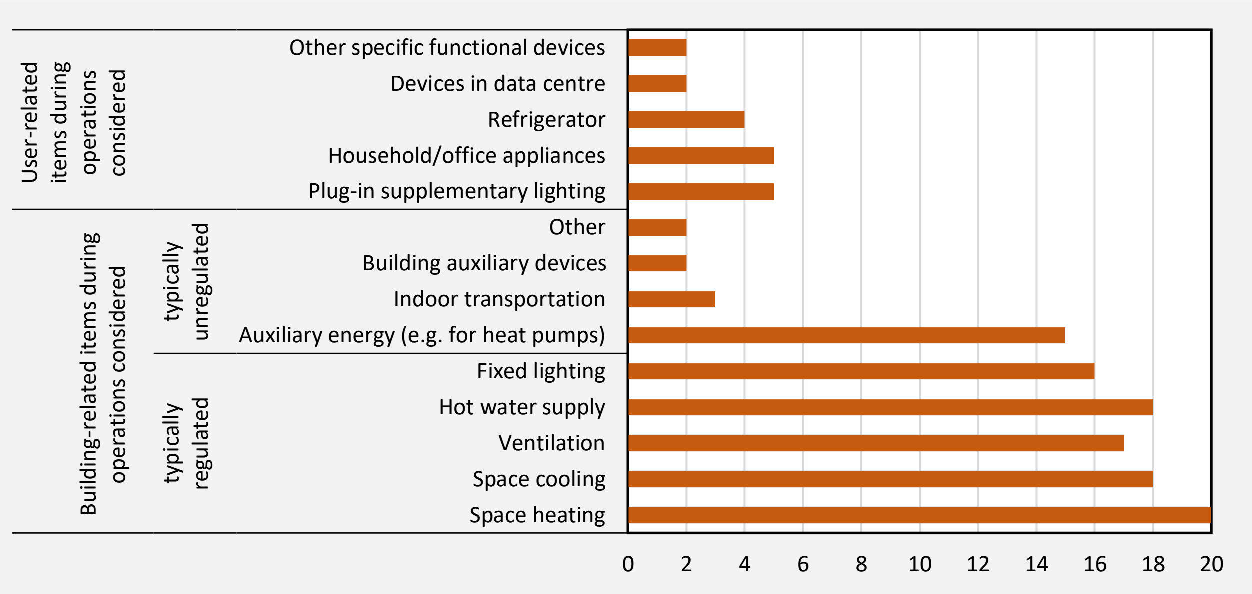

Figure 3.3 Energy uses included by the different methods. Details are given in Table C.2 (Appendix) Note than building-related items are Carbon Metric 1 (CM1) and both building-related and user-related items are Carbon Metric 2 (CM2) acc. to ISO 16745-1.

3.1.3 Typically considered building elements

The physical system boundaries of the different methods show great variance, especially when it comes to the inclusion of building services (see Table A.2 in the Appendix for a detailed overview). As seen in Figure 3.3, about 80% of the methods show completeness in the consideration of substructure, superstructure and finishes. The inclusion/exclusion of elements that cause variance are:

- **with respect to substructure**: foundations (e.g. piling), which are excluded in three methods (i.e. Belgian MMG method, Portuguese SBToolPT-H method and British BRE Global IMPACT Building LCA method) despite their importance for the embodied impacts when it comes to high-rise buildings or buildings built on harsh ground conditions.
- **with respect to superstructure**: stairs and ramps, which are excluded in four methods as well as internal doors, perhaps due to the use of simple building geometric models by some methods.

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[47] See: https://www.ogni.at/leistungen/zertifizierung/
[48] See: https://www.branz.co.nz/environment-zero-carbon-research/framework/lcaquick/
[49] See the manuals (in German): https://www.nachhaltigesbauen.de/austausch/beg/

- **with respect to finishes**: In general finishes are not easy to define during early design stages. three out of 24 methods exclude all types of finishes, while two only internal finishes.

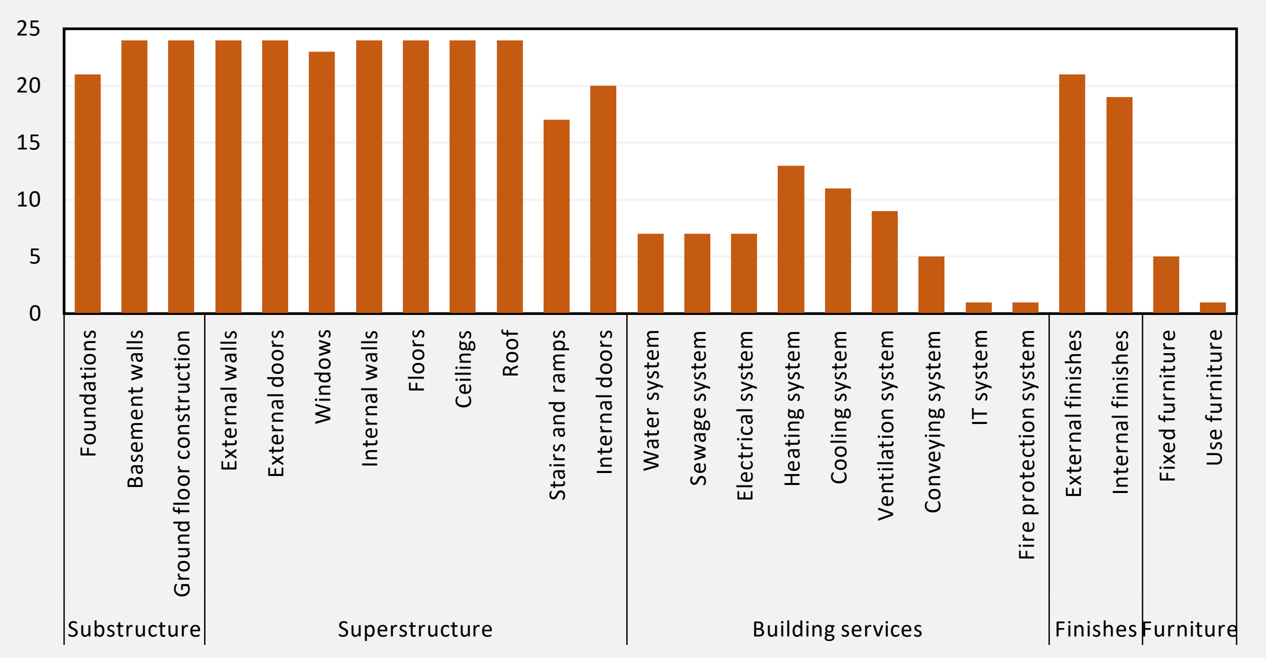

Figure 3.3: Variance of completeness of building description (i.e. physical boundaries) based on the typically considered building elements of 24 methods from 18 countries. Details are given in Table A.2 (Appendix)

Regarding **building systems**, if included, most methods tend to focus on heating, cooling and ventilation systems, which are also the systems responsible for regulated operational energy consumption in most countries. Less than 1/3 of the methods include water, sewage and electrical systems. The reason for omission of building services is, in most countries, the lack of data. Regarding furniture, about 20% of the methods include fixed furniture (e.g. sinks and basins), while only the Spanish method additionally includes user furniture. The latter is hard to predict not only during a building's design, but also at the handover, since it depends on the tenant's choices.

Methods also vary regarding the calculation of material quantities (Figure 3.4). Most methods exclusively follow an element-based approach, while some of them allow/provide multiple possibilities. For the latter, one example is DGNB, which proposes a list of tools that can be used for LCA calculations. Some methods vary the quantity take-off method dependent on the design stage (e.g. LCAbyg in Denmark). The consequence is that when several tools are proposed/allowed by a method, these must be checked and approved - based on a reference calculation so that to ensure that they do not lead to different results even if the boundary conditions and databases applied are the same.

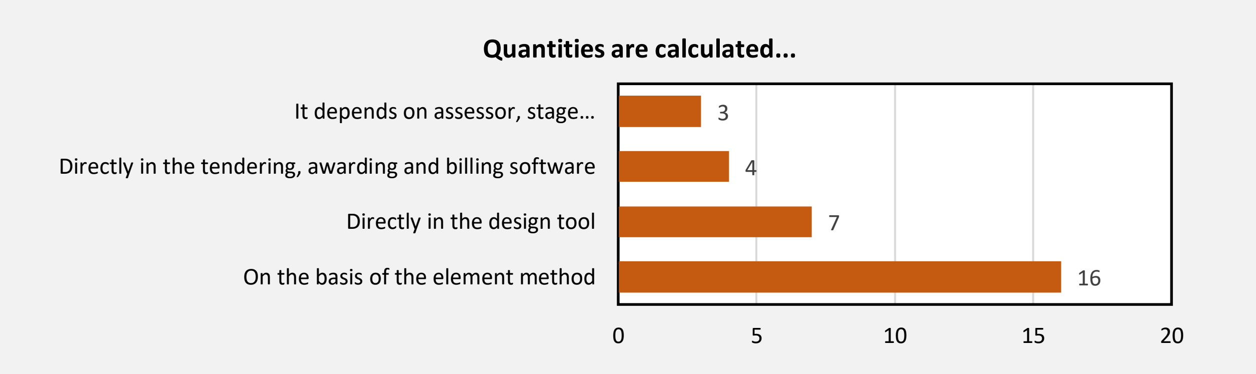

Figure 3.4. Overview of methods used to calculate material quantities based on 24 methods by 18 countries (multiple answers were possible). Details are given in Table A.2 (Appendix).

3.2 Modelling Aspects

During the questionnaire survey, the respondents were also asked to shortly mention essential modelling aspects per life cycle module considered in their national methods. The raw answers are presented in Tables B.1-3. These methods led to investigate some of these aspects in more in-depth surveys and present the analyses in special reports. There reports are:

- Basics and recommendations on **modelling of processes for transport, construction and deconstruction** in building LCA (Soust-Verdaguer et al., 2023)
- Basics and recommendations on **influence of service life of building components on replacement rates** and LCA-based assessment results (Lasvaux et al., 2023)
- Basics and recommendations on **electricity mix models** and their application in buildings LCA (Peuportier et al., 2023)
- Basics and recommendations on **influence of future electricity supplies** on LCA-based building assessments (Zhang 2023)
- Basics and recommendations on **assessment of biomass-based products** in building LCAs: the case of biogenic carbon (Saade et al., 2023)
- Basics and recommendations on **influence of future climate change on prediction of operational energy** consumption (Guarino et al., 2023)
- Basics and recommendations in **aggregation and communication** of LCA-based building assessment results (Gomes et al., 2023).
- Basics and recommendations on **discounting in LCA** and consideration of external cost of GHG emissions (Szalay et al. 2023)

3.3 Environmental Indicators

Figure 3.5 shows that all methods include the indicator GWP, with 3/24 of them (13%) focusing exclusively on this one, i.e. the Danish Sustainability code LCA, the Swedish Act on climate declarations for buildings and the British RICS method. The next most popular indicators are Photochemical Ozone Creation Potential (POCP), Acidification potential (AC), Ozone Depletion Potential (ODP) and non-renewable primary energy demand/use. Surprisingly, despite most methods reported are from Europe, only 6/24 (25%) of the methods fully include the minimum list of indicators recommended by the European standard EN15978 as well as ISO 21929-1:2011 standards. A lower acceptance/consideration of the indicators ADP_{fossil} and $ADP_{elements}$ can be especially observed.

An additional observation is that the methods with the broadest list of indicators exceeding standards expectations are choosing to present their final results in a partially or even fully aggregated form, e.g. the Belgian method MMG, the Dutch method GWW and the British method BRE. More details are given in Table C1 (Appendix). The topic of indicators aggregation is further discussed in the A72 background report by Gomes et al. (2023).

Methods do not differ only in terms of which indicators are considered but also with respect to the scope of each individual indicator. For example, looking at the scope of the indicator(s) used for quantifying embodied energy consumption different types and uses of energy resources can be quantified and considered in the indicator(s). A differentiation between the various types and uses of primary energy resources is provided in Balouktsi et at. (2016) and Annex 57[50] and shown in Figure 3.6.

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[50] See: http://www.annex57.org/wp/wp-content/uploads/2017/05/ST1-Report.pdf

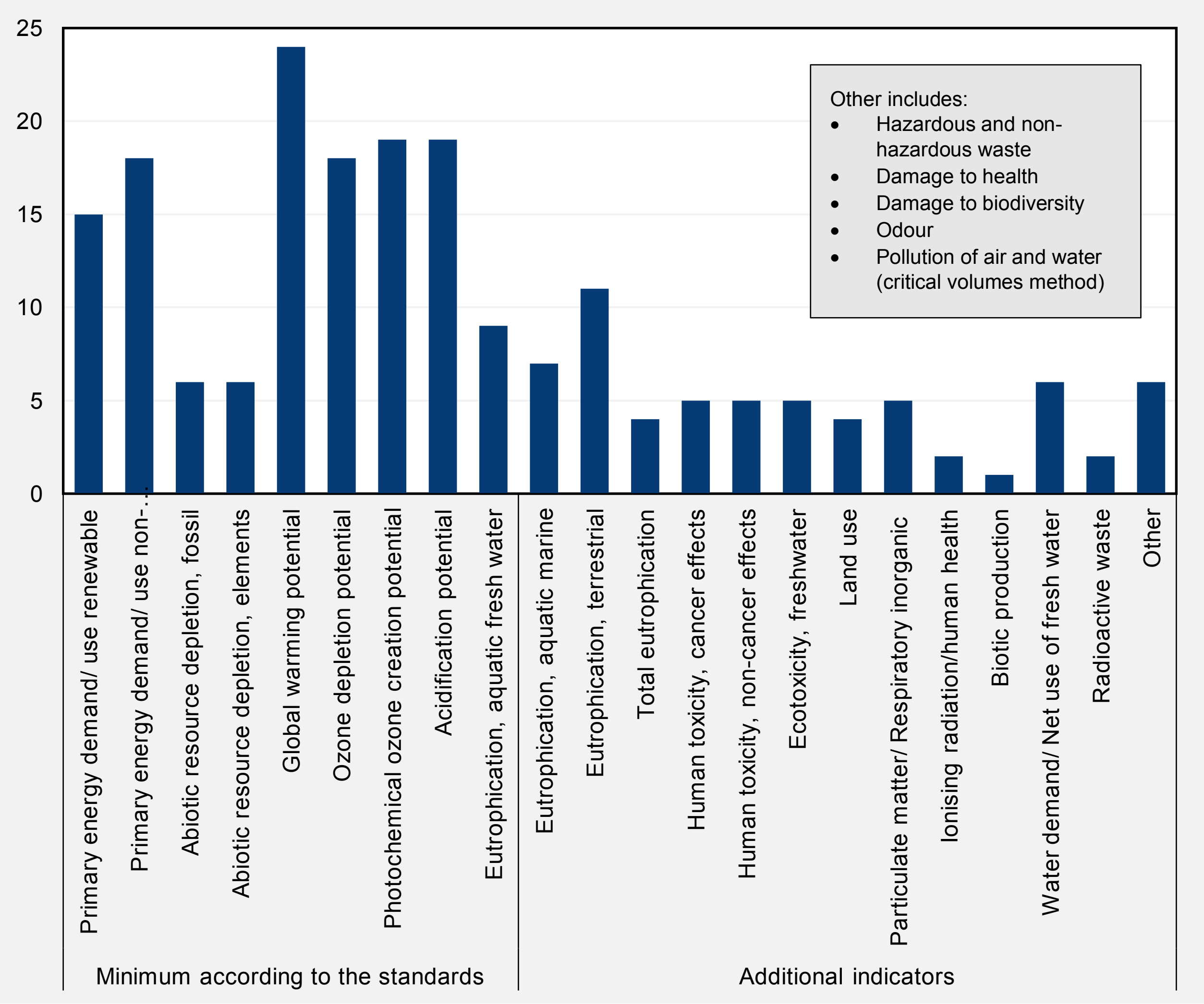

Figure 3.5: Overview of considered indicators in selected national methods. Details are given in Table C1 (Appendix)

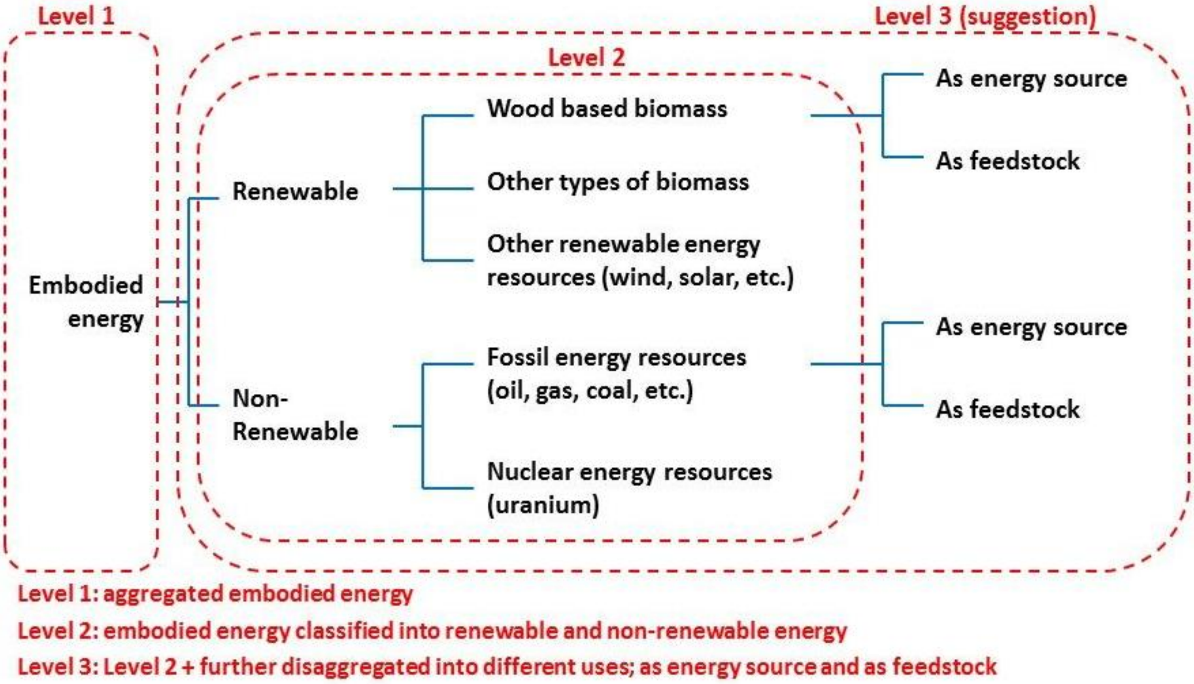

Figure 3.6: Aggregation levels in embodied energy indicator based on the types and uses of resources (adapted from Balouktsi et al. 2016)

Among the methods reported, the biggest variation is seen is the inclusion/exclusion of feedstock energy (Figure 3.7). ISO 14040 (ISO 2006) defined feedstock energy as the “heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value.” Feedstock energy is the heat of combustion or the energy content of raw material inputs used as ingredients in the process of manufacturing a product (Dixit, 2017). For instance, petrochemicals may be used as raw materials, i.e. feedstock, to manufacture plastics and rubber. This energy (calorific value) is not released but retained (contained in the product) throughout the product lifecycle, and therefore, is available for use as fuel energy outside the system boundary. This must be accounted for as non-renewable feedstock energy. Similarly, wood is used to produce a wide variety of building products and the energy contents of wood can be accounted for as renewable feedstock energy.

Methods considering non-renewable feedstock energy are the ones applied in North American and Oceanian countries, as well as China, while in Europe the situation is mixed: only France, Netherlands, Slovenia, Switzerland and United Kingdom do consider it. The consideration of renewable feedstock energy is even less common.

As earlier shown in Figure 3.5, some countries consider only non-renewable energy sources (specifically certification-based methods SBToolCZ and BREEAM), but among the ones which consider both renewables and non-renewables, most of them report them separately as two indicators (Figure 3.8). This shows that most methods at least present an aggregation level 2.

Some approaches that stand out in general:

- The method in the French tool EQUER does not include solar, because “using solar energy does not reduce the resource for others”[51].
- Methods which report non renewable energy sources via the indicator ADP fossil, include uranium (i.e. nuclear energy) in ADP elements
- Spanish method reports fossil and nuclear separately; hydropower and biomass separately; solar and geothermal jointly.

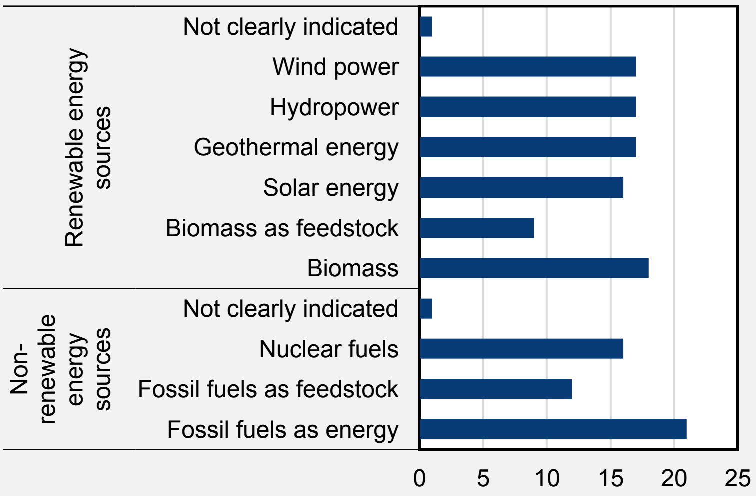

Figure 3.7. Considered sources of renewable and non-renewable energy

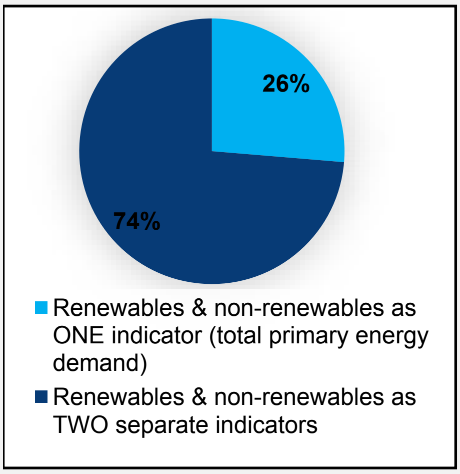

Figure 3.8: Total primary energy demand vs presentation of renewable and non-renewable sources as two indicators.

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[51] Answer by B. Peuportier

Regarding the scope of the indicator GWP which is the most widely used, Figure 3.9 shows the variations among the different methods. Besides the fossil fuel-related GHG emissions, nearly 90% of methods also consider process emissions. For concrete products, process emissions occur due to calcination and carbonation. Calcination reactions of concrete products only occur during the production of cement in the kiln, while carbonation occurs throughout the life cycle of concrete products. Calcination emissions are quite important as constitute more than 60% of manufacturing related emissions (Sanjuán et al. 2020). This share changes dependent on the type of concrete and its mixtures. However, the carbonation results in an uptake corresponding to 45 percent of the emissions through calcination.

More than 1/3 of the methods (9/25) consider biogenic carbon (removals from atmosphere). A more detailed specification on how the different methods differ and the implications can be found in the study by Ouellet-Plamondon et al. (2023) which compares the life cycle assessment of the same wood-based multi-residential building from the perspective of 16 countries participating in Annex 72. In terms of land use, only four methods consider GHG emissions due to land use, with only one of them being an official national method (SIA 2032); The other three are academic/company-based methods. It is not clear though whether both direct and indirect land-use change are considered.

3.4 Assessment Standards, Databases, Tools and Benchmarks

Table D.1 shows that most of the methods are based on the European standard EN 15978, even in the case of non-European countries. Only about 50% of the investigated countries have a national standard in place in addition.

In terms of the databases in place, around one third of the methods analysed are not connected to a national database. To calculate LCA results some methods either apply Ecoinvent or databases from other countries such as Ökobau.dat. Regarding the tools, only a few countries have developed national ones; most of the methods are supported by multiple tools.

In relation to benchmarks, several countries have already benchmarks in place or are in the process of developing them to support assessments. Existing benchmarks are presented in a special background report by Rasmussen et al. (2023).

3.5 Market Conditions and Driving Forces

Despite most countries have some kind of method in place, official, voluntary or more academic, with some methods being almost a decade old, the level of acceptance and application of these methods still lags behind (Figure 3.10). An example of a country with "high" acceptability is Sweden since the method is already part of the public procurement and will have a legal character soon; this means that 100% of developers of new buildings (the types included in the regulation) in Sweden will have to use it. An example for "medium" acceptance and application is BREAAM method; despite its overall voluntary nature in the UK, obtaining a BREEAM rating can help with the planning approval as well as has become a mandatory requirement for many Local Planning Authorities (LPAs). Some reasons for "low" or "very low" acceptability and application are that, despite LCA methods are increasingly being part of public procurement, individual investors and builders are often confused about the real benefit of using such methods. They also often consider related certification expensive and time consuming. Therefore, without clients or the regulators demanding such results, architects are not motivated to apply such methods. The overall dissemination of LCA methods among architects and their level of knowledge in this topic are also discussed in another A72 background report by Lützkendorf, Balouktsi and Röck et al. (2023).

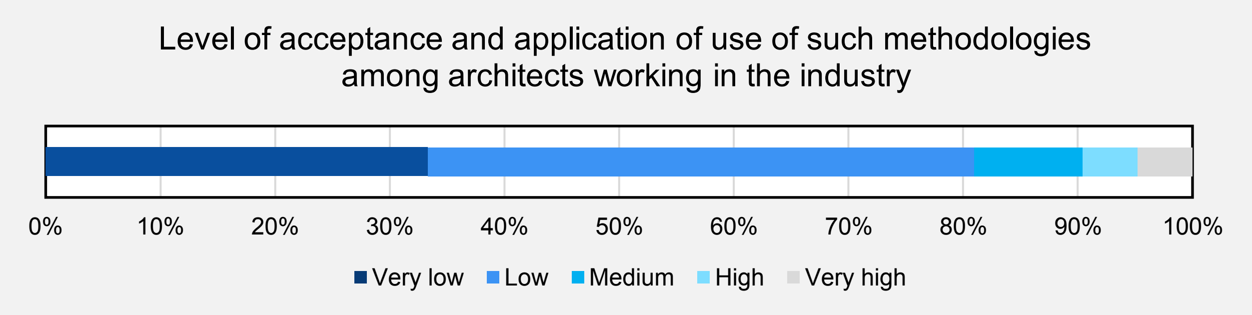

Figure 3.10. Level of acceptance and application of LCA methods among architects working in the industry. Details are given in Table G1 (Appendix)

Having specific requirements either in legislation or funding programmes always drives application and request for such results. More than 60% of the countries have legal requirements in place for operational primary energy, while for operational GHG emissions only about 20% have such requirements in place (e.g. Austria, Portugal, United Kingdom and Australia). It should be noted though that some methods are focused on embodied impacts, which does not necessarily mean that there are no legal requirements for operational impacts. In terms of embodied impacts legal requirements are only in place for GHG emissions in one country, the Netherlands, as of late 2020. However, legal requirements are in preparation in Sweden, France and Denmark among others (see also report by Lützkendorf, Balouktsi, Frischknecht et al. 2023).

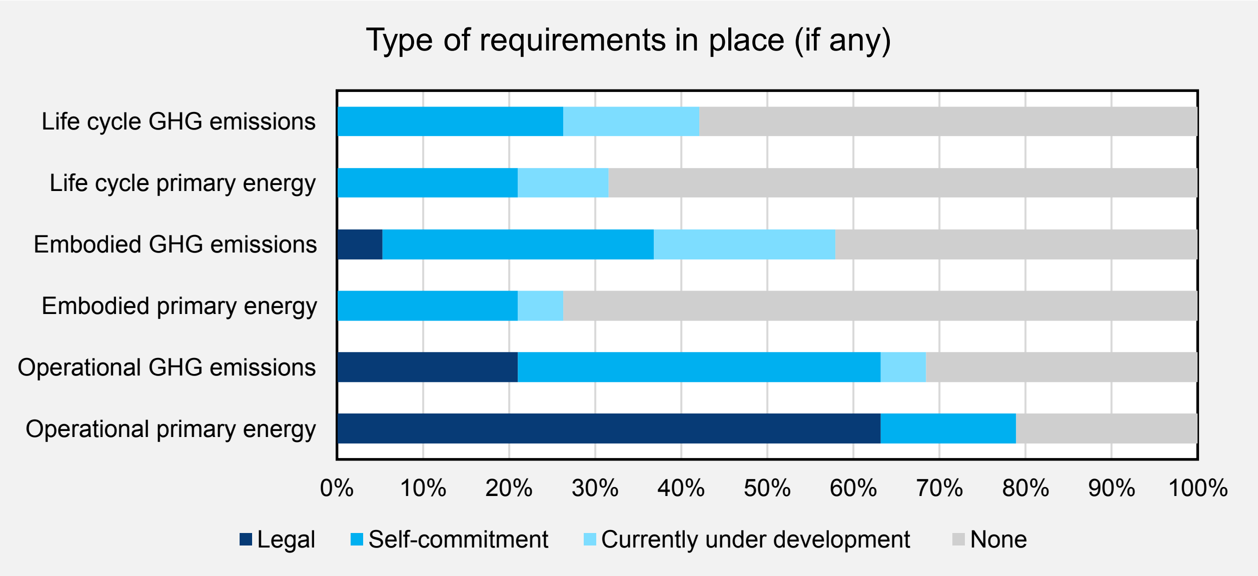

Figure 3.11. Percentage of countries having different types of requirements in place to reduce operational, embodied or lifecycle energy and GHG emissions. Details are given in Table G1.

4. Overall Findings & Recommendations

The following key points arise from the survey among A72 experts and analyses:

- Despite most countries having some kind of method in place, some of them official, voluntary (e.g. part of a certification system) or more academic, and some are almost a decade old, the level of acceptance and application of these methods still lags behind. The highest acceptance is mostly seen for methods that are already part of the public procurement and have or will have a legal character soon (e.g. Sweden and Denmark). Therefore, having specific requirements either in legislation or funding programmes always drives application and request for such results.
- While most countries have legal requirements in place for operational primary energy, only a few have such requirements for operational GHG emissions and even fewer for embodied impacts. Particularly, legal limits for the embodied GHG emissions are currently only in place in the Netherlands and France, while they are soon expected to be in force in Denmark, Sweden, Finland and the UK among others (see: Lützkendorf & Balouktsi, 2022).
- The most common reference study period (RSP) indicated by the various national methods is 50 years irrespective of the type of building. What changes is the range of the RSPs considered, with the largest ranges seen for residential buildings.
- Most methods focus on residential and office buildings. This can be the case because most assessments have been so far done for these types of buildings. Only a few methods go beyond these two types and consider e.g. industrial and/or educational buildings.
- Transport and construction processes have started being more and more integrated into the scope of national methods. Modules A4-5 are now considered by a significant number of methods. This trend can be observed especially in countries where transport distances seem to be non-negligible, such as Spain and New Zealand or in countries where the methods are or will be part of building regulations. Such a trend is not the case for C1-2 modules (deconstruction and transport to landfill or waste processing) with the justification that these activities happen far into the future.
- Although replacements typically constitute the most important embodied share after product stage impacts, especially in the case of buildings with a significant share of technical equipment, some methods prefer to focus on emissions that happen today in the short-term. This means that replacement (module B4) is not considered by all methods at least not in the minimum scope.
- Modules such as B1, B2 and B3 are the least considered. This may be the case because they are still unclear to method developers, and/or are considered unimportant.
- The overwhelming majority of methods focus for the operational part on regulated building-related energy use (B6.1 in the context of recent standard updates like EN 15643). An extended scope of operational energy use including user-related energy consumption is considered in only a few countries at the moment, despite its importance in dealing with questions of the dimensioning of PV systems and the determination of the degree of self-use of solar-generated electricity.
- The physical system boundaries of the different methods show great variance, especially when it comes to the inclusion of building services like HVAC-systems. Most methods show completeness in the consideration of substructure, superstructure and finishes. The inclusion/exclusion of elements that cause variance are (1) stairs and ramps, as well as internal doors, perhaps due to the use of simple building geometric models by some methods; (2) building systems, due to the lack of data; (3) furniture, especially user furniture as it is hard to predict not only during a building's design, but also at the handover, since it is dependent on the tenant's choices.
- Due to climate emergency, some methods now focus exclusively on GHG emissions. This will cause problems with burden-shifting. In any case, most methods choose a limited list of indicators, e.g. also including indicators such as Photochemical Ozone Creation Potential (POCP), Acidification potential (AC), Ozone Depletion Potential (ODP) and non-renewable primary energy demand/use. A lower acceptance/consideration of the dis-aggregated indicators ADPfossil and ADPelements can be especially

observed. On the one hand, this subdivision is still very new - see EN 15804 - on the other hand, hardly any data is available so far.

- The methods with the broadest list of indicators are choosing to present their final results in a partially or even fully aggregated form. Different approaches of aggregation can be observed.
- There are different perspectives on biogenic carbon consideration in life cycle assessment. Different options are currently followed in assessments and it can influence the outcome of a study and the decisions and actions of some stakeholders.

Each country has a different starting point and is at a different stage of development in this field. However, to enable comparability and usability of LCA results, the provision of a consistent and transparent basis for a methodology and reporting structure for environmental performance assessment of buildings in line with international and regional standards is needed. This background report, but especially the main A72 report by Lützkendorf et al. (2023) with its rules and recommendations, are intended to support a development in this direction. Methodologically, the approaches should be aligned in the medium term. International, and in particular, European standardization will continue to make contributions to this. Observation of developments regarding the new EN 15978-1, which is scheduled to be published in 2023, is recommended.

The standards themselves, to foster transparency and facilitate communication among different methods, should introduce typologies for system boundary description and other methodological aspects to declare the broader scope, completeness and background of a method.

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APPENDIX: Detailed reporting of 25 methods

A.0. HOW AND WHERE THE LCA METHODOLOGY CAN BE FOUND

#	Country	Name of the methodology	Years in place (since…)	Developer	Name of the source (e.g. standard, tool, ...)	Version	Source
					EUROPE		
1	AUSTRIA	DGNB/ÖGNI Certification System	Since 2009	German Sustainable Building Council	German Sustainable Building Council Certification System	2014	https://www.ogni.at/leistungen/zertifizierung/dgnbzertifizierung/
2	BELGIUM	MMG (Environmental profile of building elements)	Since 2012	KU Leuven (university), VITO (Flemish Institute for Technological Research) and BBRI (Belgian Research Institute) – research project financed by OVAM (Flemish Waste Agency)	MMG (Environmental profile of building elements)	2017	www.vlaanderen.be/nl/publicaties/detail/environmental-profile-of-building-elements-update-2017
3	CZECH REPUBLIC	SBToolCZ	Since 2013	CTU in Prague, Faculty of civil engineering	SBToolCZ Guide	-	https://www-sbtool-cz.translate.goog/online/?_x_tr_sl=cs&_x_tr_tl=en&_x_tr_hl=de
4	DENMARK (1)	DGNB LCA procedure	Since 2012	University/ Green building council	as applied in the tool LCAbyg	2018	https://www.lcabyg.dk/en/
5	DENMARK (2)	Voluntary Sustainability code LCA	Since 2020	Academia, authorities, interest organizations, companies	Baeredygtighedsklasse.dk	2020	Baeredygtighedsklasse.dk
6	FRANCE(1)	EQUER	Since 1995	MINES ParisTech	ISO 14040 and 14044, PhD thesis and articles of B. Polster, A. Guiavarch, E. Popovici, S. Thiers, G. Herfray, C. Roux, T. Recht, M.L. Pannier, P. Schalbart & B. Peuportier	4.18.7.2	www.ces.mines-paristech.fr/Logiciels/EQUER/
7	FRANCE(2)	E+C- Method	Since 2017	French ministry of environment	Référentiel « Energie-Carbone » pour les bâtiments neufs Méthode d'évaluation de la performance énergétique et environnementale des bâtiments neufs	1.0	www.ecologique-solidaire.gouv.fr/batiment-energie-positive-et-reduction-carbone
8	GERMANY(1)	Bewertungssystem Nachhaltiges Bauen (BNB)	Since 2008	BMUB		2015	https://www.bnb-nachhaltigesbauen.de/bewertungssystem.html
9	GERMANY(2)	Bewertungssystem Nachhaltiger Kleinwohnhausbau (BNK)	Since 2015	Research project	Bewertungssystem Nachhaltiger Kleinwohnhausbau (BNK)	V 1.0	www.nachhaltigesbauen.de/nachhaltige-wohngebaeude.html
10	GERMANY(3)	DGNB System	Since 2008	Joint development of academia, federal ministry and NGO	DGNB Criteria "Building Life Cycle Assessment" (ENV1.1)	2018	https://www.dgnb-system.de/en/system/version2018/criteria/building-life-cycle-assessment/

11	HUNGARY	No name, we can call it Hungarian LCA of buildings method	Since 2009	developed in a research project and further developed at the Budapest University of Technology and Economics	-	-	-
12	NETHERLANDS	Assessment Method Environmental Performance of Buildings and Civil Engineering Works (GWW)	Since 2014	Independent committee of experts	-	V.2	www.milieudatabase.nl/index.php?q=english-documents
13	PORTUGAL	Sustainability Assessment Method for Portuguese Residential Buildings (SBToolPT-H)	Since 2009	Adaptation to the Portuguese context of the international SBTool developed by the University of Minho	It is a method computed in an excel sheet	2019	LCIA database available at: http://hdl.handle.net/1822/20481
14	SLOVENIA	Slovenia has not developed its own methodology but follows the ISO standard rules	-	-	-	-	-
15	SPAIN	LCA-US Methodology	Since 2009	University of Seville & TEP 130 Research Group	excel + Ecoinvent database	V.3	US_LCA_System 1_2_V3.xls
16	SWITZERLAND	SIA 2032 "Graue Energie von Gebäuden"	Since 2008	Schweizerischer Ingenieur- und Architektenverein	SIA 2032 "Graue Energie von Gebäuden"	2010	www.shop.sia.ch/normenwerk/architekt/sia%202032/d/D/Product
17	SWEDEN	Act on climate declarations for buildings (coming regulation)	to enter into force on January 2022	national authority for housing, building and planning (Boverket)	Act on climate declarations for buildings	Draft	https://ec.europa.eu/growth/tools-databases/tris/en/index.cfm/search/?trisaction=search.detail&year=2020&num=439&mLang=EN
18	UNITED KINGDOM(1)	RICS Professional Statement "Whole life carbon assessment for the built environment"	Since 2017	Royal Institute of Chartered Surveyors	Publication	1st edition	www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/
19	UNITED KINGDOM(2)	BRE Global IMPACT Building LCA methodology	Since 2013	UK Consortia led by BRE, including IES, Wilmott Dixon and AEC3 with funding from UK Government (Innovate UK)	IMPACT Specification Parts 1 and 2	v1.7	BRE Global
OCEANIA							
20	AUSTRALIA	ALCAS Midpoint LCIA	Since 2014	Australian LCA Society	National LCA guideline	V.2	http://docs.wixstatic.com/ugd/ 9ffc42_aaa14dcc78a64ec794517aa9aa8bde3e.pdf
21	NEW ZEALAND	NZ whole-building whole-of-life framework	V1.0 since November 2016, V3.3 since September 2019	BRANZ, as part of a research project	EN15978, free tool is called LCAQuick	V.3.3	www.branz.co.nz/buildinglca
NORTH AMERICA							
22	CANADA(1)	Groupe AGECO	Since around 2008	Consulting firm	LEED Standards (and all the standards affiliated, EN 15978++)	Internal + standards requirements	-

23	CANADA(2)	Canada does not have a singular national methodology	not in place	Athena Institute	Source standard is EN 15978 as captured in Institute's Impact Estimator for Buildings (IE4B) software	5.3	https://calculatelca.com
24	USA	AIA Guide to Building Life Cycle Assessment in Practice	Since 2010	American Institute of Architects (AIA)	American Institute of Architects (AIA)	2010	www.brikbase.org/sites/default/files/aiab082942.pdf
					ASIA		
25	CHINA	Standard for Building Carbon Emission Calculation GB/T 51366-2019	Since 2019	National standard by the Ministry of Housing and Urban-Rural Development	Standard for Building Carbon Emission Calculation GB/T 51366-2019	2019	https://www.mohurd.gov.cn/gongkai/fdzdgknr/tzgg/201905/20190530_240723.html

A - SYSTEM DESCRIPTION

Table A.1: Typically considered RSPs and LC stages and modules

Country/ Name of the methodology		SYSTEM DESCRIPTION																										
		Reference Study Period (RSP)										Life cycle stages and modules (G = Generic; D = Detailed)																
		Single-family houses (New)	Single-family houses (Existing)	Multi-family residential buildings (New)	Multi-family residential buildings (Existing)	Office buildings (New)	Office buildings (Existing)	Industrial buildings (New)	Industrial buildings (Existing)	Educational buildings (New)	Educational buildings (Existing)	Raw material supply (A1)	Transport (A2)	Manufacturing A3)	Transport (A4)	Construction/ installation process (A5)	Use (B1)	Maintenance (B2)	Repair (B3)	Replacement (B4)	Refurbishment (B5)	Operational energy use (B6)	Operational water use (B7)	Deconstruction (C1)	Transport (C2)	Waste processing (C3)	Disposal (C4)	Additional information for recovery, reuse, recycling potential (D)
Europe	**1_AUSTRIA**: DGNB/ÖGNI Certification	50	[52]	50		50[53]		20		50		D [54]	D	D						D		D	D			D	D	D
	2_BELGIUM: MMG	60		60		60						G	G	G	G	G		G		G		G		G	G	G	G	
	3_CZECH REPUBLIC: SBToolCZ	50	[55]	50		50				60		G	G	G						G		D						
	4_DENMARK(1): LCAbyg tool			120		80						D	D	D						D		D				D	D	
	5_DENMARK(2): Sustainability code	50	50	50	50	50	50	50	50	50	50	D	D	D	D	D				D		D				D	D	D
	6_FRANCE(1): EQUER	80[56]	80	80	80	80	80			80	80	G	G	G	D	G				G	[57]	D	D	G	G	G	G	G
	7_FRANCE (2): E+C-	50		50		50				50		G	G	D	G	G				G		D	D	G	G	G	G	G
	8_GERMANY(1): BNB					50	50			50[58]	50	D	D	D				D		D		D	D			D	D	D
	9_GERMANY(2): BNK	50										G	G	G			G	G	G	G	G	G		G	G	G	G	
	10_GERMANY(3): DGNB	50		50		50		20		50[59]		G [60]	G	G						G		D				G	G	G
	11_HUNGARY: Hungarian LCA	50		50		50		50				G	G	G	G	G			G	G	G	D			G	G	G	
	12_NETHERLANDS: GWW	75		75		50						D	G	D	G	D	D	D	D	G	G			D	G	D	D	
	13_PORTUGAL: SBToolPT-H	50		50								G	G	G	G		G					D	D					

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[52] Certification can be pursued also for existing buildings but no certain RSP is defined in (to the respondent's knowledge) the system

[53] Other types are: Hotel (50), Hypermarket (50), Shopping Center (50), Commercial house (50), Interior Office (10), Interior Retail (5)

[54] Acc. to DGNB 2018, in the generic (simplified method) only A1-A3 are considered. The detailed method uses the LCS indicated above.

[55] it is up to the practitioner of SbTool to decide, how long is the RSP.

[56] chosen by the user, default value 80 years

[57] Refurbishment is not considered at the design phase, but it can be addressed in a specific study (e.g. comparative LCA of different retrofit strategies for a building)

[58] Universities (both new & exist., 50); Laboratories (only new, 50)

[59] Other types are: Hotel (50), Hypermarket (50), Shopping Center (50), Commercial house (50), Interior Office (10), Interior Retail (5)

[60] In DGNB, in general the use of EPDs is encouraged. The question is not 100 % clear if background data is meant or foreground data (physical model).

(Table A.1 continues)

Country/ Name of the methodology		SYSTEM DESCRIPTION																										
		Reference Study Period (RSP)										Life cycle stages and modules (G = Generic; D = Detailed)																
		Single-family houses (New)	Single-family houses (Existing)	Multi-family residential buildings (New)	Multi-family residential buildings (Existing)	Office buildings (New)	Office buildings (Existing)	Industrial buildings (New)	Industrial buildings (Existing)	Educational buildings (New)	Educational buildings (Existing)	Raw material supply (A1)	Transport (A2)	Manufacturing (A3)	Transport (A4)	Construction/ installation process (A5)	Use (B1)	Maintenance (B2)	Repair (B3)	Replacement (B4)	Refurbishment (B5)	Operational energy use (B6)	Operational water use (B7)	Deconstruction (C1)	Transport (C2)	Waste processing (C3)	Disposal (C4)	Additional information for recovery, reuse, recycling potential (D)
Europe	**14_SLOVENIA:** No official methodology	[61]										G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	
	15_SPAIN: LCA-US Methodology	50		50		50		50				G	G	G	D	G	D	G	G	G	G	D	D	G	D	D	D	D
	16_SWEDEN: Act on climate declarations for buildings (coming law)	50[62]		50		50						D	D	D	D	D												
	17_SWITZERLAND: SIA 2032	60		60		60						D	G	D				D		D		D		G	G	G	G	
	18_UNITED KINGDOM(1): RICS	50		50		50						G[63]	G	G	G	G				G		D						
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	60		60		60		60				G	G	G	D	D		G	D	D	D			G	G	D	D	[64]
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	?[65]				?[66]						G	G	G	G	G	G	G		G		G		G	G		G	
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	90		90		60						G	G	G	G	G		G		G		G	G	G	G	G	G	G
N. America	**22_CANADA(1):** Groupe AGECO	60		60		60		60				D	D	D	D	D	D	D	G	D	G	D	D	G	D	G	G	G
	23_CANADA(2): IE4B	60[67]		60		60		60				G	G	G	G	G								G	G	G	G	G
	24_USA: AIA Guide	50		50		50		50				D[68]	D	D	D	D		G		D		G		D	D		D	D
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	50[69]	50[69]	50[69]	50[69]	50[69]	50[69]			50[69]	50[69]	G	G	G	G	G	G[70]					G[71]		G				G

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[61] Not a lot of LCAs of buildings are made in Slovenia: These, which are made, are made individually and with data derived from literature (regarding RSL). Slovenia has developed the RSL based on the materials used in the construction- online under: http://www.pisrs.si/Pis.web/pregledPredpisa?id=PRAV5263#

[62] n/a, but 50 years is common to use in Sweden

[63] The choices of the LC stages represent the “minimum” requirements as stated in this guidance documents (seen by the processor, the respondent left these question unanswered)

[64] Module D is optional.

[65] Stand-alone single dwelling family house with brick veneer

[66] Commercial office building which that are used for professional or commercial purposes (e.g., offices for lawyers, accountants, general medical practitioners, government agencies and architects)

[67] 60 to 100 years for all building types

[68] Thus information is based on ATHENA Impact Estimator, which is used in North America

[69] If the design life is not mentioned in design documents, the default value is 50 years. The tool and database are generic, which is not specially designed and applied to buildings. However, it can be used to analyse buildings based on the material decomposition approach.

[70] Only refrigerant of cooling system is included.

[71] Including carbon emissions caused by HVAC, DHW, lighting and elevators, renewable energy, carbon sink on the site.

Table A.2: Typically considered building elements

Country/ Name of the methodology		SYSTEM DESCRIPTION																												
		Building elements (Y = Yes)																									Quantities are calculated…			
		Substructure			Superstructure									Building services									Finishes		Furniture					
		Foundations	Basement walls	Ground floor construction	External walls	External doors	Windows	Internal walls	Floors	Ceilings	Roof	Stairs and ramps	Internal doors	Water system	Sewage system	Electrical system	Heating system	Cooling system	Ventilation system	Conveying system	IT system	Fire protection system	External finishes	Internal finishes	Fixed furniture	User furniture	On the basis of the element method	Directly in the design tool	Directly in the tendering, awarding and billing software	It depends on assessor, stage…
Europe	**1_AUSTRIA**: DGNB/ÖGNI Certification	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y	Y					Y	Y			Y			
	2_BELGIUM: MMG		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y										Y	Y			Y			
	3_CZECH REPUBLIC: SBToolCZ	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y										Y	Y			Y		Y	
	4_DENMARK(1): LCAbyg tool	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y	Y	Y	Y			Y	Y						Y
	5_DENMARK(2): Sustainability Code LCA	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y	Y						Y
	6_FRANCE(1): EQUER	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	[72]	Y	Y	Y	Y	Y	Y	Y				Y	Y				Y		
	7_FRANCE(2): E+C-	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y	Y				Y		
	8_GERMANY(1): BNB	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y	Y			Y			
	9_GERMANY(2): BNK	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y						Y	Y	Y		Y			
	10_GERMANY(3): DGNB	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y	Y					Y	Y			Y	Y	Y	
	11_HUNGARY: Hungarian LCA	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y				Y	Y	Y				Y	Y			Y			
	12_NETHERLANDS: GWW	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y	Y	Y			Y		
	13_PORTUGAL: SBToolPT-H		Y	Y	Y	Y	Y	Y	Y	Y	Y												Y	Y	Y		Y			
	14_SLOVENIA: No official methodology	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y						Y	Y			Y			
	15_SPAIN: LCA-US Methodology	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			[73]
	16_SWEDEN: Act on climate declarations for buildings (coming law)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y											Y				Y		Y	

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[72] It can be accounted for if the user adds it to the automatic quantification of the software made from the 3D modeler

[73] Building Information Model

(Table A.2 continues)

Country/ Name of the methodology		SYSTEM DESCRIPTION																												
		Building elements																									Quantities are calculated…			
		Substructure			Superstructure									Building services									Finishes		Furniture					
		Foundations	Basement walls	Ground floor construction	External walls	External doors	Windows	Internal walls	Floors	Ceilings	Roof	Stairs and ramps	Internal doors	Water system	Sewage system	Electrical system	Heating system	Cooling system	Ventilation system	Conveying system	IT system	Fire protection system	External finishes	Internal finishes	Fixed furniture	User furniture	On the basis of the element method	Directly in the design tool	Directly in the tendering, awarding and billing software	It depends on assessor, stage…
Europe	**17_SWITZERLAND**: SIA 2032	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	[74]	Y	Y	Y	Y	Y	Y	Y				Y	Y			Y	Y		
	18_UNITED KINGDOM(1): RICS	Y[75]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y														[76]			
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y										Y	Y			Y			
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Y	Y	Y	Y	Y		Y	Y	Y	Y		Y														Y			
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y										Y	Y				Y		
N. America	**22_CANADA(1):** Groupe AGECO	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y														Y		Y			
	23_CANADA(2): IE4B	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y										Y				Y	Y	Y	
	24_USA: AIA Guide	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y										Y	Y			Y			
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y[77]	Y[77]	Y[77]	Y[77]	Y[77]	Y[77]	Y[77]		Y[77]	Y[77]	Y[77]	Y[77]			Y[78]		

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[74] No with uncertainty

[75] The choices of the LC building elements represent the “minimum” requirements as stated in this guidance documents (seen by the processor, the respondent left these question unanswered)

[76] This question remained unanswered

[77] Not specified. It is specified that “the weight of materials calculated should exceed 95% of the total weight; and when more than 95% materials are calculated, materials whose weight is less than 0.1% can be ignored.”

[78] There are several tools available. PKPM-CES and T20-CE are based on CAD documents, while AIARCH just use collected data (way of collection is not specified).

B – MODELLING ASPECTS

Table B.1: Assumptions for pre-use and use stages (A and B modules)

Country/ Name of the methodology		MODELLING ASPECTS – Assumptions					
		Assumptions and scenarios for transport (A4)	Assumptions and scenarios for construction/ installation process (A5)	Assumptions and scenarios for maintenance and repair (B2-B3)	Assumptions and scenarios for Replacement (B4)	Assumptions and scenarios for Refurbishment (B5)	Assumptions and scenarios for Operational energy and water use (B6-B7)
Europe	**1_AUSTRIA**: DGNB/ÖGNI Certification	Not covered	Not covered	Maintenance processes are represented incompletely as water consumption in ENV2.2. Not included in Building LCA	The replacement frequency of components/products according to their expected useful life are determined under the assumption of replacement with the originally calculated component/ product. Only the complete (integer) exchange (no partial exchange) is permissible.	Not covered	**B6**: Measured or simulated acc. to "OIB RL 6 - Energy saving and thermal insulation" (depending on the project stage) https://www.oib.or.at/en/node/149964 For LCA Module simulation: Austrian electricity mix taken form Ecoinvent 3.5 Database **B7**: Measured or calculated (depending on the project stage) For LCA Module simulation: Swiss tab water process taken from Ecoinvent 3.5 Database
	2_BELGIUM: MMG	Scenarios per material category (including transport routes, transport modes and average transport distances)	5% material losses - limited number of construction activities included (e.g. excavation, energy related processes and specific emissions at the construction site)	Maintenance scenarios based on a number of reference works (BCIS 2006; Jacobs et al. 2005; Ten Hagen & Stam 2000; SBR 1998; Perret 1995; den Hollander et al. 1993, Pasman et al. 1993; CSTC et al. 1991; BBRI et al. 2011)	Replacement scenarios based on a number of reference works (BCIS 2006; Jacobs et al. 2005; Ten Hagen & Stam 2000; SBR 1998; Perret 1995; den Hollander et al. 1993, Pasman et al. 1993; CSTC et al. 1991; BBRI et al. 2011)	Not covered	The operational energy use for heating due to transmission losses is calculated based on the equivalent degree-day method
	3_CZECH REPUBLIC: SBToolCZ	Not covered	Not covered	Not covered	The method provides an estimated service life of each building element. If the service life of an element is shorter than the service life of a building, its replacement is counted.	Not covered	Data from EPBD (mandatory for each building). Energy for heating, cooling and air conditioning, ventilation, domestic hot water, lighting and auxiliary energy for pumps, control and automation. Water use is not considered.
	4_DENMARK(1): LCAbyg tool	Not covered	Not covered	Not covered	National service life table of construction products is used	Not covered	Expected use of electricity and heating is estimated via the energy calculations that are mandatory to obtain a building permit
	5_DENMARK(2): Sustainability code LCA	Specific to the product	Specific to the on-site operations	Not covered	National service life table of construction products is used	Not covered	Expected use of electricity and heating is estimated via the energy calculations that are mandatory to obtain a building permit
	6_FRANCE(1): EQUER	average transport distance given by the user (default value is proposed), truck is considered	% waste given by the user (surplus, broken elements...)	Not covered	life span given by the user for building finishes (painting...), windows, equipment, default values are proposed	specific study (see previous comment)	link with energy simulation
	7_FRANCE(2): E+C-	Fixed in the EPDs	Fixed in the EPDs	Fixed in the EPDs	Fixed in the EPDs	Not covered	Link with energy calculation (regulation) calculation of water demand

(Table B.1 continues)

Country/ Name of the methodology		MODELLING ASPECTS – Assumptions					
		Assumptions and scenarios for transport (A4)	Assumptions and scenarios for construction/ installation process (A5)	Assumptions and scenarios for maintenance and repair (B2-B3)	Assumptions and scenarios for Replacement (B4)	Assumptions and scenarios for Refurbishment (B5)	Assumptions and scenarios for Operational energy and water use (B6-B7)
Europe	**8_GERMANY(1):** BNB	Not covered	Not covered	-	Includes the production and the EoL of each component renewal. Service life data are provided by BNB.	Not covered	Operational final energy according to EnEV (B6).
	9_GERMANY(2): BNK	[79]					
	10_GERMANY(3): DGNB	-	-	-	Generic list of replacement cycles	-	Calculations according to energy regulation
	11_HUNGARY: Hungarian LCA	Building materials are classified into 3 categories depending on the number and location of production plants and export. (1) 50km transport lorry 16-32t, (2) 150 km lorry 16-32t + 30 van, (3) 800km freight rail + 30 km van	Assuming cutting waste for all materials plus a default 8 MJ/m3 electricity and 50 MJ/m3 diesel consumption per m3 of building.	Repair is considered as 10% of the total replacement impact.	Replacement is considered based on default lifetimes.	Energy related refurbishment or major conversion.	Operational energy is calculated according to the Hungarian national methodology based on EPBD or by dynamic simulation. National static electricity mix is considered. Sold onsite electricity is subtracted with the same factors.
	12_NETHERLANDS: GWW	Depends on product	Depends on product	Depends on product	Depends on product	Depends on product	Depends on product
	13_PORTUGAL: SBToolPT-H	The real distance from the building site to the nearest manufacture	Not considered	Maintenance can be included if there are significant differences in the lifetime of the materials used in the different design scenarios.	Not considered	Not considered	Only the energy use for heating, cooling and domestic hot water is considered. Calculations are based on the method of the Portuguese thermal code.
	14_SLOVENIA: No official methodology	mostly 50 km	-	-	-	-	Slovenian average electricity mix
	15_SPAIN: LCA-US Methodology	Assumption regarding probable location of the building material factories in relation to the building site	Kellemberger assumptions for energy quantification - depending of building material quantities-	Kellemberger assumptions for energy quantification - depending of building material quantities	Kellemberger assumptions for energy quantification - depending of building material quantities	Kellemberger assumptions for energy quantification - depending of building material quantities	Operational Energy using specific software (DesigBuilder). Water use based on CTE assumptions
	16_SWEDEN: Act on climate declarations for buildings (coming law)	Default scenarios in national database for typical for each material concerning transport distance, type of transport and fuel. specific values to be used for the 3 heaviest materials	specific data inserted by user	Not covered	Not covered	Not covered	Not covered

(Table B.1 continues)

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[79] Question skipped by the respondent

Country/ Name of the methodology		MODELLING ASPECTS – Assumptions					
		Assumptions and scenarios for transport (A4)	Assumptions and scenarios for construction/ installation process (A5)	Assumptions and scenarios for maintenance and repair (B2-B3)	Assumptions and scenarios for Replacement (B4)	Assumptions and scenarios for Refurbishment (B5)	Assumptions and scenarios for Operational energy and water use (B6-B7)
Europe	**17_SWITZERLAND:** SIA 2032	Not covered	Not covered	-	generic service life of building elements	starts a new life cycle	onsite electricity fed into the grid bears the impacts of the power plant (PV) producing this electricity
	18_UNITED KINGDOM(1): RICS	Specific distance from manufacturer to site. Defaults before specification: Locally manufactured e.g. concrete, aggregate, earth 50km; Nationally manufactured e.g. plasterboard, blockwork, insulation 300km; European manufactured e.g. CLT, façade modules, carpet 1,500km by road; Globally manufactured e.g. specialist stone cladding 200km by road, 10,000 km by sea.	Specific data to be used. Average for building construction site emissions, in the absence of more specific information: 1400kgCO2e/£100k of project value (BRE Meeting Construction 2025 Targets – SMARTWaste KPI p.3, footnote 9). Default wastage rates and disposal routes based on Sweett, C. (2008) Reference guide: Net Waste Tool User Guide, Version 1.1. London: WRAP.	Based on EPD. B3 = B2*25% if no other data.	Table 9 in document provides default service lives for major elements.	-	Regulated energy use based on SAP or SBEM (EPBD for UK).
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	Based on UK freight statistics reviewed by BRE. Varies for different products. Includes import where relevant. Not publicly available. Can be varied by user.	Wastage % based on UK research by BRE. varies for different products. Not publicly available. Can be varied by user.	Based on service life data provided by BRE. Not publicly available. can be varied by user.	Based on service life data provided by BRE. Not publicly available. can be varied by user.	Based on service life data provided by BRE. Not publicly available. can be varied by user. Covers planned replacement/ refurbishment of facades, roofs, windows etc. Includes flooring replacement?	Impact is considered based on data produced from separate energy modelling programmes to UK regulations.
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Assumed 100 km by rigid truck	Assumed negligible	Considered based on replacement rates of key components	Key components replacement rates (e.g., 50 years for external cladding, internal wall for 100 years, concrete for 100 years, windows & doors 25 years, 10 years of painting for external/internal	Not covered	Only heating and cooling energy
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Varies according to material - see Module A4 datasheet at www.branz.co.nz/buildinglca under "Data"	Waste rates and end-of-life routes vary with material - see Module A5 datasheet at www.branz.co.nz/buildinglca under "Data"	Varies with material (used for enclosure) - see Module B2 datasheet at www.branz.co.nz/buildinglca under "Data"	Varies according to material - see Module B4 datasheet at www.branz.co.nz/buildinglca under "Data"	Not covered	Grid electricity dataset available at www.branz.co.nz/buildinglca under "Data". Also default approach to energy simulation for offices available in Module B6 datasheet at www.branz.co.nz/buildinglca under "Data". Water use defaults in offices in Module B7 datasheet at www.branz.co.nz/buildinglca under "Data"

(Table B.1 continues)

Country/ Name of the methodology		MODELLING ASPECTS – Assumptions					
		Assumptions and scenarios for transport (A4)	Assumptions and scenarios for construction/ installation process (A5)	Assumptions and scenarios for maintenance and repair (B2-B3)	Assumptions and scenarios for Replacement (B4)	Assumptions and scenarios for Refurbishment (B5)	Assumptions and scenarios for Operational energy and water use (B6-B7)
N. America	**22_CANADA(1):** Groupe AGECO	[80]					
	23_CANADA(2): IE4B	based on regional analyses	crane operation + other on-site energy use (hot welding of seams, etc.)	-	based on product service lives in various regions and building archetypes	-	-
	24_USA: AIA Guide	The transportation distances are based on regional surveys. Only material transportation covered.	Construction & installation, waste factors for materials, loss factors for formwork.	Typical frequency of maintenance for each of the urban centers supported in the software Typical transportation mode and distance by region from the distributor to the site for the relative components. Waste factors included for materials.	Typical life expectancy (service life) of each material/product by region, based on empirical evidence and or product warranty periods. Typical transportation mode and distance by region from the distributor to the site for the relative components. Waste factors included for materials. Replacement materials assumed to be the same as new construction	-	-
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	Based on empirical data[81]	Actual/predicted number of construction machine, and default energy consumption data of each machine[82]	Not covered	Not covered	Not covered	Calculate according to the method provided in the standard[83]. (energy consumption every year is constant)

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[80] Question skipped by the respondent

[81] If no empirical data is available, default data provided in Annex E of Standard for Building Carbon Emission Calculation GB/T 51366-2019 should be used. Default transport distance of concrete is 40km while that of other materials is 500km. Carbon emissions [Kg CO2e/(t·km)] of different transport vehicles are specified in Annex E.

[82] Energy consumption (kg diesel/machine or kwh electricity/machine) for every type construction machine is specified in Annex C.

[83] Reference values are provided, including room temperature setpoints, RH, illumination, equipment power density, lighting power density, Lighting hours per month, Fresh air volume per capita.

Table B.2: Assumptions for after use stages (C modules)

Country/ Name of the methodology		MODELLING ASPECTS – Assumptions				
		Assumptions and scenarios for deconstruction (C1)	Assumptions and scenarios for Transport (C2)	Assumptions and scenarios for waste processing (C3)	Assumptions and scenarios for disposal (C4)	(D)
Europe	**1_AUSTRIA**: DGNB/ÖGNI/ Austrian PCRs	Scenarios based on Austrian PCRs, where available, else based on Belgium scenario	Scenarios per waste category (including transport routes, transport modes and average transport distances)	Scenarios per waste category (including share of reuse, recycling and energy recovery)	Scenarios per waste category (including share of landfilling and incineration)	Not covered
	2_BELGIUM: MMG	Scenarios based "Ecoinvent 2 rapport 13 part V Building material disposal"	Scenarios per waste category (including transport routes, transport modes and average transport distances)	Scenarios per waste category (including share of reuse, recycling and energy recovery)	Scenarios per waste category (including share of landfilling and incineration)	Not covered
	3_CZECH REPUBLIC: SBToolCZ	Not covered	Not covered	Not covered	Not covered	Not covered
	4_DENMARK(1): LCAbyg tool			Typical waste scenario for each material is predefined	Typical waste scenario for each material is predefined	
	5_DENMARK(2): Sustainability code	-	-	Product specific or according to waste regulations	Product specific or according to waste regulations	Product/material specific
	6_FRANCE(1): EQUER	processes indicated by the user for some materials	transport distance to landfill, incinerator and recycling given by the user (default values are proposed), truck is considered	recycling processes chosen by the user	generic data for incineration of wood, plastics etc, landfill	50% avoided impacts by recycling at end of life, 50% at fabrication
	7_FRANCE(2): E+C-	Fixed in the EPDs	Fixed in the EPDs	Fixed in the EPDs	Fixed in the EPDs	1/3 of module D
	8_GERMANY(1): BNB	Not covered	Not covered	Fixed in the EPDs	Fixed in the EPDs	Module D is not balanced in the end of life phase.
	9_GERMANY(2): BNK					
	10_GERMANY(3): DGNB	-	-	material specific waste scenarios (typical scenarios)	material specific disposal scenarios (typical scenarios)	material specific recovery, reuse, recycling scenarios (typical scenarios)
	11_HUNGARY: Hungarian LCA	-	Transport (C2) is considered by a default value.	Waste processing/ disposal is considered based on a probable end-of-life scenario for each material.	-	-
	12_NETHERLANDS: GWW	Depends on product	Depends on product	Depends on product	Depends on product	Depends on product
	13_PORTUGAL: SBToolPT-H	-	Deconstruction waste is transported by road (medium-size truck) for 50km to a waste sorting facility	Only metals are recycled (95% for profiles and 80% for reinforcing steel). The other materials are placed in landfills.	All materials, except metals, are treated to be placed in landfills	Not considered. In situ energy production from renewables is used to offset energy consumption.
	14_SLOVENIA: No official methodology	-	mostly 50 km	-	-	-
	15_SPAIN: LCA-US Methodology	Kellemberger assumptions for energy quantification - depending of building material quantities	Assumption regarding probable location of the final disposal site in relation to the building site	Depending on the technical scenario (mean or best practice)	Depending on the technical scenario (mean or best practice)	Depending on the technical scenario (mean or best practice)
	16_SWEDEN: Act on climate declarations for buildings (coming law)	Not covered	Not covered	Not covered	Not covered	Not covered

(Table B.2 continues)

Country/ Name of the methodology		MODELLING ASPECTS – Assumptions				
		Assumptions and scenarios for deconstruction (C1)	Assumptions and scenarios for Transport (C2)	Assumptions and scenarios for waste processing (C3)	Assumptions and scenarios for disposal (C4)	(D)
	17_SWITZERLAND: SIA 2032	generic, simplified assumptions and data		material dependent "modal" split of waste processing technologies	dito	explicitly not allowed to account for benefits occurring after end of life of the building
	18_UNITED KINGDOM(1): RICS	An average rate of 3.4 kgCO2e/m2 GIA (rate from monitored demolition case studies in central London)	Defaults: Reuse on site 0km, recycling elsewhere, 50km by road, landfill: average of 2 closest landfill sites.	Default waste route is landfill if no other information available.	Where no other data, Landfilling – no landfill gas recovery: 2.15 kgCO2e/kg of timber product (Weight 2011) (Symons, Moncaster and Symons 2013).	-
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	Based on data provided by BRE. Not publicly available.	Based on data provided by BRE. Not publicly available.	Based on data provided by BRE. % varies by material. Not publicly available. % to recycling can be varied by user.	Based on data provided by BRE. % varies by material. Not publicly available. % to landfill and to incineration can be varied by user.	Optional to include.
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Assumed negligible	Assumed 50 km to recycling or landfill site considering material recovery rate	Not considered	Landfill processes employed (GHG emissions of organic products)	Not considered
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	End-of-life routes for materials in Module C1 datasheet at www.branz.co.nz/buildinglca under "Data"	-	-	-	-
N. America	**22_CANADA(1):** Groupe AGECO	[84]				
	23_CANADA(2): IE4B	demolition/deconstruction analyses	preset by region	various third-party commercial datasets (e.g., ecoinvent)	Final disposition of each product based on recycling	applies primarily to metals recycling and biogenic carbon sequestration in landfill
	24_USA: AIA Guide	At the user-defined expected building end of life, the software first estimates the energy required to deconstruct/demolish the major structural systems of the building (wood, steel and/or concrete). It is assumed that the envelope materials are demolished during the structural demolition, but have little influence on the demolition energy use.	Transportation to the landfill assuming typical distances to landfill for the region	-	The IE4B assumes that materials commonly landfilled today will continue to be landfilled, and those currently recycled or re-used will continue to be recycled and reused.	-
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	Actual/predicted number of construction machine, and default energy consumption data of each machine[85]	Not covered	Not covered	Not covered	Default value[86]

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[84] Question skipped by the respondent

[85] Energy consumption (kg diesel/machine or kwh electricity/machine) for every type construction machine is specified in Annex C.

[86] If scrap materials/products of low value are used for construction, GWP caused by their upstream process should be ignored; If other scrap renewable materials/products are used for construction, 50% GWP of their upstream process should be calculated; If there are scrap materials/products at construction and deconstruction stages, 50% GWP of their upstream process should be cut off from the total GWP of construction and deconstruction.

Table B.3: Consideration of future changes (dynamic elements)

Country/ Name of the methodology		MODELLING ASPECTS – Consideration of future changes				
		Variation in occupancy behaviour	Changes to the building's layout	Changes in the climate	Technological progress	Discounting of future impacts
Europe	**1_FRANCE(1)**: EQUER	Statistical model[87]	No	IPCC scenarios[88]	energy mix[89]	No
	2_FRANCE(2): E+C-	No	No	No	No	No
	3_GERMANY(1): BNB	No	No	No	No	No
	4_GERMANY(2): BNK	No	No	No	No	No
	5_GERMANY(3): DGNB	No	No	No	No	No
	6_DENMARK: LCAbyg tool	No	No	No	B6: Forecasting of electricity and district heating mixes towards more renewable energy in 2050, as visioned by the energy authorities	No
	7_DENMARK: Sustainability code LCA	No	No	No	B6: Forecasting of electricity and district heating mixes towards more renewable energy in 2040, as adopted by the parliament	No
	8_NETHERLANDS: GWW	No	No	No	No	1) better allocation procedure of impact from recycling, to avoid double counting. 2) improved specification of product recycling and reuse
	9_HUNGARY: Hungarian LCA	No	No	No	No	No
	10_SPAIN: LCA-US Methodology	No	No	No	No	No
	11_SWITZERLAND: SIA 2032	No	No	No	No	No
	12_SWEDEN: Act on climate declarations for buildings (coming law)	No	No	No	No	No
	13_BELGIUM: MMG	No	No	No	No	No
	14_UNITED KINGDOM(1): RICS	No	No	No	No	No
	15_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	No	No	No	No	No
	16_CZECH REPUBLIC: SBToolCZ	No	No	No	No	No
	17_SLOVENIA: No official methodology	No	No	No	No	No

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[87] Source: Vorger E., Schalbart P., Peuportier B., Integration of a Comprehensive Stochastic Model of Occupancy in Building Simulation to Study how Inhabitants Influence Energy Performance, 30th International PLEA Conference, Ahmedabad, December 2014

[88] Source: Roux C., Schalbart P., Assoumou E. and Peuportier B., Integrating climate change and energy mix scenarios in LCA of buildings and districts, Applied Energy 184 (2016), pp. 619-629

[89] Source: Roux C., Schalbart P., Assoumou E. and Peuportier B., Integrating climate change and energy mix scenarios in LCA of buildings and districts, Applied Energy 184 (2016), pp. 619-629

(Table B.3 continues)

Country/ Name of the methodology		MODELLING ASPECTS – Consideration of future changes				
		Variation in occupancy behaviour	Changes to the building's layout	Changes in the climate	Technological progress	Discounting of future impacts
Europe	**18_AUSTRIA**: DGNB/ÖGNI Certification	No	No	No[90]	No[30]	No
	19_PORTUGAL: SBToolPT-H	No	No	No	No	No
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	No	No	No	No	No
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	No	No	No	Grid electricity based on the Mixed Renewables scenario to 2050, published by the Ministry of Business, Innovation & Employment (MBIE) in its 2016 *Electricity demand and generation scenarios* report. The scenario assumes a mix of geothermal and wind plant built, starting in 2020. Annual electricity demand growth is 1%, reflecting moderate GDP and population growth. Grid impacts in 2050 assumed to continue beyond 2050.	No
N. America	**22_CANADA(1):** Groupe AGECO	No	No	No	No	No
	23_CANADA(2): IE4B	No	No	No	No	No
	24_USA: AIA Guide	No	No	No	No	No
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	No	No	No	No	No

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[90] These aspects are included in the latest DGNB guidelines and will be included in our assessments in the future.

C – ENVIRONMENTAL INDICATORS

Table C.1: Indicators typically considered, including their assessment and aggregation

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS																							
		Minimum according to the standards									Additional indicators													Method	Aggregation
		Primary energy demand/ use renewable	Primary energy demand/ use non-renewable	Abiotic resource depletion, fossil	Abiotic resource depletion, elements	Global warming potential	Ozone depletion potential	Photochemical ozone creation potential	Acidification potential	Eutrophication, aquatic fresh water	Eutrophication, aquatic marine	Eutrophication, terrestrial	Total eutrophication	Human toxicity, cancer effects	Human toxicity, non-cancer effects	Ecotoxicity, freshwater	Land use	Particulate matter/ Respiratory inorganic	Ionising radiation/human health	Biotic production	Water demand/ Net use of fresh water	Radioactive waste	Other	For the selected environmental impact indicators, according to which method?	Is there the possibility of partial or full aggregation?
Europe	**1_AUSTRIA**: DGNB/ÖGNI Certification	Y	Y			Y	Y	Y	Y				Y								Y			Indicators and LCIA method acc to ÖNORM EN 15804	Yes, full aggregation[91]
	2_BELGIUM: MMG			Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y				Y[92]	CML version 2012 and others[93]	Yes, full aggregation
	3_CZECH REPUBLIC: SBToolCZ		Y			Y	Y	Y	Y			Y												CML-IA	No
	4_DENMARK: LCAbyg tool	Y	Y			Y	Y	Y	Y			Y												CML 2001 as practiced in Ökobau dat	No
	5_DENMARK: Sustainability code LCA					Y																		GWP100, IPCC 2013	
	6_FRANCE: EQUER		Y	Y	Y	Y		Y	Y				Y				Y				Y	Y	Y[94]	CML 2001, Eco-indicator 99 (will soon be updated)	No
	7_FRANCE(2): E+C-	Y	Y	Y	Y	Y	Y	Y	Y[95]				Y								Y		Y[96]	CML 2001, IPCC, CED	?
	8_GERMANY(1): BNB		Y			Y	Y		Y															CML	No
	9_GERMANY(2): BNK	Y	Y			Y																		CML 2002	Yes, partial aggregation
	10_GERMANY(3): DGNB	Y	Y			Y	Y	Y	Y			Y									Y				
	11_HUNGARY: Hungarian LCA	Y	Y			Y	Y	Y	Y	Y	Y	Y												CML and ReCiPe aggregated values	Yes, partial aggregation
	12_NETHERLANDS: GWW	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y								CML Impact Assessment method, 2013	Yes, partial aggregation

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[91] Weighting of Checklist points following the DGNB System

[92] Water resource depletion

[93] CML version 2012 (Global warming, Ozone depletion, Acidification, Eutrophication, Photochemical Ozone Formation, Abiotic depletion of non-fossil resources, Abiotic depletion of fossil resources); Rosenbaum et al., 2008 (Human toxicity); Rabl et al, 2004 (Particulate matter); Frishknecht et al., 2000 (Ionising radiation); Rosenbaum et al., 2008 (Ecotoxicity, freshwater); Frishknecht et al, 2006 (Water scarcity); Milà i Canals et al., 2007 (Land use occupation and transformation – soil organic matter); Köllner, 2000 (Land use occupation and transformation – biodiversity)

[94] other waste, damage to health, damage to biodiversity, odour

[95] In practice, only energy and carbon indicators are used

[96] Other waste, pollution of air and water (critical volumes method).

(Table C.1 continues)

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS																						
		Minimum according to the standards									Additional indicators												Method	Aggregation
		Primary energy demand/ use renewable	Primary energy demand /use non-renewable	Abiotic resource depletion, fossil	Abiotic resource depletion, elements	Global warming potential	Ozone depletion potential	Photochemical ozone creation potential	Acidification potential	Eutrophication, aquatic fresh water	Eutrophication, aquatic marine	Eutrophication, terrestrial	Total eutrophication	Human toxicity, cancer effects	Human toxicity, non-cancer effects	Ecotoxicity, freshwater	Land use	Particulate matter/ Respiratory inorganic	Ionising radiation/human health	Biotic production	Water demand/ Net use of fresh water	Radioactive waste	Other	For the selected environmental impact indicators, according to which method?	Is there the possibility of partial or full aggregation?
Europe	**13_PORTUGAL**: SBToolPT-H	Y	Y			Y	Y	Y	Y	Y	Y	Y												CML baseline 2000, V3.04	Yes, full aggregation
	14_SLOVENIA: No official methodology	[97]																						Mostly the researchers use the CML method.	No
	15_SPAIN: LCA-US Methodology	Y	Y			Y	Y	Y	Y	Y						Y		Y						CML 2001 and CED	No
	16_SWEDEN: Act on climate declarations for buildings (coming law)					Y																		EN 15804/15978, IPCC GWP100	Yes, partial aggregation
	17_SWITZERLAND: SIA 2032	Y	Y			Y																	Y[98]	CED[99], GWP[100], environmental impacts according to ecological scarcity method	Yes, full aggregation
	18_UNITED KINGDOM(1): RICS					Y																		GWP 100 years (IPCC 4th AR), as per EN 15804+A1:2013[101]	No
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA			Y	Y	Y	Y	Y	Y				Y								Y[102]	Y	Y[103]	GWP, POCP, ODP, EP, AP, ADPE, ADPF - CML v4.2 based on EN 15804. Net water consumption based on ISO 14046; inventory indicators based on aggregated total of inventory flows.	Yes, full aggregation
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Y	Y			Y	Y	Y	Y		Y						Y							LCIA (midpoint approach) based on ISO 14044	Yes, partial aggregation
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Y	Y	Y	Y	Y	Y	Y	Y	Y														Based on EN15804	No

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[97] Slovenia has no regulations which environmental indicators to use since it has not developed its own method

[98] total environmental impacts according to ecological scarcity method

[99] Frischknecht et al. 2015

[100] IPCC 2013 (not including short term climate forcers

[101] Additionally, operational emissions are also considered using a National Decarbonisation scenario: slow progression from the National Grid Future Energy Scenarios 2015.

[102] Net use of fresh water,

[103] Hazardous waste disposed, Non-hazardous disposed

(Table C.1 continues)

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS																							
		Minimum according to the standards									Additional indicators													Method	Aggregation
		Primary energy demand/ use renewable	Primary energy demand /use non-renewable	Abiotic resource depletion, fossil	Abiotic resource depletion, elements	Global warming potential	Ozone depletion potential	Photochemical ozone creation potential	Acidification potential	Eutrophication, aquatic fresh water	Eutrophication, aquatic marine	Eutrophication, terrestrial	Total eutrophication	Human toxicity, cancer effects	Human toxicity, non-cancer effects	Ecotoxicity, freshwater	Land use	Particulate matter/ Respiratory inorganic	Ionising radiation/human health	Biotic production	Water demand/ Net use of fresh water	Radioactive waste	Other	For the selected environmental impact indicators, according to which method?	Is there the possibility of partial or full aggregation?
N. America	**22_CANADA(1):** Groupe AGECO	Y	Y			Y	Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y	Y				Impact 2002+ or TRACI 2.1	Yes, partial aggregation
	23_CANADA(2): IE4B	Y	Y			Y	Y	Y	Y	Y		Y						Y						Primarily US EPA TRACI but also CED model/method (CML)	Yes, partial aggregation
	24_USA: AIA Guide	Y	Y			Y	Y	Y	Y		Y	Y		Y	Y	Y					Y			Athena, BEES, EIO-LCA, AIA Guide to Building LCA in Practice	Yes, partial aggregation
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019					Y																		IPCC2006	Yes, full aggregation

Table C.2: Details of the primary energy use indicator – what is in and what is out?

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS – Primary energy demand/use indicator																											
		Non-renewable energy sources				Renewable energy sources							Building-related items during operations considered									User-related items during operations considered					Method		
		Fossil fuels as energy	Fossil fuels as feedstock	Nuclear fuels	Other	Biomass	Biomass as feedstock	Solar energy	Geothermal energy	Hydropower	Wind power	Other	Space heating	Space cooling	Ventilation	Hot water supply	Fixed lighting	Auxiliary energy (e.g. for heat pumps)	Indoor transportation	Building auxiliary devices	Other	Plug-in supplem. lighting	Household/office appliances	Refrigerator	Devices in data centre	Other specific functional devices	Only non-renewables	Renewables & non-renewables as **ONE** indicator (total primary energy demand)	Renewables & non-renewables as **TWO** separate indicators
Europe	**1_AUSTRIA**: DGNB/ÖGNI Certification	Y				Y		Y	Y	Y	Y		Y[104]	Y	Y	Y	Y[105]	Y	Y										Y
	2_BELGIUM: MMG												Y																
	3_CZECH REPUBLIC: SBToolCZ	Y		Y									Y	Y	Y	Y	Y	Y									Y		
	4_DENMARK: LCAbyg tool	Y[106]				Y		Y	Y	Y	Y		Y	Y	Y	Y	Y	Y											Y
	5_DENMARK: Sustainability code LCA																												
	6_FRANCE: EQUER	Y	Y	Y		Y	Y		Y	Y	Y		Y	Y	Y	Y	Y	Y				Y	Y	Y	Y	Y		Y[107]	
	7_FRANCE(2): E+C-	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y				Y	Y	Y	Y	Y			Y
	8_GERMANY(1): BNB	Y		Y		Y							Y	Y	Y	Y	Y	Y										Y	
	9_GERMANY(2): BNK	Y				Y		Y	Y	Y	Y		Y	Y	Y	Y		Y											Y
	10_GERMANY(3): DGNB	Y				Y		Y	Y	Y	Y		Y	Y	Y	Y	Y	Y											Y
	11_HUNGARY: Hungarian LCA	Y		Y		Y		Y	Y	Y	Y		Y	Y	Y	Y	Y	Y											Y
	12_NETHERLANDS: GWW	Y	Y	Y		Y	Y	Y	Y	Y	Y		108																Y
	13_PORTUGAL: SBToolPT-H	Y[109]		Y		Y[110]		Y	Y	Y	Y		Y	Y	Y	Y		Y											Y

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[104] All taken from OIB RL 6

[105] For non-residential buildings

[106] The included items for non-renewable and renewable energy sources is a guess as Danish method is based on DGNB procedure, and is built on Ökobau. In reality, there is no access to documents describing what really is in the PE category.

[107] Not all renewables, because using solar energy does not reduce the resource for others

[108] all operational energy use for the building is excluded

[109] All energy is reported in one figure for embodied energy and operational energy

[110] All energy is reported in one figure for embodied energy and operational energy

(Table C.2 continues)

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS – Primary energy demand/use indicator																											
		Non-renewable energy sources				Renewable energy sources							Building-related items during operations considered									User-related items during operations considered					Method		
		Fossil fuels as energy	Fossil fuels as feedstock	Nuclear fuels	Other	Biomass	Biomass as feedstock	Solar energy	Geothermal energy	Hydropower	Wind power	Other	Space heating	Space cooling	Ventilation	Hot water supply	Fixed lighting	Auxiliary energy (e.g. for heat pumps)	Indoor transportation	Building auxiliary devices	Other	Plug-in supplem. lighting	Household/office appliances	Refrigerator	Devices in data centre	Other specific functional devices	Only non-renewables	Renewables & non-renewables as **ONE** indicator (total primary energy demand)	Renewables & non-renewables as **TWO** separate indicators
Europe	**14_SLOVENIA:** No official methodology	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y											Y
	15_SPAIN: LCA-US Methodology	Y		Y		Y		Y	Y	Y	Y		Y	Y	Y	Y	Y				Y[111]	Y	Y	Y					Y[112]
	16_SWEDEN: Act on climate declarations for buildings (coming law)												[113]																
	17_SWITZERLAND: SIA 2032	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y									Y
	18_UNITED KINGDOM(1): RICS												Y	Y	Y	Y	Y												
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	Y	Y	Y									Y		Y	Y	Y				[114]						Y[115]		
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Y	Y			Y	Y	Y	Y	Y	Y		Y	Y														Y	
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y					Y
N. America	**22_CANADA(1):** Groupe AGECO	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y	Y										Y
	23_CANADA(2): IE4B	Y	Y	Y		Y		Y	Y	Y	Y																	Y	
	24_USA: AIA Guide	Y	Y	Y		[116]							Y	Y	Y	Y	Y	Y			[117]	Y	Y						Y
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	Y[152]	Y[152]	Y[152]		Y[152]	Y[152]	Y[152]	Y[152]		Y[152]		Y[152]	Y[152]	Y[152]	Y[152]	Y[152]		Y[152]									Y[152]	

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[111] occupants out door transportation, waste transportation, water consumption

[112] Fossil and nuclear are reported separately; Hydropower and Biomass are reported separately; wind solar and geothermal are reported jointly

[113] all operational energy use for the building is excluded

[114] Based on UK implementation of EPBD in SBEM and SAP.

[115] only non-renewable energy sources reported as ADP Fossil (excluding uranium) and with uranium included in ADP Elements.

[116] No clearly indicated which renewables are included

[117] In ATHENA, user inputs data for each category of fuel using energy simulation

Table C.3: Details of the GWP indicator – what is in and what is out?

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS – GWP indicator									
		Sources of GHGs considered				Types of GHG emissions considered					
		Carbon dioxide (CO_2) alone	The 7 main (groups of) GHGs identified in the Kyoto Protocol	All the GHGs specified by the 5th IPCC report	The F-gases regulated under Montreal Protocol	Fuel-related GHG emissions	Non-fuel related GHG emissions – process emissions	Non-fuel related GHG emissions – Freon gases due to insulation	GHG emissions due to land use	CO_2 removals from atmosphere	Other
Europe	**1_AUSTRIA:** DGNB/ÖGNI Certification System			Y	Y[118]	Y	Y	Y			
	2_BELGIUM: MMG			Y		Y	Y	Y			
	3_ CZECH REPUBLIC: SBToolCZ			Y		Y	Y	Y			
	4_DENMARK: LCAbyg tool			Y[119]	Y	Y	Y	Y			
	5_DENMARK: Sustainability code LCA			Y	Y	Y	Y	Y		Y	
	6_FRANCE(1): EQUER			Y		Y	Y	Y		Y	
	7_FRANCE(2): E+C-			Y		Y	Y	Y			
	8_GERMANY(1): BNB			Y		Y					
	9_GERMANY(2): BNK		Y			Y	Y				
	10_GERMANY(3): DGNB			Y	Y	Y	Y	Y			
	11_HUNGARY: Hungarian LCA			Y		Y					Y[120]
	12_NETHERLANDS: GWW			Y	Y	Y	Y	Y		Y	
	13_PORTUGAL: SBToolPT-H			Y		Y[121]	Y	Y			
	14_SLOVENIA: No official methodology					Y	Y	Y	Y	Y	
	15_SPAIN: LCA-US Methodology		Y			Y	Y	Y	Y		
	16_SWEDEN: Act on climate declarations for buildings (coming law)			Y		Y	Y				
	17_SWITZERLAND: SIA 2032			Y		Y	Y	Y	Y		

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[118] Educated guess

[119] The same applies as in the previous table. The included types of emissions is a guess

[120] according to the ecoinvent methodology

[121] All types of emissions are reported together

(Table C.3 continues)

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS – GWP indicator									
		Sources of GHGs considered				Types of GHG emissions considered					
		Carbon dioxide (CO_2) alone	The 7 main (groups of) GHGs identified in the Kyoto Protocol	All the GHGs specified by the 5th IPCC report	The F-gases regulated under Montreal Protocol	Fuel-related GHG emissions	Non-fuel related GHG emissions – process emissions	Non-fuel related GHG emissions – Freon gases due to insulation	GHG emissions due to land use	CO_2 removals from atmosphere	Other
Europe	**18_UNITED KINGDOM(1):** RICS	Y	Y	Y	Y	Y	Y	Y		Y	
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA		Y	Y	Y	Y	Y	Y		Y	
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA			Y		Y					
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick			Y		Y	Y	Y		Y	
N. America	**22_CANADA(1):** Groupe AGECO			Y		Y	Y	Y	Y	Y	
	23_CANADA(2): IE4B			Y		Y	Y			Y	
	24_USA: AIA Guide			Y		Y	Y				
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019			Y		Y	Y				

Table C.4: Reference units

	Country/ Name of the methodology	ENVIRONMENTAL INDICATORS - Normalisation																																		
		Reference Unit																																		
		Single-family houses							Multi-family residential buildings							Office buildings							Industrial buildings							Educational buildings						
		GFA[122]	NFA[123]	ERA[124]	RFA[125]	NRA[126]	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other
Europe	**1_AUSTRIA:** DGNB/ÖGNI Certification System		Y							Y							Y							Y							Y					
	2_BELGIUM: MMG	Y							Y							Y																				
	3_CZECH REPUBLIC: SBToolCZ			Y							Y							Y																		
	4_DENMARK: LCAbyg tool								Y							Y														Y						
	5_DENMARK: Sustainability code LCA	Y							Y							Y							Y							Y						
	6_FRANCE(1): EQUER		Y	Y						Y	Y						Y	Y													Y	Y				
	7_FRANCE(2): E+C-		Y	Y						Y	Y						Y	Y													Y	Y				
	8_GERMANY(1): BNB																Y																			
	9_GERMANY(2): BNK		Y							Y																										
	10_GERMANY(3): DGNB		Y							Y							Y							Y							Y					
	11_HUNGARY: Hungarian LCA			Y							Y							Y							Y											
	12_NETHERLANDS: GWW	Y							Y							Y							Y													
	13_PORTUGAL: SBToolPT-H			Y							Y																									
	14_SLOVENIA: No official methodology		Y							Y							Y							Y												
	15_SPAIN: LCA-US Methodology	Y					Y		Y					Y		Y					Y		Y					Y								
	16_SWEDEN: Act on climate declarations for buildings (coming law)	Y							Y							Y														Y						
	17_SWITZERLAND: SIA 2032	Y		Y					Y			Y				Y		Y																		

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[122] Gross Floor Area (GFA)
[123] Net Floor Area (NFA)
[124] Energy Reference Area (ERA)
[125] Rentable Floor Area (RFA)
[126] Net Rentable Floor Area (NRA)

(Table C.4 continues)

Country/ Name of the methodology		ENVIRONMENTAL INDICATORS - Normalisation																																		
		Reference Unit																																		
		Single-family houses							Multi-family residential buildings							Office buildings							Industrial buildings							Educational buildings						
		GFA[127]	NFA[128]	ERA[129]	RFA[130]	NRA[131]	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other	GFA	NFA	ERA	RFA	NRA	Person	Other
Europe	**18_UNITED KINGDOM(1):** RICS							Y							Y							Y[132]							Y							
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	[133]																																		
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Y	Y			Y										Y	Y			Y																
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Y	Y				Y		Y	Y				Y		Y	Y			Y	Y															
N. America	**22_CANADA(1):** Groupe AGECO	Y							Y							Y							Y													
	23_CANADA(2): IE4B	Y							Y							Y							Y													
	24_USA: AIA Guide	Y							Y							Y							Y													
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019Ebalance	Y							Y							Y														Y						

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[127] Gross Floor Area (GFA)
[128] Net Floor Area (NFA)
[129] Energy Reference Area (ERA)
[130] Rentable Floor Area (RFA)
[131] Net Rentable Floor Area (NRA)
[132] see http://www.rics.org/uk/knowledge/bcis/about-bcis/forms-and-documents/gross-internal-floor-area-gifa-and-ipms-for-offices/
[133] The respondent skipped this question

Table C.5: Detailed description of the reference unit

Country/ Name of the methodology		Definition of the reference unit
Europe	**1_AUSTRIA:** DGNB/ÖGNI Certification System	According to ÖNORM EN 15221-6 Net floor area ; Nettogeschossfläche (NGF) The net floor area is the calculated area difference from the inner floor area and inner wall construction floor area. For clarification: The inner floor area is the area calculated from the gross floor area minus the exterior wall construction floor area. The interior wall construction floor area is a measuring surface consisting of the load-bearing interior construction of the building (e.g. columns and load-bearing walls).
	2_BELGIUM: MMG	no clear definition of gross floor area in MMG publications
	3_CZECH REPUBLIC: SBToolCZ	Floor area in this case means the total internal floor area of all floors of the building, defined by the inner surface of the outer walls. Inhabited and separated unheated areas are excluded.
	4_DENMARK: LCAbyg tool	GFA is heated+unheated space, measured to the outside of the walls. This is used for assessing the embodied impacts. Heated floor area (heated space, measured to the outside of the walls) is used for assessing the B6 impacts.
	5_DENMARK: Sustainability code LCA	
	6_FRANCE(1): EQUER	The floor area is defined by the user. It can be the net floor area (the user draws the plans or uses a BIM and the net floor area is calculated by the software), the area considered in the energy regulation, or the inhabitable area.
	7_FRANCE(2): E+C-	area considered in the energy regulation for the energy indicators, net floor area for other indicators
	8_GERMANY(1): BNB	NFA according to DIN 277 – The net floor area is the sum of all areas on all storeys of a building minus the construction area. The net floor area can be subdivided into usable area UA, service area SA and circulation area CA.
	9_GERMANY(2): BNK	
	10_GERMANY(3): DGNB	
	11_HUNGARY: Hungarian LCA	Net heated/ cooled floor area without the area or partition walls
	12_NETHERLANDS: GWW	The Dutch standard NEN 2580 (no English version available)
	13_PORTUGAL: SBToolPT-H	-
	14_SLOVENIA: No official methodology	Usable area of the building (m2) representing the internal floor area of the heated floor premises according to the project, is determined according to the standard SIST ISO 9836.
	15_SPAIN: LCA-US Methodology	Gross Floor Area (GFA). Surface covered by ceiling included the surface of vertical building partitions and walls. Person. One occupant of the assessed building. The number of people in the building is determined following the Building Technical Code in case of office and industrial buildings and statically in residential cases.
	16_SWEDEN: Act on climate declarations for buildings (coming law)	The proposal of mandatory regulation suggests GFA: Gross floor area is the measurable space of the floor plan. Gross area is limited by the exterior wall exterior and no account is taken of minor profiling and moldings. In the gross area, the recessed middle floor (mezzanine floor) or the like is counted with the front edge of the floor as a limitation
	17_SWITZERLAND: SIA 2032	-
	18_UNITED KINGDOM(1): RICS	-
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	-

Country/ Name of the methodology		Definition of the reference unit
Oceania	**20_AUSTRALIA:** ALCAS Midpoint LCIA	NFA: Net floor area of building excluding garage Gross floor area: total floor area including garage Net rentable floor area: Net letable area, which is conditioned
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Gross floor area (GFA) - area measured over all the exterior walls of the building, over partitions, columns, interior structural or party walls, stair wells, lift wells, ducts, enclosed roof top structures and basement service areas. All exposed areas such as balconies, terraces, open floor areas and the like are excluded. Generally, projections beyond the outer face of the exterior walls of a building such as projecting columns, floor slabs, beams, sunshades and the like are excluded. Net rentable area (or "net lettable area (NLA)") - sum of the floors of a building measured from the exterior faces of the exterior walls or from the centrelines of walls separating two uses within a building, excluding all common areas such as hallways, elevators, voids and unused parts of buildings.
N.America	**22_CANADA(1):** Groupe AGECO	-
	23_CANADA(2): IE4B	Gross floor area as measured at the exterior of the building
	24_USA: AIA Guide	-
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019Ebalance	Total floor area of the building, including all the spaces enclosed by the outer surface of exterior walls and facades. Balconies without roofs are not counted in GFA. Balconies with roof and without exterior wall is counted in as half of the areas. Basement area is included in the GFA.

D, E & F – ASSESSMENT STANDARDS, DATA, TOOLS & BENCHMARKS

Table D.1: Instruments connected to the method

Country/ Name of the methodology		Is the assessment methodology described in the previous questions linked to…				
		…a specific national standard	…a specific regional or international standard, such as ISO 21931-1	…a specific national, regional, or other database?	…any software tool(s) supporting this methodology?	…a specific set of benchmarks?
Europe	**1_AUSTRIA:** DGNB/ÖGNI Certification System	ÖN EN 15978	EN 15978	Ecoinvent	Excel-based workflow using information from e.g. energy certificate and quantities from BIM model, custom scripts for hotspot analysis	No
	2_BELGIUM: MMG	No	CEN/TC 350 standards (EN 15804:2012+A1 and EN15978), PEF guide (EC, 2013), ILCD handbook (EC-JRC, 2011)	Ecoinvent (version 3.3)	TOTEM tool (https://www.totem-building.be/) No BIM-enabled	No
	3_CZECH REPUBLIC: SBToolCZ	No	No	Envimat (based on Ecoinvent 2)	No	Yes
	4_DENMARK: LCAbyg tool 3.2	No	EN15978	Ökobau.dat 2016	LCAbyg (www.lcabyg.dk) No BIM-enabled	Yes
	5_DENMARK: Sustainability code LCA	No	EN15978	Ökobau.dat 2020	LCAbyg v 4.0	No
	6_FRANCE(1): EQUER	No	mostly EN 15978 but with a few differences	Ecoinvent	EQUER, http://www.ces.mines-paristech.fr/Logiciels/EQUER/ EQUER is the calculation engine of PLEIADES ACV BIM-enabled: IFC4 (with requirements about specific options) or gbXML	Yes
	7_FRANCE(2): E+C-	No	mostly EN 15978 but with a few differences	INIES	ELODIE, PLEIADES E+C-, OneClick LCA, ThermACV, Bea, Archiwizard, Vizcab	Yes
	8_GERMANY(1): BNB	DIN EN 15978	EN 15978	ökobau.dat	ELCA; LEGEP No BIM-enabled	Yes
	9_GERMANY(2): BNK	No	No	ökobau.dat	eLCA, https://www.bauteileditor.de/ No BIM-enabled	Yes
	10_GERMANY(3): DGNB	DIN EN 15978	EN 15978	ökobau.dat	■ CAALA: Software für eine ganzheitliche energetische Optimierung und Lebenszyklusanalyse (www.caala.de) ■ eLCA: Online Ökobilanz-Tool vom Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) (www.bauteileditor.de) ■ GaBi-Software (www.gabi-software.com) ■ LEGEP Bausoftware: Software für die integrale Planung nachhaltiger Gebäude (www.legep.de) ■ oekobilanz-bau.de (www.tool.oekobilanz-bau.de) ■ SBS Online Tool (www.sbs-onlinetool.com) No BIM-enabled	Yes

(Table D 1 continues)

Country/ Name of the methodology		Is the assessment methodology described in the previous questions linked to…				
		…a specific national standard	…a specific regional or international standard, such as ISO 21931-1	…a specific national, regional, or other database?	…any software tool(s) supporting this methodology?	…a specific set of benchmarks?
Europe	**11_HUNGARY:** Hungarian LCA	No	EN 15978	ecoinvent database adapted to national conditions	Excel tools: Belso Udvar E-P-LCA-LCC, KESZ-LCC-LCA No BIM-enabled	No
	12_NETHERLANDS: GWW	MPG - Milieu Prestatie van Gebouwen ("Environmental Performance of Buildings")	EN 15804:2012 + Amendment A1 (2013)	Nationale Milieu database (NMD) - National Environmental database	GPR Building,see http://www.gprgebouw.nl/ No BIM-enabled	Yes
	13_PORTUGAL: SBToolPT-H	-	European CEN TC 350 standards	The assessment of the potential environmental impacts is based on a specific LCIA database: http://hdl.handle.net/1822/20481	There is an Excel sheet No BIM-enabled	Yes
	14_SLOVENIA: No official methodology	No	ISO and EN standards	No	No	No
	15_SPAIN: LCA-US Methodology	No	EN 15978, EN 15804	No	Autodesk Revit, Microsoft excel and Ecoinvent V.2 database BIM-enabled: Autodesk Revit	No
	16_SWEDEN: Act on climate declarations for buildings (coming law)	The proposed mandatory climate declaration for buildings. https://www.boverket.se/sv/om-boverket/publicerat-avboverket/publikationer/2018/klimatdeklaration-av-byggnader2/	EN 15804/EN 15978	A database is being developed that will be launched in 2021. It includes primarily generic data that shall be used for making the climate declaration, unless specific EPD´s are used.	Byggsektorns miljöberäkningsverktyg No BIM-enabled	is under development and will be launched in 2021
	17_SWITZERLAND: SIA 2032	SIA 2032 and SIA 2040, and KBOB guidelines for construction material and building LCA	Except for the indicators, KBOB guidelines adhere to EN 15804:2012+A1:2013	KBOB LCI data DQRv2:2016 and KBOB recommendation 2009/1:2016	Bauteilkataklog, Eco-Devis, Enerweb/1 eco, Greg, Lesosai, Thermo No BIM-enabled	Yes
	18_UNITED KINGDOM(1): RICS	No	EN 15978 and EN 15804:2012+A1:2013	The sources below are listed in order of preference: Type III environmental declarations (EPDs and equivalent) and datasets in accordance with EN 15804 • Type III environmental declarations (EPDs and equivalent) and datasets in accordance with ISO 21930 • Type III environmental declarations (EPDs and equivalent) and datasets in accordance with ISO 14067 • EPDs and datasets in accordance with ISO 14025, ISO 14040 and 14044 • Type III environmental declarations (EPDs and equivalent) and datasets in accordance with PAS 2050.	No	Yes

(Table D 1 continues)

Country/ Name of the methodology		Is the assessment methodology described in the previous questions linked to…				
		…a specific national standard	…a specific regional or international standard, such as ISO 21931-1	…a specific national, regional, or other database?	…any software tool(s) supporting this methodology?	…a specific set of benchmarks?
Europe	**19_UNITED KINGDOM(2):** BRE Global IMPACT Building LCA	Additional inventory indicator and normalisation and weighting approach set out in BRE paper "BRE global Environmental weighting for construction products using Selected parameters from EN 15804, (2017) bit.ly/2P0V9we	BS EN 15804:2012+A1:2013.	BRE EN 15804 IMPACT Database	OneClickLCA (BREEAM) version, eTool (IMPACT) version. BIM-enabled: Various, including Revit, ArchiCAD, Tekla Structures, Simplebim and Naviate Simple BIM, DesignBuilder, plus IES-VE and output as IFC 2x3 and IFC4 and gbXML.	?
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	No	No	Australian and Australasian	Etool LCA, SimaPro No BIM-enabled	No
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	No	Based on EN15978.	BRANZ has developed a database to support the assessment. Some of the materials data are published in the BRANZ CO₂NSTRUCT database, available at www.branz.co.nz/co2nstruct. Scenario or activity data available in "Data" at www.branz.co.nz/buildinglca.	LCAQuick (downloadable from www.branz.co.nz/buildinglca and select "LCAQuick" BIM-enabled: No direct links to BIM, but a material take-off from any BIM software can be pasted into LCAQuick	No
N. America	**22_CANADA(1):** Groupe AGECO	No	No	No	SIMAPRO No BIM-enabled	No
	23_CANADA(2): IE4B	No	EN15978 for building and ISO21930 for products	The Athena Institute's own database	The Impact Estimator for Buildings - see link https://calculatelca.com No BIM-enabled	No
	24_USA: AIA Guide	No	ISO 21930/21931; ISO 14040/14044; ISO/TC 14067; EN 15804/15978; PAS 2050; US EPA Guidelines from Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)	ATHENA Database; US Life Cycle Inventory (USLCI) Database by National Renewable Energy Lab (NREL); Building for Environmental and Economic Sustainability (BEES) by the National Institute of Standards and Technology (NIST); EIO-LCA by Carnegie Mellon University.	ATHENA Impact Estimator; ATHENA EcoCalculator; BEES Software; Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)	No
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	Standard for Building Carbon Emission Calculation GB/T 51366-2019	No	Annexes of the Standard[134]	PKPM-CES; T20-CE, AIARCH	No

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[134] Original database is unclear.

G – MARKET CONDITIONS AND DRIVING FORCES

Table G.1: Instruments connected to the method

Country/ Name of the methodology		METHOD DISSEMINATION AND DRIVING FORCES							
		What is the level of acceptance and application of such methodologies among architects working in the industry?	Who is primarily asking for such results? And why?	Are there already requirements in place to limit… (L= Yes, Legal; SC= Yes, self-commitment; UD= Currently, under development)					
				Operational primary energy	Operational GHG emissions	Embodied primary energy	Embodied GHG emissions	Life cycle primary energy	Life cycle GHG emissions
Europe	**1_AUSTRIA:** DGNB/ÖGNI Certification System	Low	**Property developers/ investors** WHY: ÖGNI is a national certification methodology based on DGNB. A high certification can result in a higher property value.	L	L	UD	UD	UD	UD
	2_BELGIUM: MMG	Low	**Public sector** WHY: it is part of the public procurement.						
	3_CZECH REPUBLIC: SBToolCZ	Low	**Public sector** WHY: Confidence in the evaluation method developed at the Czech University and adapted to the Czech conditions (SbToolCZ). In the private sector, companies prefer international BREEAM.	L	SC				
	4_DENMARK: LCAbyg tool	Low	**Companies/ firms** WHY: Driven by building organisations, representing architect/engineering firms as well as building material producers	SC	SC	SC	SC	SC	SC[135]
	5_DENMARK: Sustainability code LCA	-	-						
	6_FRANCE(1): EQUER	Very low	**Companies/ firms/ clients** WHY: social responsibility	SC	SC			SC	SC
	7_FRANCE(2): E+C-	Very low	**Public sector** WHY: future regulation	L			UD		UD
	8_GERMANY(1): BNB		**Public sector** WHY: It is part of the public procurement.	L	SC	SC	SC	SC	SC
	9_GERMANY(2): BNK	Very low	**Property developers/ investors** Pre-fabricated housing developers						
	10_GERMANY(3): DGNB	Low	**Public sector** WHY: It is part of the public procurement Private sector uses LCA only in the context of DGNB certification (because they have to obtain a certificate), seldom used for optimization or communication	L			SC		SC[136]

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[135] Currently only as part of the Danish DGNB certification. Voluntary 'sustainability building code' under development.

[136] Various initiatives, DGNB developed the "Framework for carbon neutral buildings and sites" in 2018, which is basis for self-commitments: https://issuu.com/dgnb1/docs/dgnb_framework_carbon-neutral_build?e=32742991/66043810

(Table G.1 continues)

Country/ Name of the methodology		METHOD DISSEMINATION AND DRIVING FORCES							
		What is the level of acceptance and application of such methodologies among architects working in the industry?	Who is primarily asking for such results? And why?	Are there already requirements in place to limit… (L= Yes, Legal; SC= Yes, Self-Commitment; UD= Under Development)					
				operational primary energy	operational GHG emissions	embodied primary energy	embodied GHG emissions	life cycle primary energy	life cycle GHG emissions
Europe	**11_HUNGARY:** Hungarian LCA	Very low	**Individuals/ homebuilders** WHY: The tool is currently used for education and research, and in a very limited way in the architectural practice by a few designers designing smaller buildings. But investors are also increasingly interested in such results as part of a BREEAM or LEED certification. However, for that they use international tools and not our methodology.	L[137]					
	12_NETHERLANDS: GWW	Low	**Public sector** WHY: It is part of the public procurement. There is a limit value applicable in order to receive a building permit, but most architects will not perform the assessment themselves. In most cases they will request an external consultant to perform the calculations				L[138]		
	13_PORTUGAL: SBToolPT-H	Very low	**Property developers/ investors** WHY: Most of existing tools are market driven and individuals are confused about the real benefit of using such methods. The assessment/ sustainability certification is expensive and time consuming.	L[139]	L				
	14_SLOVENIA: No official methodology	Low[140]	**Public sector** WHY: it is part of the public procurement.	L[141]	SC				
	15_SPAIN: LCA-US Methodology	Very low	**Public sector** WHY: it is part of the public procurement. Sometimes LCA is condition given by the specification of the public contest						
	16_SWEDEN: Act on climate declarations for buildings (coming law)	High[142]	**Public sector** WHY: it is part of the public procurement. The interest is increasing, and requirements are sometimes set by municipalities	L	SC		UD[143]		

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[137] Primary energy is calculated in the national energy performance methodology based on the EPBD. However, primary energy factors are not based on LCA results. Operational GHG emissions are not compulsory by the law, but in many cases it is compulsory in the application for grants and funding.

[138] There is a limit value in place, but this applies to an aggregated indicator (MPG score) which includes embodied GHG as well as other environmental impacts (see Assessment method p.37, table 5). In practice embodied GHG can contribute 40-70% of the MPG score.

[139] The source is the Portuguese thermal regulation that limits the operational energy consumption during the operation phase of the building. The method is based on the EPBD.

[140] There is a growing interest in EPDs from the industry, but no demand for LCA of buildings (except in research area)

[141] The government set a target point how much energy per m2 is suitable for new or refurbished buildings. There are factors developed how much CO2 the building is producing regarding the source used for heating and cooling. Online under: http://www.energetika-portal.si/fileadmin/dokumenti/publikacije/an_snes/an_snes_slovenija_en.pdf

[142] 100% of developers of new buildings (included in the regulation) will use it

[143] https://ec.europa.eu/growth/tools-databases/tris/en/index.cfm/search/?trisaction=search.detail&year=2020&num=439&mLang=en&CFID=995299&CFTOKEN=e0e52b5820b0e82e-F0A573AB-F2C2-EC14-02289396E7B15E26

(Table G.1 continues)

	Country/ Name of the methodology	METHOD DISSEMINATION AND DRIVING FORCES		Are there already requirements in place to limit… (L= Yes, Legal; SC= Yes, Self-Commitment; UD= Under Development)					
		What is the level of acceptance and application of such methodologies among architects working in the industry?	Who is primarily asking for such results? And why?	operational primary energy	operational GHG emissions	embodied primary energy	embodied GHG emissions	life cycle primary energy	life cycle GHG emissions
Europe	**17_SWITZERLAND:** SIA 2032	Low	**Public sector** WHY: it is part of the public procurement. Many communities care for environment and climate and ask for increased requirements regarding GHG emissions etc.	SC[144]	SC	SC	SC	SC	SC
	18_UNITED KINGDOM(1): RICS								
	19_UNITED KINGDOM(2): BRE Global IMPACT Building LCA	Medium	**Property developers/ investors** WHY: Use of this method is required by BREEAM to obtain up to a maximum of 10% optional credits. Property developers/investors are the major group requesting BREEAM.		L		SC[145]		
Oceania	**20_ AUSTRALIA:** ALCAS Midpoint LCIA	Medium	**Public sector** WHY: it is part of the public procurement.	L[146]	L	SC	SC	UD	UD
	21_NEW ZEALAND: NZ whole-building whole-of-life framework / LCAQuick	Very low	**Companies/firms** WHY: for recognition in building environmental rating tools **Public sector** WHY: interest to include in procurement.[147]						
N. America	**22_CANADA(1):** Groupe AGECO	Very high	**Companies/ firms** WHY: LEED points are given for construction projects involving the use of material products for which an EPD was performed. As a result, producing an EPD gives the manufacturer a competitive edge.		L[148]				
	23_CANADA(2): IE4B	Low	**Public sector** WHY: it is part of the public procurement. Public sector is leading the advancement and use of LCA as an evidenced based decision-making method	L[149]	UD		UD		
	24_USA: AIA Guide	Low	**Public sector** WHY: it is part of the public procurement. Some states as well as private companies require LCA	L[150]	SC				

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[144] In general, ALL requirements are documented in SIA technical bulletin 2040 SIA energy efficiency path, 2017

[145] Some developers have put in place requirements to reduce embodied impact, for example Landsec (https://sciencebasedtargets.org/case-studies/case-study-land-securities/).

[146] Minimum residential building energy requirements (operational heating/cooling) is mandatory by building code. Embodied energy and GHG emissions are not but it is included in the national building rating tool (e.g., Green Star by Green Building Council Australia)

[147] Christchurch City Council (CCC) has a target to be carbon neutral by 2030. CCC is looking at using LCAQuick as a mandatory tool to understand the greenhouse gas impacts of new Council buildings.

[148] There are Canadian regulations on GHG emissions for the renewable fuels and electricity sectors. There are also regulations on exhaust emissions from passenger and heavy-duty vehicles, light-weight trucks. For more information: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gasemissions/regulations.html#X-201105241638261

[149] National Building code stipulates operational energy performance. Embodied carbon is now discussed with likely targets coming in the future

[150] American Society for Heating Refrigerating and Air-conditioning Engineers (ASHRAE) publishes mandatory energy codes for residential and commercial buildings

(Table G.1 continues)

Country/ Name of the methodology		METHOD DISSEMINATION AND DRIVING FORCES										
		To what percentage is the methodology described here used by…			What is the level of acceptance and application of such methodologies among architects working in the industry?	Who is primarily asking for such results? And why?	Are there already requirements in place to limit… (L= Yes, Legal; SC= Yes, Self-Commitment; UD= Under Development)					
		researchers/ universities	Public authorities	Daily practice of architects			operational primary energy	operational GHG emissions	embodied primary energy	embodied GHG emissions	life cycle primary energy	life cycle GHG emissions
Asia	**25_China:** Standard for Building Carbon Emission Calculation GB/T 51366-2019	[151]			Low	**Companies/ firms** WHY: A bonus can be achieved for the calculation of life cycle GWP according to Assessment Standard for Green Buildings GB/T 50387-2019. But investors are also increasingly interested in such results as part of a Green Building certification.	SC[152]	SC	UD	SC	UD	SC

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[151] It is relatively new and under development.

[152] It was specified in Technical Standard for Nearly Zero Energy Building GB/T 51350-2019.

Table G.2: National definitions for net zero building concepts, carbon budgets for building stock and requirements for circular economy.

Country/ Name of the methodology		NATIONAL REQUIREMENTS					
		Is there any national definition with regard to…				Is there already a specific carbon budget(s) in your country for building stock?	Are there any specific requirements in your country for building stock relating to the promotion of circular economy?
		Net zero energy buildings	Net zero emissions buildings	Carbon neutral buildings	Climate neutral buildings		
Europe	**1_AUSTRIA**	Yes	Under dev.	Under dev.	Under dev.	No (UD)	No
	2_BELGIUM	No	No	No	No	No	No
	3_ CZECH REPUBLIC: SBToolCZ	No	No	No	No	No	No
	4/5_DENMARK	Yes[153]	No	No	No	No	Recent governmental strategy (September 2018) on circular economy sets out to implement: - A voluntary sustainability building class - Encourage selective demolition of buildings
	6/7_FRANCE[154]	Under dev.[155]	No	Under dev.[156]	No	No	No
	8/9_GERMANY(1): BNB BNK					Yes 2030 and 2050 targets defined in "Klimaschutzplan"	Private initiatives, e.g. DGNB promotes circular buildings
	10_GERMANY(3): DGNB	Yes[157]	No	Yes	Yes		
	11_HUNGARY: Hungarian LCA	No	No	No	No	No	No
	12_NETHERLANDS: GWW	Yes[158]	No	No	No		only target values for reuse of building materials Information: https://www.circulaireeconomienederland.nl/rijksbreed+programma+circulaire+economie/Programma+documenten/handlerdownloadfiles.ashx?idnv=806449 But this document is not very specific about the targets for the construction sector. Also there are more specific covenants for certain subsectors, e.g. the concrete products industry
	13_PORTUGAL: SBToolPT-H	Under dev.	Under dev.	Under dev.	Under dev.	No	No
	14_SLOVENIA: No official methodology	Yes[159]	No	No	No	No	No

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[153] NZEB is the upper level of building classifications from the current building regulations (called '2020 building class').

[154] National requirements concern only E+C-

[155] French regulation, only in French

[156] French regulation, only in French

[157] Various initiatives, Effizienzhaus Plus, Aktivhausplus https://aktivplusev.de/, ... DGNB developed the "Framework for carbon neutral buildings and sites" in 2018, which is basis for self-commitments:https://issuu.com/dgnb1/docs/dgnb_framework_carbon-neutral_build?e=32742991/66043810

[158] There is a standard in place for Nearly Zero Energy Buildings, in order to comply with EPBD. But this only considers operational energy use, not embodied.

[159] Slovenia has developed an action plan for building nearly nZEB until 2020. Online under: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwjK2rOgjengAhWO-aQKHfx5AYMQFjAAegQIABAB&url=http%3A%2F%2Fwww.energetika-portal.si%2Ffileadmin%2Fdokumenti%2Fpublikacije%2Fan_snes%2Fan_snes_slovenija_en.pdf&usg=AOvVaw2Tg8OPqWEBKf-CHojSX9m5

(Table G.2 continues)

Country/ Name of the methodology		NATIONAL REQUIREMENTS					
		Is there any national definition with regard to…				Is there already a specific carbon budget(s) in your country for building stock?	Are there any specific requirements in your country for building stock relating to the promotion of circular economy?
		Net zero energy buildings	Net zero emissions buildings	Carbon neutral buildings	Climate neutral buildings		
	15_SPAIN	Under dev.	Under dev.	No	No	No	No
	16_SWEDEN	Yes	Yes[160]	No	No	No	No
	17_SWITZERLAND	No	No	No	No	GHG emission benchmark values of SIA 2040 derived from carbon budget.	No
	1819_UNITED KINGDOM	No	No	No	No	UK Government target of 80% reduction in GHG emissions in the built environment vs 1990 levels by 2050. (https://www.greenconstructionboard.org/index.php/resources/routemap) A 50% reduction in greenhouse gas emissions in the built environment – supporting the Industrial Strategy's Clean Growth Grand Challenge https://www.gov.uk/government/publications/construction-sector-deal Halve the energy use of new buildings by 2030: https://www.gov.uk/government/publications/construction-sector-deal	
Oceania	**20_ AUSTRALIA**	Yes[161]	Yes	Yes	No	No specific carbon budget for building, but many other academic or research publications exist by regional.	No
	21_NEW ZEALAND	No	Yes[162]	No	No	Massey University and BRANZ are developing absolute, science-based greenhouse gas design thresholds for residential and office buildings.	No
N. America	**222/23_CANADA**	Yes[163]	Under dev.	No	No	No	No
	24_USA	No	No	No	No	No	No
Asia	**25_China**	Yes[152]	No	No	No	No official data. CO_2 emission reduction was predicted by several institutions, such as Energy Foundation China [164]	No

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[160] The Sweden Green building council has launched a test version of a new certification system called ZeroCO2: https://www.sgbc.se/utveckling/utveckling-av-nollco2/. Unfortunately, no info in English so far. It is linked to the WGBC initiative on this, but this is a version developed in Sweden for the Swedish context (and also embracing embodied GHG emissions).

[161] Net zero energy: The annual on-site renewable energy generation is equal to or more than the annual energy consumption (operational only); Zero carbon: Refers to a building with no net annual greenhouse gas emissions resulting from on-site energy or energy procurement (Scope 1 and Scope 2) from its operation; Net zero emissions: No clear definition in Australia. But Australia in general share the global definition such as Net zero carbon footprint, which refers to achieving net zero carbon emissions by balancing a measured amount of carbon released with an equivalent amount sequestered or offset, or buying enough carbon credits to make up the difference; Carbon neutral: Zero net greenhouse gas emissions (source: National Carbon Offset Standard, Carbon Neutral Program.

[162] New Zealand Green Building Council launched Net Zero Carbon Roadmap for Aotearoa in 2019. Online under: https://www.nzgbc.org .nz/zerocarbon/roadmap

[163] Net zero energy housing, definition from Natural Resources Canada: https://www.nrcan.gc.ca/energy/efficiency/housing/research/5131

[164] Synthesis Report 2020on China's Carbon Neutrality. Online under: https://www.efchina.org/Attachments/Report/report-lceg-20201210/Synthesis-Report-2020-on-Chinas-Carbon-Neutrality.pdf.

Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report "Benchmarking and target-setting for the life cycle-based environmental performance of buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al. 2023).

It is important to mention that the analysis of net zero definitions in this report is based on a survey among experts which was realized during the first half of 2020. The authors would like to acknowledge the following survey contributors: Seongwon Seo (AU), Damian Trigaux (BE), Claudiane Ouellet-Plamondon (CA), Panu Pasanen (FI), Wei Yang (CN), Harpa Birgisdottir and Freja Rasmussen (DK), Bruno Peuportier (FR), Erik Alsema (NL), Dave Dowdell (NZ), Marianne Kjendseth Wiik (NO), Ricardo Mateus (PT), Antonio García (SP), Tove Malmqvist and Nicolas Francart (SE), Rolf Frischknecht and Livia Ramseier (CH) Jane Anderson (UK), Siva-kumar Palaniappan (IN), Tajda Potrc Obrecht (SI).

Summary

Introduction

Around 40% of global CO_2 emissions can be attributed to the construction, maintenance, and use of buildings. Reducing these greenhouse gas (GHG) emissions is an essential goal in the context of sustainable development (IEA 2019). This is expressed, among other things, in SDG 13: Climate change. Reducing these emissions requires considerable efforts from all those involved in the construction and building sector as actors, decision makers and service providers, including upstream and downstream industries. In order to be able to design and implement appropriate reduction measures, the calculation and assessment of GHG emissions in the life cycle of buildings with the help of indicators, calculation rules, assessment methods and benchmarks is a prerequisite. Particularly benchmarks provide the basis for requirements for carbon performance as part of the environmental performance of buildings. They can be used both in the context of sustainability assessment systems, funding programs, building standards, and policymakers' actions as well as provide the basis for individual design targets.

A new approach is the top-down derivation of benchmarks in an effort to respect planetary boundaries. This involves protecting the natural basis of life by ensuring that future new construction and refurbishment measures lead to buildings with (almost) no negative effects on the climate during their lifecycle which led to the "climate-neutral building" approach in line with numerous are global initiatives.

Objectives and contents of the report

The main aim of the present report was to analyse the status of the discussion on "climate-neutral" buildings and to develop proposals for the standardization of terms, definitions, system boundaries and rules for assessment and communication. At a minimum, these recommendations should be viewed as a means for improving transparency and traceability which should also be drawn up to maintain the credibility of the relevant statements.

Although not exhaustive, key international initiatives were identified and analysed that could relate to the topic of "climate-neutral buildings". Key thematic areas which were investigated include (1) terms and definitions, (2) system boundaries for the recording and assessment of GHG emissions, (3) calculation and evaluation rules, (4) balancing and offsetting options when demonstrating "climate neutrality".

Key findings arising from the analysis

Significant differences were found in all the thematic areas examined which makes it difficult to compare the approaches directly, however, the following key points can be deduced:

- **The survey showed that great variations exist in current schemes about (net) zero greenhouse gas emissions buildings (as an alternative term to "climate neutral building") and will probably continue to exist.** These variations raise some important questions on how this concept is evolving. At the minimum, the transparency of the declaration and communication of the system boundaries, calculation, and evaluation rules as part of an assessment process, as well as balancing and offsetting options, must be improved. It is recommended that such information be made publicly accessible.

- **Various terms are used by various countries to describe (net) zero approaches which often leads to confusion.** It is recommended to use the term climate-neutral only colloquially, but to use the term “(net) greenhouse gas-neutral” or “(net) zero GHG-emissions” for approaches in assessment systems, funding programs or legislation. It is also recommended to distinguish between ‘absolute’ and ‘net zero’ GHG emissions (as proposed and explained by Lützkendorf and Frischknecht (2020)) and between greenhouse gas neutral (1) in operation, (2) in operation including supply chains (upstream and downstream) and (3) in the life cycle.
- **The survey showed that range of activities included in the operation itself varies;** Some approaches focus on balancing only the regulated building-related energy demand (B6.1), while others also include the non-regulated building-related part (B6.2) and/or user-related energy part (B6.3). The increasing use of renewable energy to the point of the obligation to install systems on the building or on its site makes it necessary to deal methodically with questions relating to BIPV, among other things. It also forces to expand the traditionally considered system boundaries within Module B6. It would be useful to include Modules B6.2 and B6.3 to be able to represent the self-consumed share of the energy generated on-site in a more complete fashion.
- **Most approaches currently follow a net-balance approach with on-site energy generation options, where the embodied impacts of parts of the generated energy exported to third parties and its potentially avoided emissions form also part of the balance (not only the self-used part).** This is indicated in the present report as Type Aa approach. However, when dealing with the effects of exported energy (here potentially avoided emissions from third parties), it is recommended to use solutions that do not involve the risk of double counting. Perhaps such issues will be treated under the ongoing standardization activities recently started for a new standard ISO 14068 about ‘Carbon neutrality’.
- **Several approaches allow a variety of balancing and offsetting measures to achieve the net zero status.** However, it should be made sure that the excess use of such measures shall be avoided in order to prevent buildings which are highly energy inefficient from achieving the net-zero carbon/GHG emissions target level. The implementation of energy efficiency measures shall be prioritised with the setting of energy use intensity targets (EUI) for both new and existing buildings. Additionally, it is recommended to ask for the reporting of the results (i.e. achievement of net-zero status) in such a way that both parts of the balance are visible, i.e. the carbon footprint of the building and the amount and kind of offset emissions.

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Abbreviations

Abbreviations	Meaning
AU	Australia
AT	Austria
BE	Belgium
BECSS	Biogenic energy resources with carbon capture and storage
BIPV	Building integrated photovoltaic
BISS	Building integrated solar systems
BR	Brazil
CA	Canada
CED	Cumulated energy demand
CEN	European Committee for Standardization
CH	Switzerland
CN	China
CZ	Czech Republic
DACSS	Direct air capture with carbon separation and storage
DE	Germany
DHW	Domestic hot water
DK	Denmark
EN	European Norm
EPBD	Energy Performance of Buildings Directive
ES	Spain
FI	Finland
FR	France
GHG	Greenhouse gas
HP	Heat pump
HU	Hungary
GWP	Global warming potential
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
IN	India
IT	Italy
ISO	International Organization for Standardization
JP	Japan
KR	South Korea
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
LC	Life cycle
LCIA	Life cycle impact analysis
MJ	Mega joule; 1 kWh = 3.6 MJ

Abbreviations	Meaning
NL	Netherland
NO	Norway
NET	Negative emission technology
NRE	Non-renewable energy (fossil, nuclear, wood from primary forests)
NZ	New Zealand
NZEB	Nearly zero energy building or nearly zero emissions building or net zero emission building (depending on the country)
PE	Primary energy
PL	Poland
PT	Portugal
PV	Photovoltaic (cell or panel)
RES	Renewable energy sources
RSP	Reference Study Period
SE	Sweden
SG	Singapore
SI	Slovenia
SFB	Single family building
SDG	Sustainable development goals
UK	United Kingdom
US	United States of America
UNFCCC	United Nations Framework Convention on Climate Change
ZK	South Africa

Definitions

Potentially avoided emissions: Potentially avoided emissions are the net potential GHG emissions reduction caused by exporting renewable energy produced on-site beyond the building system boundary. This exported renewable energy potentially substitutes demand for fossil fuel derived energy outside the system boundary, e.g. as part of the national/regional grid mix. The determination of potentially avoided emissions requires the definition of a “what if” scenario

Carbon/GHG emission offset: An offset is where a measure of reduction (direct or indirect) or removal of a GHG emission is used to compensate for or neutralise a CO_2 or other GHG emission that occurs elsewhere.

Carbon/GHG emission reduction offset: a measure which reduces emissions in a source outside the value chain of the entity. Emissions can be reduced by e.g. investing in energy efficiency retrofits and renovations of other buildings. A reference scenario is needed to determine the amount of emissions reduced.

Carbon/GHG emission removal offset: measures that removes CO_2 or other GHG emission from the atmosphere.

Negative emission technologies (NETs): NETs refer to all possible options for GHG emissions removal from the atmosphere. The following general categories can be assigned to NETs (EASAC 2018): (1) Afforestation and reforestation; (2) Land management to increase and fix carbon in soils; (3) Bioenergy production with carbon capture and storage (BECCS); (4) Enhanced weathering; (5) Direct capture of CO_2 from ambient air with CO2 storage (DACCS); (6) Ocean fertilisation to increase CO_2.
Note: In some countries like Australia and New Zealand wood landfilling is considered as a partly permanent carbon storage (see: A72 background report by Saade et al. (2023) for more information). However, landfilling wood (and other organic material) does not qualify as NET in the majority of countries as it bears the risk of anaerobic digestion, producing methane and thus potentially be a substantial source of GHG emissions. That is why landfilling organic material is forbidden by law in Europe.

Energy attribute certificate (EAC): A contractual instrument that represents information about the origin of the energy generated. Various energy attribute certificates exist in a variety of markets, e.g., guarantees of origin (GOs) in Europe, renewable energy certificates (RECs) in the United States and international certificates – such as I-RECs. Unbundled EACs (such as GO, REC and I-REC) are the ones that can be purchased separately from the purchase of the generation of electricity (IRENA 2018).

1. Introduction

Since climate neutrality is a target of high priority to be achieved at different scales, such as countries, sectors, building stocks, cities, or single buildings, a clear definition and specific assessment rules are urgently needed. This is not only critical in order to be able to plan and achieve climate neutrality but to also ensure the implementation of international sustainable development goals.

Avoided or balanced GHG emissions, commonly referred to as (net) zero GHG emissions, are interpreted here as a design target, ambition level, benchmark, or a budget for buildings. Such an approach, is also sometimes called carbon performance (Huang et al., 2017) and is a crucial part of an environmental performance assessment.

The aim is to achieve a state in which buildings, during their operation or during their full lifecycle, make only a minimal contribution to GHG emissions and thus to global warming. This state is referred to as (nearly) climate neutral (BMWi, 2010). One ambition level is where a (net) zero GHG emissions balance is achieved for the life cycle of buildings, while (net) zero GHG emissions for the operational part (here B6) is a subgoal that focuses only on balancing emissions from the buildings' operation. From these goals, actual target values for the design and assessment of buildings in relation to their carbon performance can be derived. It should be stressed that carbon performance (expressed as $kgCO_2eq.$) is one of several aspects of environmental performance. Additional environmental impacts need to be quantified and assessed to avoid burden-shifting between different environmental impacts. Furthermore, social and economic performance shall be assessed, and technical and functional requirements must be met.

A new norm is emerging with goals described by various synonyms, such as: (nearly) carbon-neutral buildings, (net) zero carbon, climate neutral, (net) zero emission, as well as target values such as (net) zero GHG emission in operation or in the full life cycle. For the first time, target values are derived top-down from science based targets (Chandrakumar et al., 2020), i.e. compliance with the ecosystem's carrying capacity (planetary boundaries (Andersen et al., 2020)) and serve to maintain the natural foundations of life. For example, Switzerland began early on to develop standards such as SIA 2040 (SIA, 2011, 2017) which introduced top-down derived benchmarks for buildings (for GHG emissions and non-renewable primary energy). In the past, target values were mainly developed based on technical and/or economic feasibility or by statistically deriving "best in class" values according to the "less is more" approach (Lützkendorf & Balouktsi, 2019). They were different depending on the type of building and use. The top-down approach uses a universal benchmark for the first time - (net) zero GHG emissions for all buildings, regardless of the type of building and use, location, climate or energy supply system (Lützkendorf & Balouktsi, 2019).

To date, however, there is little experience with the development and application of top-down benchmarks. Attempts are currently being made in many countries, organisations and other institutions to define the term 'climate neutrality', to translate it into measurable target values and to develop calculation and accounting rules, including the definition of system boundaries. This development has so far led to a plethora of terms, definitions, calculation and accounting procedures. The number of different variants is currently still increasing. There is an urgent need to improve transparency. Ideally, either a system into which different approaches can be classified or an internationally harmonised approach should emerge. The new ISO 14068 about carbon neutrality may provide the preconditions for this (currently under an early-stage development).

1.1 Purpose of Report

In the construction and real estate sector, there has been a discussion that has lasted for decades on the possibilities of describing, assessing, and improving the environmental performance of buildings as part of their overall sustainability performance. This led to the creation of standards, such as ISO 21931-1 (ISO, 2010) (updated in 2022). Only a few of the environmental performance indicators mentioned there have so far been incorporated into the legislation of countries. Therefore, during the past decades, a buildings' energy performance has been regulated based on delivered/final or primary energy use (primary energy, non-renewable in most of the cases), while legal requirements to reduce GHG emissions in the life cycle of buildings or their parts have not been in existence or are just emerging (e.g. in France (ECOLOGIQUE, 2020), Sweden (Boverket, 2019), Finland (Kuittinen & Häkkinen, 2020) or New Zealand (Ministry of Business New Zealand, 2020). For a long time, the protection goal of conserving natural resources (here fossil fuels) was in the foreground. The development of the discussion led to the increasing recognition of the need also to include embodied energy. Consequently, a significant number of net-zero energy approaches occurred in the market, whose approaches are already well covered in the existing body of literature (D'Agostino & Mazzarella, 2019; Marszal et al., 2011; Panagiotidou & Fuller, 2013; Sartori et al., 2012). However, discussions about net-zero energy targets in operation or life cycle, as part of building policy, are now supplemented by a focus on net-zero GHG emissions buildings and GHG emissions as a metric instead of relying on energy demand as a proxy for measuring a buildings' performance in relation to its impact on global warming.

Therefore, this report focuses mainly on the principles related to concepts of net-zero GHG emissions buildings as a contribution to the climate change mitigation process and SDG 13 “Climate action”. The aim of the report and the subsequent analysis is threefold:
- to develop a basis for systematisation and harmonisation of building assessment approaches in relation to (net) zero GHG emissions buildings to rule out misunderstandings and avoid greenwashing;
- to provide an overview of the key parameters, boundaries and performance targets mentioned in such approaches in different parts of the world;
- to provide a detailed analysis of the terms, definitions, system boundaries, calculation methodology and offsetting rules used for GHG emissions balance.

To achieve these objectives, data extracted from 35 energy- or GHG emissions-based building assessment approaches were used. The approaches were identified through a survey conducted among Annex 72 participants and selected external stakeholders. The primary target audiences for this report are policymakers, as well as researchers and consultants (incl. architects/designers) interested in the market implementation of (net)zero GHG emissions buildings and/or the development of related standards or certification/assessment systems.

It is important to note that a publication by (Satola et al., 2021) was incorporated into the preparation of this report, in which the interim results of the survey were presented. The results of the survey represent the status in summer 2020. The report presented here takes current developments into account and represents the status in spring 2021, i.e. it additionally includes updated information on new activities and modifications with respect to net net-zero assessment approaches occurring during 2020-21. Finally, it also presents a more detailed overview of the survey responses together with further recommendations.

1.2 Key Features Extracted from the Survey

In the first step of the research, the survey among IEA EBC Annex 72 experts was performed in order to extract the general data related to key features (Table 1.1) occurring in the respective country of the building assessment approach in relation to achieving climate neutrality and/or net zero GHG emission ambition levels. The extracted data from 35 building assessment approaches in 31 countries were crosschecked with the provided references and existing literature.

Table 1.1: Overview of methodological features, extracted from the analysed building assessment approaches (see also Satola et al. 2021)

Feature	Description of analysed information
General data (First step of data extraction from 35 building assessment approaches)	
Status and launching year	The legal status of standard/scheme (voluntary, mandatory, framework draft) with launching year.
Founder	The initiator of standard/scheme (government, non-government organisation (NGO) or research organisation.
Object of assessment	Application scale of standard/scheme (single building, neighbourhood, building stock)
Metric	Indicator/metric of building performance (primary energy, delivered energy of GHG emissions)
Type of regulation	Type of regulation and performance requirements according to Table 2.2 (Section 2.2)
Detailed data (Second step of data extraction from 13 building assessment approaches)	
Modules in relation to building operation	
System boundaries	Scope of life cycle modules included in the operational life cycle part
Electricity GHG emissions factor	Principle for environmental impact assessment of electricity use (average, marginal, hybrid)
Approach to ''time'' factor	Approach to ''time factor" in operational life cycle impact assessment (static vs dynamic modelling)
Verification requirements of building performance	Type of data and performance indicators, which needs to be verified during real-time operation of certified building
Modules in relation to production, construction replacement and end-of-life	
System boundaries	Scope of life cycle modules included in embodied life cycle part
LCA data source	Reference to calculation standard, recommended LCA database, calculation software
Approach to ''time'' factor	Approach to ''time factor" in embodied life cycle impact assessment (static vs dynamic modelling)
Principles for GHG emissions balance/offsetting	
Requirements	Avoidance of double counting
Allowable options for achieving net zero GHG emissions	Net balance options (Allowable renewable energy generation/supply options, allocation of exported energy outside the system boundaries, etc.), offsetting options (i.e. technical reduction and technical removal options outside the system boundaries)
Timing of compensation	What is the time frame for a building to become "GHG emissions net-zero/neutral"?

In the second step, a more detailed review and analysis was performed of the methodology used, particularly in GHG emissions-based building assessment approaches. This meant that the energy metric based approaches were excluded from the second step since those methodologies and approaches were already extensively described in previous research (D'Agostino & Mazzarella, 2019; Marszal et al., 2011; Panagiotidou & Fuller, 2013; Sartori et al., 2012). Consequently, the main analysis in this report focuses on 13 GHG emissions metric-based building assessment approaches in 11 countries on four continents. Specifically, the general data from the first step of the data extraction was complemented by the extraction of detailed data covering features related to the operational and embodied part (including the life cycle modules according to EN 15978) and possibilities of GHG emissions compensation as presented in Table 1.1.

2. Theoretical Basics

2.1 Features Relevant to all Kinds of Benchmarks

Table 2.1 shows a list of generic methodological features against which the different net-zero assessment approaches were checked. These features are not particular to net-zero approaches, and extensive analyses of them have been covered elsewhere (see the last column of Table 2.1), therefore, only the essential information is given here in short explanations. This report later chooses to go more in-depth on the balance/offsetting options, which is a unique characteristic for net-zero approaches.

Table 2.1: Overview of A72 reports where theoretical basics for common benchmark features can be found

Feature	Explanation	Where theoretical basics are provided
Object of assessment	Application scale of standard/scheme (single building, neighbourhood, building stock)	Lützkendorf et al. (2023a), Section 4.5
Metric	Indicator/metric of building performance (primary energy, delivered energy of GHG emissions)	Lützkendorf et al. (2023a), Section 4.4 Lützkendorf et al. (2023b), Section 4.4
Type of regulation	Type of regulation and performance requirements	See Table 2.2
Modules in relation to building operation		
System boundaries	Scope of life cycle modules included in the operational life cycle part	Lützkendorf et al. (2023b), Section 4.1.8
Electricity GHG emissions factor	Principle for environmental impact assessment of electricity use (average, marginal, hybrid)	Lützkendorf et al. (2023b), Section 4.3.25 Peuportier et al. 2023
Approach to ‘’time’’ factor	Approach to ‘’time factor” in operational life cycle impact assessment (static vs dynamic modelling)	
Verification requirements of building performance	Type of data and performance indicators, which need to be verified during real time operation of certified building	Lützkendorf et al. (2023a), Section 4.8
Modules in relation to production, construction replacement and end of-life		
System boundaries	Scope of life cycle modules included in embodied life cycle part	Lützkendorf et al. (2023b), Section 4.1.8
LCA data source	Reference to calculation standard, recommended LCA database, calculation software if any.	Lützkendorf et al. (2023b)
Approach to ‘’time’’ factor	Approach to ‘’time factor” in embodied life cycle impact assessment (static vs dynamic modelling)	Lützkendorf et al. (2023b), Section 4.3.1

2.2 Framework for Different Options of Regulations and Requirements in Building Assessment Approaches

The system boundaries and performance requirements may vary greatly among building assessment approaches. To systemise the different regulations occurring in building assessment approaches, the authors developed the classification framework (Table 2.2), which presents the options for different regulations and performance requirements related to the operational and embodied parts of the building lifecycle. In total, there are 81 possible combinations, which may be present in building assessment approaches.

The developed matrix may be useful for mapping and creating the code system for existing regulations. For example, a *G.8.c* code would represent a “net-zero GHG emissions” approach, where the operational part is balanced and limited by mandatory regulatory values in law, while the embodied part is not balanced but is instead limited by informal guide values. Guide values are understood as nonbinding orientation values for partial sizes. For example, SIA 2040 (SIA, 2017) contains such values for the operational and embodied part to support architects in their design process, in addition to the mandatory requirements for reducing GHG emissions in the full life cycle of buildings.

Table 2.2: Classification framework for system boundaries and performance requirements in building assessment approaches

		TYPE OF ACTION AND REGULATION	**Embodied part of the life cycle**								
			a	b	c	d	e	f	g	h	i
			Ignored	Calculated	Calculated and limited by informal guide values[1]	Calculated and mandatorily limited by	Calculated and mandatorily limited by law[3]	Calculated and balanced (individual approach)	Calculated and balanced, incl. limitation by informal guide values	Calculated and balanced, incl. mandatory limit values as part of a scheme	Calculated and balanced, incl. mandatory limit values as part of a law
Operational part of the life cycle	1	Calculated									
	2	Calculated and limited by informal guide values									
	3	Calculated and mandatorily limited by building assessment approach									
	4	Calculated and mandatorily limited by law									
	5	Calculated and balanced (individual approach)									
	6	Calculated and balanced, incl. limitation by informal guide values									
	7	Calculated and balanced, incl. mandatory limit values as part of a scheme									
	8	Calculated and balanced, incl. mandatory limit values as part of a law									
	9	Calculated and mandatorily limited – only selfuse of renewable energy produced at the building is part of the balance[4]									

[1] i.e. design guidelines, which set informal voluntary requirements

[2] i.e. voluntary building certification schemes, standards, and other building assessment approaches which set mandatory indirect or direct requirements for achieving certification

[3] i.e. national construction codes or standards, which set mandatory requirements for building construction and operation

[4] i.e. the exported energy is seen as additional information (benefits beyond system boundaries).

2.3 GHG Emissions Balance: Special Feature of Net-zero Approaches

2.3.1 Distinction between absolute zero and net-zero-GHG-emission approaches

To achieve climate-neutral buildings that fulfil the Paris Agreement requires that the GHG emissions caused during their life cycle needs to be (absolute) zero or net-zero (balanced).

A prerequisite for net zero GHG emissions is always the balance of GHG emissions, taking into account defined system boundaries and agreed conventions while with a variant that reaches the ‘absolute zero’ level, no more GHG emissions occur. For the ‘net-zero’ level, the first step is to reduce emissions to a technically / economically feasible level. In a second step, a zero (or positive) balance must be achieved with suitable and approved measures.

The question arises as to whether such a target should first be considered for the emissions associated with the operation of a building. The aim is to ensure the continuity of such considerations but also to supplement existing energy balances for the operation of buildings (B6) with a corresponding emissions balance.

Today, zero direct GHG emissions during the operation of buildings and thus absolute zero operational GHG emissions (direct part) are feasible using renewable energy (whether self-produced or not). For the operational GHG-emissions including upstream and downstream chains this is not yet the case. Still, GHG emissions are possibly emitted in the supply chains of systems generating renewable energies and, in addition, in construction material and building element manufacture and end-of-life management (Lützkendorf & Frischknecht, 2020). Thus, absolute zero operational (incl. supply chains) and life-cycle-based GHG-emission buildings are, to date, still difficult to practically achieve. However, there are studies that show in which direction the decarbonisation process in energy supply as well as the construction and real estate sector can be advanced and achieved (Alig et al., 2020).

2.3.2 GHG Emission balance/compensation options

An absolute zero life-cycle-based GHG-emission status is currently not within reach for buildings and leads to the necessary inclusion of measures for GHG emission reductions and ways to balance such emissions in the strategy to achieve a (net) zero target. There are related consequences for the assessment of GHG emissions of buildings. These are discussed in detail in the next below.

GHG Emissions and associated reductions can be assessed for direct operational, both direct and indirect operational (i.e. on-site and supply chain) and for full life-cycle-GHG emissions of buildings. The scope of the analysis and the system boundary needs to be identical for the assessment of the GHG emissions and associated balancing/offsetting options (Lützkendorf & Frischknecht, 2020).

There are three major approaches for balancing/offsetting a building’s carbon footprint (Lützkendorf et al. 2023a): (A) a net balance with potentially avoided emissions beyond the system boundary of the building; (B) investing in GHG emission reduction projects either directly or by purchasing certificates; or (C) investing in negative emission technologies that extract CO_2 or CH_4 (the latter only if from biogenic carbon and stored away safely/not reemitted) from the atmosphere either directly or by purchasing certificates.

Options B and C are usually not emission ‘reductions’ or ‘removals’ within buildings’ value chain, i.e. GHG emissions are not completely avoided, reduced or removed by organizational, structural and technical means applied to the building – therefore these are seen as ‘offsets’. When the possibility of offsetting is allowed as part of a net zero approach, the question of the specification of a time period within which the ‘arithmetical’ compensation must have taken place plays an important role. Usually, one calendar year is specified for this, there are also variants that allow offsetting over longer periods of time or the entire useful life of the building.

It notable that, often, these offsets are realized by the purchase of eligible units that support projects that reduce or remove emissions from the atmosphere. The general framework of measurement and validation of carbon off-set programs, which can be traded on a marketplace was established under the development mechanism (CDM) developed under the Kyoto Protocol. Off-sets certificates/units are considered as an essential tool to improve sustainability and to boost global decarbonisation by financing initiatives related to carbon reduction in developing countries. On the other hand, the compensation by off-set units may lead to the controversy regarding effectivity, and reliability (Gillenwater et al. 2007).

The most important questions in relation to the balance/offsetting options A—C are discussed below:

A) System boundaries for generation, procurement, and assessment of renewable energy

GHG emissions caused by the building construction and operation (or only operation) can be described, according to some suggestions in the literature (Panwar et al., 2011), as being compensated by potentially "avoided" GHG emissions outside the system boundary through the export of renewable energy. Other authors suggest presenting the benefits of exported energy as additional information, e.g. under module D (D2 in the new EN 15978-1, expected in 2021), in line with European (i.e. EN 15978 (15978, 2011)) and international standards (ISO 16475-1 (ISO, 2017)) (Dodd et al., 2017).

Options with respect to attribution of embodied impacts of on-site energy generation equipment

Options are currently being discussed to either assign the embodied GHG emissions of the renewable energy generation systems to the building or split them proportionally between the building and exported energy according to the self-used and exported energy proportions. Further information on the subject can be found in Lützkendorf et al. (2023b) and Peuportier et al. (2023). Specifically, a clear distinction must be made between four approaches (Table 2.3):
Option 1: Attribute all embodied impacts of energy generation equipment to the building and allow balancing by avoided GHG emissions outside the system boundaries
Option 2: Attribute all embodied impacts of energy generation equipment to the building and show potential effects beyond the system boundary separately in module D (or D2), or
Option 3: Attribute the embodied impacts of energy generation equipment corresponding to the self-consumed part and provide a separate balance for the exported energy (including embodied, operational impacts and potentially occurring benefits and loads outside the system boundary).
Option 4: Attribute the embodied impacts of energy generation equipment corresponding to the self-consumed part and provide the results of a separate balance for the exported energy (including embodied, operational impacts and potentially occurring benefits and loads outside the system boundary) as additional information in module D (D2).

Table 2.3. Overview of the four options with respect to attribution of embodied impacts of on-site energy generation equipment

	Embodied emissions of the renewable energy system are fully allocated to the building	Embodied emissions of the renewable energy system is proportionally allocated to the building (self-use share)
Avoided emissions can be considered in the balance	Option 1	
Avoided emissions are not considered in the balance, but in D2	Option 2	Option 4

Avoided emissions are considered in the balance of exported energy	Option 3

<u>Options with respect to allowable types of renewable energy generation</u>

In addition to the handling of the (embodied) energy and/or GHG emissions associated with manufacturing and maintaining the system generating the exported energy, it must also be clarified which type of renewables generation can be attributed to the building and within which system boundaries. There are different options for system boundaries for the generation of renewable energy as defined by (Marszal et al., 2011) and presented in Figure 2.1.

Option 1 (building-integrated generation) employs the energy generation from the renewable energy sources installed/mounted on the building. In most cases, as part of this option, the photovoltaic and solar thermal technologies, installed on the building roof or integrated into the building façade (known as building integrated photovoltaic (BIPV) or building-integrated solar systems (BISS)), are used and directly connected to building energy system.

Option 2 (generation within building site boundaries) addresses renewable energy generation technologies located within building site boundaries, typically from parking-lot PV systems, tower-based wind turbines, and ground-mounted PV or solar hot water systems.

Option 3 (generation off building site but used on-site) is typically less preferable than option 1 and 2, since significant environmental impacts related to transportation of renewable sources (mainly biomass) to the building site may occur (Amponsah et al., 2014). Additionally, some biomass resources which come from unsustainable fields and forests, or dedicated energy crops with a short rotation period, should not be treated as GHG emissions-free sources.

Option 4 (generation off-site) uses renewable energy sources available off-site to generate energy through on-site processes connected to building energy systems, while off-site supply.

Options 1 and 2 are of particular importance. After the internal requirements (energy demand) have been met, the surplus of energy produced is exported. The effects of potentially avoided emissions are included in the balance or given as additional information, depending on the convention - see also discussion above.

<u>Purchasing of energy</u>

A special case of “imported” renewable energy (generation fully offsite) is the purchasing of energy (seen as **Option 5 – “Off-site supply”** in Figure 2.1). Despite being widely recognised as a cost-effective and easy to implement strategy for reducing building-related GHG emissions (Lützkendorf & Frischknecht, 2020), the application of this solution may be controversial. Existing research (Pless & Torcellini, 2010; UKGBC, 2021) discusses the fact that buildings that rely on only purchased off-site renewable energy may present a lack of initiative to reduce the building energy demand and related environmental loads. If minimum performance requirements are part of a definition, this is not an issue though. The use of generic primary energy and emission factors for the national mix is commonly appropriate because e.g. in the design phase the occupant is generally not known and neither the electricity provider so that a specific mix cannot be identified, unless the electricity provider is known and verified via long-term contracts (see also Peuportier et al. 2023).

<u>Risk of double-counting</u>

If renewable energy is generated on-site, the excess can be delivered (exported) to third parties after deducting self-consumption. This possibly/eventually reduces the emissions elsewhere compared to an alternative energy generation or procurement scenario. Therefore, from the perspective of the building under study, there are possible effects outside its system boundary. There is currently a debate as to whether these shall be given for information only (e.g. in module D2 following latest developments in European standardisation in CEN TC 350) or considered in the balance sheet. Consideration in the balance sheet involves the risk of double counting (1 x for the building and 1 x for the purchaser of the exported energy). The risk of double-counting decreases when the building is part of a self-sufficient net zero GHG emission group of buildings or district/neighbourhood (i.e. no exported energy), therefore, part of a larger system which does not export energy.

Similar to on-site generation options, the purchase of renewable energy generated off-site presents the risk of double-counting since it requires a power grid to transfer the generated energy to the building site. The increased number of off-site renewable energy supply options will lead to the decarbonisation of the whole electricity grid and, consequently, decreasing of GHG emissions factors. The guideline developed by U.S Energy Agency (United States Environmental Protection Agency, 2018) presents the best practices related to making environmental claims from purchased green energy in the form of renewable energy certificates (RECs). One of the essential recommendations is connected to avoiding the double-counting of imported clean energy by retiring the RECs just after making an official environmental claim. This measure can prevent double counting of environmental benefits in case of selling or transferring the certified green power certificates. Finally, as long as physical production and electricity certificates are purchased from the same (renewable)power plants, the purchase of green electricity is not problematic (see also Peurportier et al. 2023; Lützkendorf et al. 2023b).

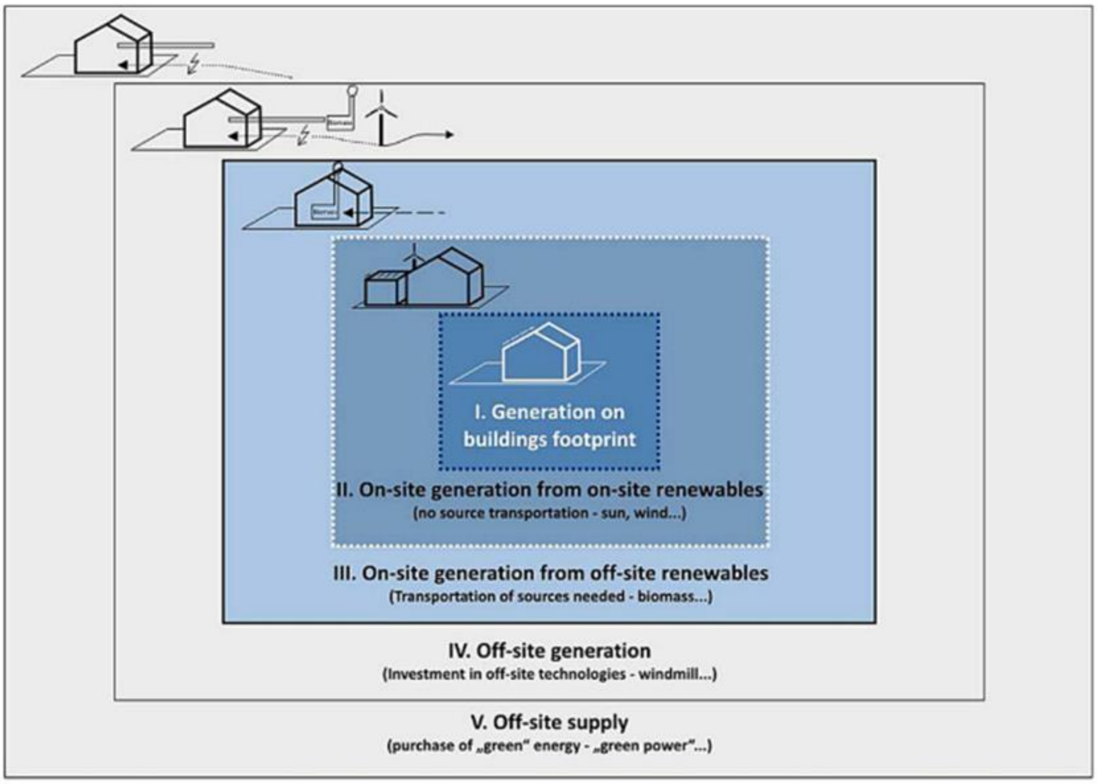

Figure 2.2: Overview of possible renewable supply options by Marszal et al. (2011)

B) GHG emissions reduction compared to a reference scenario through technical measures

There are different types of reduction projects, but not of the same traceability. For example, for some type of projects the emission reduction is directly measurable and therefore real reductions are claimed and shared between the building at issue and the offset project (e.g. CCS equipment in coal power plants). Others are simply leading to potentially avoided emissions elsewhere (investments in renewable energy production plants), and therefore potential (i.e. scenario-based) reductions are claimed and shared between the building at issue and the offset project. Based on this consideration, Approach B is further distinguished between two categories: ‘direct’ (Ba) and ‘indirect’ (Bb). An issue particularly with Approach B is that with an emission reduction outside the building’s boundary (real or scenario-based), CO_2 is still being emitted by the building at issue. Therefore, on a global level, net-zero emissions cannot be reached with reductions only, but they can help to reach a maximum reduction of 50% of GHG emissions: per 1 tonne emission reduction, 1 tonne is still being emitted (by the entity purchasing the certificate or investing on a project). Furthermore, considering that the cheapest reduction potentials are likely located in emerging and developing economies, these countries may face high costs in future when it is their turn to reduce their GHG emissions (Lützkendorf & Frischknecht, 2020). Based on these considerations, the transition from reductions to removals becomes critical because even if the building sector would stop emitting GHG emissions right now, the quantity of emissions in the atmosphere is still vast to stop the warming trajectory

C) Negative GHG emissions through technical measures

Off-setting takes place with negative GHG-emissions achieved via negative emissions technologies (NETs). Not all NETs are the same, therefore this approach can be further distinguished into two categories (Ca and Cb) based on the reversibility of the storage permanence (see Minx et al. (2018) for a more detailed analysis). It is important to note that, currently, most carbon offset projects available to invest in are either a type of emission reduction or a type of carbon removal with reversible permanence. These can provide additional social and environmental co-benefits that advance the UN Sustainable Development Goals as well as contributing to overall emissions reductions and sector decarbonisation (WEF, 2021). This makes them essential also for years to come. However, several organisations acknowledge the need to shift to more high-technology permanent carbon removal offsets, such as bioenergy with carbon capture storage (BECCS), which will require more investment and development in many cases. It is not only possible but also necessary for net zero GHG emission definitions to encourage investment in the research and development of these technologies as part of a carbon offsetting strategy.

2.3.3 Typology of options

Terms such as zero carbon or zero emissions are often used in politics and science, yet it often remains unclear whether such terms refer to an “absolute zero” or a “net zero” in terms of the energy and emissions balance. In the literature, a typology for the designation of approaches without GHG emissions (absolute zero) or with a balance of GHG emissions (net zero) is proposed by Lützkendorf and Frischknecht (2020). Based on the latter authors and all approaches and options laid out in the previous section, a more detailed division is proposed by Lützkendorf et al. (2023a) and shown in Table 2.4.

In order to deliver clarity, limit misunderstanding and avoid potential greenwashing, it is therefore important to state the chosen term in connection with related system boundaries, calculation and balancing rules very clearly and specifically. The same applies to the term “(net) zero emission”, which is used for both CO_2 emissions and GHG emissions. However, there are cases that do not cause CO_2 emissions, but still contribute to GHG emissions through the release of methane and other GHGs.

It must be declared whether the goal is to avoid in absolute terms, non-renewable primary energy consumption and emissions, or whether the goal is to achieve a net-zero balance, possibly even a positive balance. While for the operational part, there are at least theoretical possibilities of absolutely avoiding any CO_2 emissions, this is currently not possible for the entire scope of GHG emissions and the embodied part. Even though it is theoretically possible to achieve an absolute zero during operation or in the full life cycle, there are strong influences due to the system boundaries. It depends on whether the focus is on direct emissions, or whether and to what extent, upstream processes are included.

Based on the current state of the art, there is initially a need for multiple definitions for a series of specific cases. One of the main goals of this report is to create the basis for developing a transparent and systematic approach for a definition of (net) zero GHG emissions buildings which would be instrumental to delivering clarity, limit misunderstanding and avoid potential greenwashing. A clear description of the life cycle modules included combined with the typology presented in Table 2.4 provides a flexible, transparent classification system for different approaches for a chosen emissions balance.

Table 2.4: System of approaches for net-zero and zero-emission building during operation or full life-cycle (Source: Lützkendorf et al. 2023a)

Code	Name	Description	Note
Aa	**Net-balance approach, potentially avoided emissions**	Embodied impacts of exported energy produced on-site, and its potentially avoided emissions, as part of the GHG-emission balance of the building	Risk of double counting, unless emissions equivalent to the amount of avoided emissions booked on the building are booked by the party using the exported energy. Approach Aa is a special case of Approach Bb as the investment is made on the building under assessment.
Ab	**Net-balance approach, allocation**	Embodied impacts of exported energy produced on-site and its potentially avoided emissions as additional information (either as part of module D2 of the building or the balance of exported energy)	Life cycle related net-zero GHG-emission buildings are reachable only with additional technical reduction or removal (offsets)
Ba	**Technical reduction, direct** (emission reduction within the project)	Investment in CO_2/GHG emission reduction projects by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: carbon capture and storage (CCS) equipment in coal power plants, energy retrofit of existing buildings.	The emission reduction is directly measurable. The emission reduction is shared between the building at issue and the project, in which the technical reduction is realised. If claimed by the building, it shall not be claimed by the project.
Bb	**Technical reduction, indirect** (potential emission reduction occurs beyond the project)	Investment in projects, which lead to potential CO_2/GHG emission reductions elsewhere, by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: investments in solar or wind power plants.	The emission reduction is determined indirectly using "what-if" scenarios. The potential emission reduction is shared between the building at issue and the project, in which the technical reduction is realised. If claimed by the building, it shall not be claimed by the project.
Ca	**Technical removal** NETs with potentially reversible permanence)	Investment in projects, which remove CO_2 from the atmosphere with potentially reversible performance, by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: Biological fixation, achievable with afforestation, improved forest management; the storage of carbon in long-living buildings and wood products; the storage of carbon in the soil; and long-term underground storage of biogenic carbon	This approach allows to reach net zero GHG emissions buildings and contributes at the same time to the global net zero emissions goal. The viability of such measures is still questionable. For example, planting trees does not claim of taking care of them until they are grown up nor about the fate of the mature tree (afforestation may not be efficient in regions where there is a risk of fire).
Cb	**Technical removal** (NETs with stable permanence)	Investment in projects, which remove CO_2 from the atmosphere with stable performance, by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: biogenic energy resources with carbon capture and storage (BECCS) or direct air capture with carbon separation and storage (DACCS)	This approach allows to reach net zero GHG emissions buildings and contributes at the same time to the global net zero emissions goal, but the long-term viability of such measures is still questionable.
D	**Absolute zero approach**	Use of construction materials and components with zero GHG emissions	An absolute zero life-cycle-based GHG-emission status is currently not within reach

	(including supply chain emissions), purchase of operational energy and water with zero GHG emissions (including supply chain emissions)	for buildings and leads to the necessary inclusion of some kind of measures for GHG emission reductions and ways to balance such emissions in the strategy to achieve a (net) zero target.

3. Results and Discussion

3.1 General Data

The overview of general data from the first step of data extraction based on 35 building assessment approaches is presented in Table 3.1. Despite the high variation of key factors among the analysed building assessment approaches, general findings are summarized as follow:

1. A single building is the dominant object of assessment in the analysed data set.
2. Primary energy is the most common assessment metric, observed in most of the European countries, where the implementation of nearly zero energy building (nZEB) performance target, is applied in national policy.
3. In most of the cases, the building standards and schemes based on a GHG emissions metric (zero-carbon, zero-emissions buildings) are voluntary, and mostly created and used by NGO's or research organisations.
4. Most of reviewed building assessment approaches are titled as "zero carbon" even though their frameworks not only cover carbon dioxide (CO_2) emissions but also set of other gases, which emissions contribute to the global warming.

Table 3.1: Overview of key methodological parameters from 35 building assessment approaches. Note: the highlighted ones indicate the building assessment approaches focusing on GHG emissions as the metric of balance.

Country name and code	Building assessment approach, reference	Status, launching year	Founder	Scale of application	Metric	Regulation type (acc. to Table 2.2)
Australia (AU)	Climate active, carbon neutral standard for buildings, (Australian Government Initiative, 2019)	Voluntary, 2019	Government	Buildings and neighborhoods	GHG emissions	G5.a
Austria (AT)	OIB-300.6-009/2015, Guideline 6 (EPBD), (Austrian institute of construction engineering (OIB), n.d.)	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Belgium (BE)	Energieprestatie en Binnenklimaat (EPBD), (Vlananderen is Energie, 2013)	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a
Brazil (BR)	Zero Energy Standard, (Brazil Green Building Council, 2017)	Voluntary, 2017	Brazil Green Building Council	Buildings	Delivered energy	DE7.a
Canada (CA)	Zero Carbon Building Standard, (Canada Green Building Council, 2020)	Voluntary, 2020	Canada Green Building Council	Buildings	GHG emissions	G5.f
China (CN)	Technical Standard for Nearly Zero Energy Buildings, (Ministry of Housing and Urban-Rural Development (MOHURD), 2019)	Voluntary, 2019	Government	Buildings	Primary energy	PE4.a
Czech Republic (CZ)	Energy Management Act, 78/2013 Coll (EPBD), (Republic, 2013)	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a

Denmark (DK)	Danish Building regulations (EPBD), (Danish ministry of Transport Building and Housing, 2018)	Mandatory, 2018	Government	Buildings	Primary energy	PE4.a
Finland (FI)	Method for whole-life carbon assessment of buildings, (Kuittinen, 2019) and Finish regulatory life cycle carbon limits of buildings	Draft, 2020	Finish Green Building Council	Buildings	GHG emissions	G4.e
France (FR)	France E+C-, (MTES, 2017)	Draft, 2020	Government	Buildings	Primary energy	PE4.a
	France EQUER, (Peuportier, Thiers, & Guiavarch, 2013)	Voluntary, 2017	Research	Buildings	GHG emissions	G5.f
Germany (DE)	Framework for “carbon neutral buildings and sites” (DGNB, 2018)	Voluntary, 2018	German Sustainable Building Council (DGNB)	Buildings	GHG emissions	G5.f
	Energy efficiency for buildings. Methods for achieving a virtually climate-neutral building stock. (Federal Ministry for Economic Affairs and Energy (BMWi), 2015)	Public framework, 2015	Government	Building stock	Primary energy	PE4.a
Hungary (HU)	Decree about Determination of Energy Efficiency of Buildings (EPBD), (“7/2006. (V.24.): Hungarian Government Decree on the energy performance of buildings, 2006 (in Hungarian).,” n.d.)	Mandatory, 2016	Government	Buildings	Primary energy	PE4.a
India (IN)	Net-zero energy rating system (Council, 2018)	Voluntary, 2018	Indian Green Building Council	Buildings	Delivered energy	DE7.a
Italy (IT)	Law 90/2013 and Decree 26/06/2015 (EPBD) (Italian Republic, 2013)	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Japan (JP)	Japan’s Strategic Energy Plan, (Japan Ministry of Economy and Industry, 2018; Tanabe & Committee, 2016)	Mandatory, 2014	Government	Buildings	Primary energy	PE4.a
Netherland (NL)	Almost Energy Neutral Building requirements (EPBD), (Rijksdienst voor Ondernemend Nederland, 2019)	Mandatory, 2019	Government	Buildings	Primary energy	PE4.a
New Zealand (NZ)	CarboNZero Building Operations pilot scheme as a part of Zero Carbon Road Map for Aotearoa’s Buildings, (New Zealand Green Building Council, 2019)	Voluntary, 2019	New Zealand Green Building Council	Buildings	GHG emissions	G5.d

Norway (NO)	Zero Emission Building (ZEB) definition ,(Fufa et al., 2016)	Voluntary, 2014	Research	Buildings	GHG emissions	G5.f
	Zero emission neighborhoods in Smart Cities ,(Wiik et al., 2018)	Voluntary, 2019	Research	Neighborhood	GHG emissions	G5.f
Poland (PL)	Buildings and their location – Polish Technical Conditions (EPBD), (Ministry of Construction and Infrastructure, 2018)	Mandatory, 2018	Government	Buildings	Primary energy	PE4.a
Portugal (PT)	Art. 16 of DL 118/2013 (EPBD) (No, n.d.)	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a
Slovenia (SI)	Action plan for nZEB until 2020 (Evropskega, 2020)	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Spain (ES)	Net-zero energy buildings, (Montoro, 2016)	Voluntary, 2019	Spanish Green Building Council	Buildings	Delivered energy	DE7.a
South Korea (KR)	The green building promotion act (Kim & Yu, 2018)	Mandatory, 2013	Government	Buildings	Delivered energy	DE7.a
South Africa (ZK)	Net-zero and net positive certification scheme (Green Building Council South Africa, 2019)	Voluntary, 2019	South Africa Green Building Council	Buildings	GHG emissions	G5.a
Sweden (SE)	NollCO2 (Sweden Green Building Council, 2020)	Voluntary, 2020	Sweden Green Building Council	Buildings	GHG emissions	G5.h
	Local Roadmap Malmö (“Local Roadmap Malmo 2030,” n.d.)	Draft, 2020	Malmö municipality with industrial partners	Buildings	GHG emissions	G5.f
Switzerland (CH)	Net-zero energy building (MINERGIE-A) (MINERGIE, 2016)	Voluntary, 2012	Minergie Association	Buildings	Primary energy	PE7.d
Singapore (SG)	Green Mark for Super Low Energy Buildings, (Building and construction authority (BCA) of Singapore, 2018)	Voluntary, 2018	Building and construction authority (BCA) of Singapore	Buildings	Delivered energy	DE7.a
United Kingdom (UK)	Net-zero carbon building, (UKGBC, 2019)	Voluntary, 2019	UK Green Building Council	Buildings	GHG emissions	G5.f
USA (US)	Zero energy building, (US Department of Energy, 2015)	Voluntary, 2015	Government	Buildings and neighborhood (campus)	Delivered energy	DE7.a
	LEED zero carbon (USGBC, 2019)	Voluntary, 2016	United States Green Building Council (USGBC)	Buildings	GHG emissions	G5.a
	Zero carbon building (International Living Futures Institute, 2019)	Voluntary, 2019	International Living Future Institute	Buildings	GHG emissions	G5.h

[1] Nearly zero energy building target mandatory for all building types from 2017, except public sector which net-zero energy target is required from 2020

3.2 Type of Regulations and Performance Requirements in Analysed Building Assessment Approaches

Based on an in-depth review of 35 building assessment approaches from 31 countries worldwide and the classification framework proposed in Table 2.2, the authors identified the nine following types of regulations, which present the system boundaries and performance requirements presented in building assessment approaches (Table 3.2). The mentioned approaches are not always representative for a situation in a whole country. In most of the cases proposals and examples by organisations and private institutions are presented and discussed.

Table 3.2: Regulation type recognised in analysed building assessment approach. Note: For frameworks with multiple performance levels, the most ambitious level is here shown.

Regulation type	Description	Country code and building assessment approach reference
PE 3. a	The operational part of energy consumption of the building is regulated by minimum, voluntary requirements (limit values expressed as maximum demand for primary energy, non-renewable) introduced in the building assessment approach. The embodied part is ignored.	CN
PE 4. a	The operational part of energy consumption of the building is regulated by minimum, mandatory requirements (limit values expressed as maximum demand for primary energy, non-renewable) introduced in national law. The embodied part is ignored.	AT, BE, CZ, DK, FR1, HU, IT, JP, NL, PL, PT, SI
PE7.d	The operational part of non-renewable, primary energy consumption of the building is balanced and regulated by maximum limits included in the building assessment approach. Embodied non-renewable, primary energy consumption is mandatory limited by value introduced in the building assessment approach.	CH
DE7.a	The operational part of energy consumption (delivered energy) of the building is balanced and regulated by maximum limits included in the building assessment approach. The embodied part is ignored.	BR, IN, ES, KR, SG, US1
G4. e	Both the operational and embodied parts of GHG emissions of the building are mandatory, regulated and limited by law.	FI
G5. a	The operational part of GHG emissions of the building is balanced by an individual building assessment approach. The embodied part is ignored.	AU, ZA, US2
G5. d	The operational part of GHG emissions of the building is balanced by an individual building assessment approach. The embodied part of the GHG emissions of the building is mandatory and limited by values introduced in the building assessment approach.	NZ
G5. f	Both the operational and embodied parts of GHG emissions of the building are balanced by an individual building assessment approach.	CA, FR2, DE, NO SE1, UK

G5.h	The operational part of GHG emissions of a building is balanced by an individual building assessment approach. The embodied part of the GHG emissions of the building is balanced and limited by maximum values introduced in the building assessment approach.	SE2, US3

Definitions based on energy consumption metrics (types: PE3.a, PE4.a, PE7.d and DE7.a) are the most common, occurring in 22 of 35 analysed national building assessment approaches. The requirement in the form of maximum allowable annual primary energy consumption values (Type PE3.a and PE4.a, PE7.d) is present in 15 of 35 building assessment approaches. The net-zero energy performance target based on the metric of delivered energy (Type DE 7.a) is set in 6 of 35 analysed frameworks.

The shift from energy consumption to a GHGs emissions-based metric can be found in 13 building assessment approaches from 11 countries. In Finland, the National Green Building Council follow a government standard (Kuittinen, 2019) which proposes low-carbon building regulations (Type G4.e) based on the normative life cycle GHG emissions limits for different building types, which are planned to be published by the Finish Government.

The requirement of net-zero GHG emissions from the operational life cycle module (type G5.a, G5.d) is implemented in building assessment approaches from four countries: Australia, South Africa, New Zealand, and USA (LEED zero carbon (USGBC, 2019)) In all these assessments approaches, the GHG emissions from embodied life cycle modules are outside of the assessment scope (Type G5.a), except New Zealand (Type G5.d), where all new-buildings need to be constructed with 20% less embodied GHG emissions, relative to the baseline scenario by 2025.

The significance of including the embodied GHG emissions is highlighted in all these frameworks and are planned to be included in the next revision of the building assessment approaches. The declaration of developing criteria and requirements addressing embodied GHG emissions in the South Africa scheme is made conditional on construction market interests.

The more ambitious performance target requirement can be found in the building assessment approaches from Canada, France (EQUER (Peuportier et al., 2013)), Germany, Norway, Sweden, UK and USA (zero-carbon (International Living Futures Institute, 2019)), all of which aim to achieve a net-zero GHGs emissions balance considering the full life cycle scope (Type G5.f and G5.h).

Table 3.3 shows how the existing approaches can be mapped in the overall array of approaches that can exist as earlier presented in Table 2.2. It should be noted that this survey covers activities up to summer 2020. New regulations are emerging in different countries that will introduce benchmarks for embodied energy and/or GHG emissions among others, and such new developments are expected to also influence net zero definitions (see also the A72 background report by Rasmussen et al. 2023). For example, definitions that currently ignore embodied GHG emissions, will probably have to adapt in future if such benchmarks become part of legal requirements.

Noteworthy developments of net zero GHG emission approaches of buildings occurring after the completion of the survey, and not covered in detail here, are:

- **updated versions** of some of the covered schemes, e.g. the Zero Carbon Building Design Standard by Canada (Version 2)[1], or provision of supplementary publications covering more detailed rules for offsets and renewable energy procurement options, e.g. the guidance for Green Star on the use of offsets and renewables[2] or the Renewable Energy Procurement & Carbon Offsetting Guidance for Net Zero Carbon Buildings by UKGBC[3],

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[1] See: https://portal.cagbc.org/cagbcdocs/zerocarbon/v2/CaGBC_Zero_Carbon_Building_Standard_v2_Design.pdf

[2] See: https://gbca-web.s3.amazonaws.com/media/documents/climate-positive-buildings-net-zero-ambitions_Z3pcK5R.pdf

[3] See: https://www.ukgbc.org/ukgbc-work/renewable-energy-procurement-carbon-offsetting-guidance-for-net-zero-carbon-buildings/

- **new guidance principles and action plans** by both international organisations, such as the Net-Zero Carbon Buildings Principles by the World Economic Forum (WEF, 2021) and national collaborations of different organisations to reach consensus on definitions to support industry, such as the Net Zero FAQs[4] document in UK.
- **new drafts of laws and standards**, such as the EPBD proposal[5] and the upcoming EN 15978-1 which also deals with the question of how to allocate impacts and benefits associated with exported energy

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[4] See: https://www.leti.uk/_files/ugd/252d09_d824a0289c1e40d39cbe62514a285e10.pdf

[5] See: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021PC0802

Table 3.3: Classification framework for system boundaries and performance requirements in building assessment approaches. Note: For primary energy (**PE**), delivered energy (**DE**), or GHG emissions (**G**) metric; non-useful combinations are highlighted in grey, while the existing ones acc. to the survey are highlighted in orange (see also Table 3.2).

		TYPE OF ACTION AND REGULATION	Embodied part of the life cycle								
			a	b	c	d	e	f	g	h	i
			Ignored	*Calculated*	*Calculated and limited by informal guide values*[1]	*Calculated and mandatorily limited by scheme*[2]	*Calculated and mandatorily limited by law*[3]	*Calculated and balanced (individual approach)*	*Calculated and balanced, incl. limitation by informal guide values*	*Calculated and balanced, incl. mandatory limit values as part of a scheme*	*Calculated and balanced, incl. mandatory limit values as part of a law*
Operational part of the life cycle	1	*Calculated*	▨								
	2	*Calculated and limited by informal guide values*	▨								
	3	*Calculated and mandatorily limited by building assessment approach*	**PE**								
	4	*Calculated and mandatorily limited by law*	**PE**				**G**				
	5	*Calculated and balanced (individual approach)*	**G**			**G**		**G**		**G**	
	6	*Calculated and balanced, incl. limitation by informal guide values*									
	7	*Calculated and balanced, incl. mandatory limit values as part of a scheme*	**DE**		**PE**						
	8	*Calculated and balanced, incl. mandatory limit values as part of a law*									
	9	*Calculated and mandatorily limited – only self-use of renewable energy produced at the building is part of the balance*[4]									

[1] i.e. design guidelines, which set informal voluntary requirements

[2] i.e. voluntary building certification schemes, standards, and other building assessment approaches which set mandatory in-direct or direct requirements for achieving certification

[3] i.e. national construction codes or standards, which set mandatory requirements for building construction and operation

[4] i.e. the exported energy is seen as additional information (benefits beyond system boundaries).

3.3 Detailed Methodological Features from GHG Emissions-based Net Zero Approaches

3.3.1 Ambition levels and system boundaries

From the 13 selected building assessment approaches from 11 countries, each of which is characterized by a GHG emission-based metric, five frameworks have been selected from Australia, Germany, Norway, South Africa, and the UK. For each country, the respective standard introduces different levels of building performance target, thus providing some flexibility in the design and construction of net-zero GHG emission buildings.

Table 3.4: Overview of multiple performance levels in analysed GHG emissions-based building assessment approaches

			Regulation type[2]			
Country	**Name of building assessment approach**	**Level of performance[1]:**	**Type G1. f**	**Type G5. a**	**Type G4. e**	**Type G5. f**
Australia	Carbon neutral buildings	Base building operation		X		
		Whole building operation		X		
Germany	Carbon neutral buildings	Climate-neutral by 2050[3]			X	
		Carbon neutral in the ongoing operation		X		
		Carbon neutral through life-cycle				X
Norway	Zero-emission building	ZEB: O-EQ[4], ZEB: O[5]		X		
		ZEB:OM[6], ZEB: COM[7], ZEB: COME[8]				X
South Africa	Net-zero and net positive carbon building	Level 1: Base building emissions		X		
		Level 2: Occupant emissions		X		
United Kingdom	Net Zero Carbon	Net-zero construction	X			
		Net-zero carbon operational energy		X		
		Net-zero carbon – whole lifecycle				X

[1] Name of different, possible performance level allowed in a standard or scheme

[2] Regulation type of performance level based on Table 3.2

[3] This definition is not analysed in the next sections due to lack of information

[4] The building's renewable energy production compensate for greenhouse gas emissions from operation of the building minus the energy use for equipment (plug loads)

[5] The building's renewable energy production compensate for greenhouse gas emissions from operation of the building[6] The building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials

[7] The building's renewable energy production compensate for greenhouse gas emissions from construction, operation and production of building materials.

[8] The building's renewable energy production compensates for greenhouse gas emissions from the entire lifespan of the building. Building materials – construction – operation and demolition/recycling.

The differences between performance levels in Australia and South Africa frameworks are attributed to the scope of operational life cycle boundaries and presented in the following section. The German framework defines three levels of performance, while net zero-emission building standard in Norway provides two different types (ZEB: O-EQ, ZEB:O) which differ in terms of operational life cycle boundaries, as well as an additional three types of increasing performance (ZEB:OM, ZEB: COM, ZEB: COME) with differences in embodied life cycle system boundaries scope. The experiences from the pilot buildings projects in Norway show that reaching the highest level of ambition for ZEB (Type G5.f), which include both operational and embodied emissions is very challenging. For instance, moving the ambition from ZEB:0 (Type G5.A) to ZEB:OM (Type G5.f) in the pilot buildings implies additional implementation of renewable energy sources, which increase initial energy generation in the range between 82%-182% (Hestnes & Eik-Nes, 2017). In the UK Net Zero Carbon Framework Definition for buildings, there is a possibility for achieving two different performance levels, or a combination of those, which take into consideration the whole life-cycle approach.

3.3.2 System boundaries scope and approach to the aspect of ‘’time”: Operational part

Table 3.5 presents the detailed information about system boundaries and approach to a ‘’time” factor in the operational module assessment in the building assessment approaches. In 8 of 13 analysed building assessment approaches, the complete scope of operational energy use modules including B6.1 B6.2 and B6.3 submodules are covered (for more information on how these sub-modules are defined within A72 context see Figure 3.1 and Lützkendorf et al. 2022). The regulated, building-related energy consumption module (B6.1) is a single, scope of operational impact assessment in frameworks from the UK and Finland. The non-regulated use and user-related energy consumption (B6.3) module is not included in the scope of Sweden (Local RoadMap Malmo (“Local Roadmap Malmo 2030,” 2020)) framework, while non-regulated building-related energy consumption module (B6.2) is outside of the scope in the framework from Norway and Canada. It is important to note that all frameworks include only chimney emissions of electricity (e.g. PV electricity with 0 g CO_2-eq/kWh), and therefore ignore the supply chain, however, in some whole life cycle frameworks embodied emissions from PV systems are included in the balance.

In most of the analysed building assessment approaches, the “average electricity” principle of assessing the GHG emissions from the electricity mix is employed. The EQUER design tool uses a “marginal electricity mix” approach, where the different energy production sources are ranked according to merit order. Renewable energy sources (e.g. solar or wind that depend on the weather) that cannot be adjusted to the power demand are the bottom of this ranking, while adjustable technologies with the lowest constraints and the highest cost are at the top of the hierarchy (see Annex A of background report by Peuportier et al. 2023). To do so two methods have been implemented in the tool: (1) the GHG Protocol method (WBCSD & WRI 2007), considering a marginal mix corresponding to the 10% top ranked productions; (2) a more physical 2 steps model, evaluating the mix with and without the studied building, using a model representing the electric system (Roux et al., 2016). The marginal electricity mix can be defined for past years (historical mix) or for a long-term period (future scenario) (Frossard et al., 2020). Both the Canadian “Zero carbon” and Swedish NollCO2 frameworks present the hybrid use of the average and marginal electricity mix factor (Canada Green Building Council, 2020; Sweden Green Building Council, 2020). The emission factor for the average supply mix is used for estimating the GHG emissions from electricity use in the building. In contrast, the marginal emission factor approach is employed to determine environmental benefits from locally produced electricity exported to the grid. Both the Swedish and Canadian approach are based on the GHG Protocol method (WBCSD & WRI 2007). Sweden only considers short-term marginal (see Annex A of background report by Peuportier et al. 2023). Arguments behind the application of an “average”, “short-term marginal” or “long-term marginal” electricity mix” are provided in the background report by Peuportier et al. (2023).

Scope of operational impact assessment									
Country	**Building assessment approach and performance level**	**Building types coverage**	**B6.1**	**B6.2**	**B6.3**	**B7**	**B8**	**Assessment principle on GHG emission factor of the electricity mix**	**Approach to the aspect of 'time'**
Australia	Carbon neutral: whole buildings operation	All types excluding SF	X	X	X	X		Average	Static
	Carbon neutral: base building operation		X	X					
Canada	Zero carbon building	All types	X		X			Hybrid	Static
Finland	Method for the whole-life carbon assessment of buildings	All types	X					Average	Dynamic, because, during the RSP, energy-based emissions are expected to decrease as a result of the measures under Finland's National Energy and Climate Strategy.
France	EQUER	All types	X	X	X	X	X	Marginal	Dynamic, considering the hourly variation of emission factors from energy sources
Germany	Carbon Neutral building framework (DGNB)	All types	X	X	X			Average	Dynamic, considering dynamic emission factors for energy services
Norway	Zero-emission building: ZEB: O-EQ level	All types	X					Average	Dynamic, assuming the average value of electricity emission factor that is representative of a 60-year RSP, taking into consideration future evolutions in the European electricity generation towards 2050
	Zero-emission building: ZEB:O, ZEB: OM, ZEB: COM and ZEB: COME level		X		X				
New Zealand	A Zero Carbon Road Map for Aotearoa's Buildings	All types	X	X	X	X		Average	Static
South Africa	Net-zero and net positive carbon building: Level 1 (Base building emissions)	All types	X	X				Average	Static
	Net-zero and net positive carbon building: Level 2 (Occupant emissions)		X	X	X				
Sweden	NollCO2	All types	X	X	X	X		Hybrid	Dynamic, considering the future evolution of the electricity mix to be carbon-neutral in 2050
	Local Roadmap Malmö		X	X				Average	
United Kingdom	Net-zero carbon: operational energy and whole life	All types	X			X		Average	Static
USA	LEED zero carbon	All types	X	X	X	X	X	Average	Static

Zero Carbon Building	X	X	X	X

Table 3.5: System boundaries and approach to the time factor in operational impact assessment. Note SF = single-family houses.

By comparing the approach of the respective standard to the “time” factor in the operational GHGs emissions assessment, the significant variance was found. Six building assessment approaches follow the static approach with a constant emission factor of electricity or district heating used during the entire service life or reference study period, while seven frameworks present a dynamic approach. For example, in France, the EQUER method takes into consideration the dynamic approach by including an hourly variation of emission factors from energy sources, which provides a more accurate assessment of operational GHG emissions (mix dependent on use profile of the building under assessment). The rest five approaches follow a dynamic approach in the sense of considering the evolution of mix in the future. For example, the Swedish frameworks consider the further decarbonisation of the national electricity grid by 2050. A similar approach is proposed in Finland; however, here, the full decarbonisation of the electricity grid is expected to be achieved by 2120. The German example considers a reduction of the electricity emission factor from actual 589 gCO$_2$eq/kWh to 354 gCO$_2$eq/kWh in 2050. In contrast to the building assessment approaches, where the decrease of the energy-related emissions with the time is expected, in Norway, the ZEB framework uses the electricity emission factor (134 gCO$_2$eq/kWh), which is higher than actual values used for GHG emissions of hydro-dominant electricity (15 gCO$_2$eq/kWh) (if Norway was seen in isolation) and takes into account hourly export and import of electricity to/from Nordel and the European grid and also takes into account future decarbonisation of the grid (Statistic Norway,2019, Graabak &Feilberg, 2011, Georges et al., 2015).

The implementation of dynamic, electricity factors, which will take account of grid variations in GHG emission intensity is stated as a key priority for the future development of net-zero carbon framework in the UK (UKGBC, 2019). The GHG emission factor of electricity presents a strong influence on the relative contribution of embodied emissions to total GHG emissions (Georges et al., 2015) In case of a high emission factor, the operational GHG emissions dominate the embodied emissions, while low emission factor leads to the opposite case. The emission factors proposed in building assessment approaches, significantly influence the performance of zero-carbon buildings and the choice of optimal design strategies.

3.3.3 System boundaries scope and approach to the aspect of ‘’time”: Embodied part

By comparing the system boundaries covered in the building assessment approaches (Table 3.6), it can be indicated that the product stage (A1-A3) are the impacts included in the life cycle scope of embodied modules of all approaches, while construction (A4-A5) and replacement (B4) modules are the next most common ones (i.e. included in about 80 percent of the approaches). In relation to the remaining life cycle modules, a significant number of building assessment approaches do not take into consideration the impact coming from use and repair process (B1 and B3), and end-of-life process, i.e. demolition work (C1), transport from the site to disposal/waste treatment facility (C2) or waste management process (C3-C4). The reason for this exclusion may be often related to time-consuming calculations and significant remaining gaps in the availability of data on GHG emissions of related life-cycle phases (UKGBC, 2019). A solution for addressing this issue is presented in the Finish framework (Kuittinen, 2019) by introducing the generic, predefined GHG emissions values, which can be used in the case of unavailability of specific information. The Norwegian, (net) zero-emission building framework is the only one which includes different levels of performance requirements based on embodied, lifecycle modules scope.

Among the analysed building assessment approaches, module D (benefits and loads outside the system boundaries) is included in all the selected building assessment approaches. Furthermore, in the current draft of Sweden’s approach and the Norwegian definition, the potential benefits from reuse, recovery and recycling of building products are only reported as additional information (but all the rest approaches with D indicated aggregate it to end of life impacts). This way to deal with Module D (as additional information) is in line with current CEN TC 350 related European standards. The new versions of the related European standards recommend the effects of reuse, recovery and recycling to be assigned to module D1 – they therefore provide a new breakdown for module D into module D1 (Net flows from reuse, recycling, energy recovery and other recovery) and D2 (Exported utilities) – i.e. Figure 3.1 is based on EN 15643:2021. Table 3.6 shows only D1.

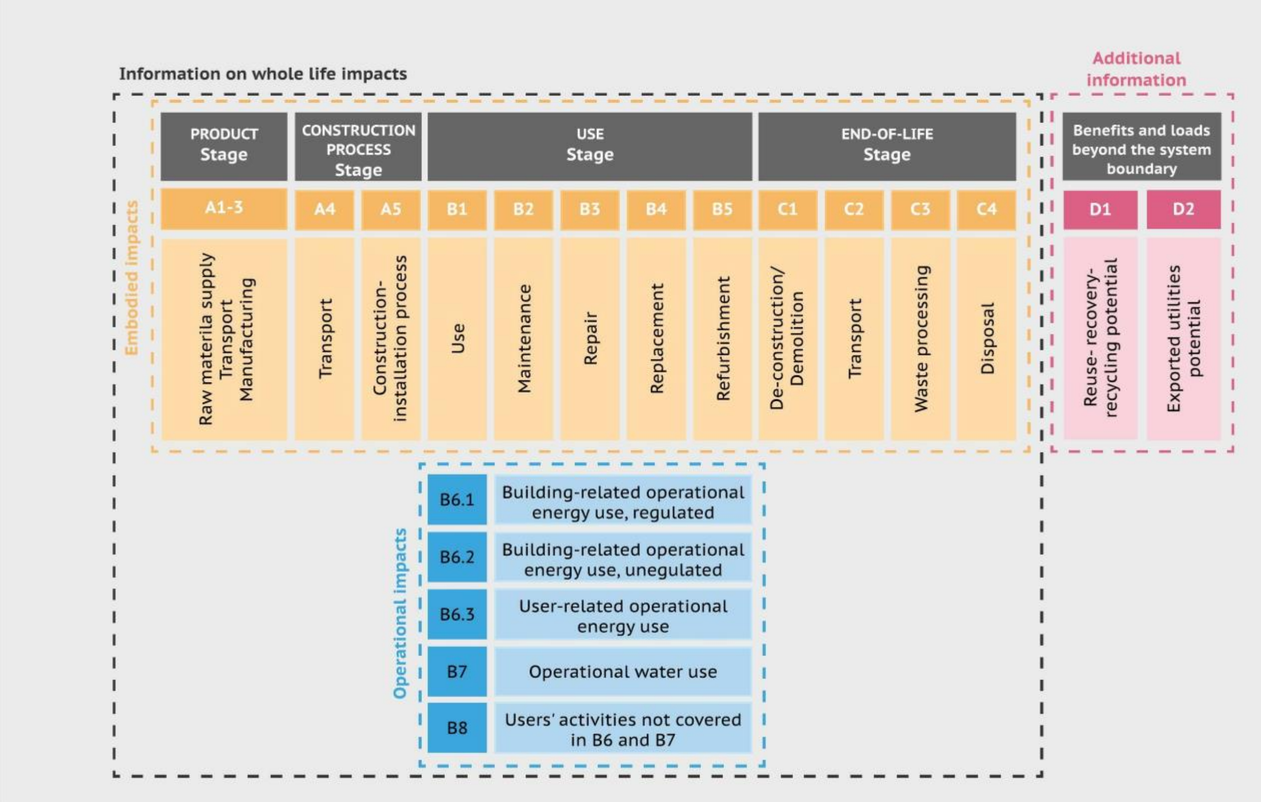

Figure 3.1: Modular approach of building life cycle impacts, distinguishing between the impacts arising from embodied (green dotted line) and operational aspects (blue dotted line). Adapted from EN 15643:2021.

Most of the methodological approaches described in analysed building assessment approaches suggest using the specific environmental product's declaration (EPD), supplemented by generic, national LCA database as the main data source for the calculation and reporting of lifecycle GHG emissions (Table 3.7). The need for reliable, country specific LCA database is highlighted in the Finnish and Swedish building assessment approaches, where a generic national LCA database is currently missing and currently under development.

A static approach to the "time" factor in embodied GHG emissions assessment during the building lifespan is evident in most of analysed building assessment approaches, (Table 3.7) except Sweden (NollCO$_2$ scheme), where GHGs emissions from the end-of-life stage (C1-C4) are assumed to be zero, due to the assumption of carbon neutrality taking into account the lifecycle of all activities up to 2050. The only exception from the static approach suggested in the Norwegian approach, is the environmental impact caused by the replacement of PV modules. Here, based on continues improvement of new technologies and material use, as well as, prospective LCA studies, the 50% reduction of GHGs emissions relative to product stage impact (A1-A3) is applied as a rule of thumb (Fufa et al., 2016; Georges et al., 2015).

Table 3.6: Included modules of embodied impacts in analysed building assessment approaches. Note 1: during the survey there was no D2 in place in standardisation. Module D is here shown in the meaning of new D1. Note 2: Following international and European standards D1 must be provided as additional information.

Country	Building assessment approach and performance level	A1 Raw material supply	A2 Transport	A3 Manufacturing	A4 Transport	A5 Construction-installation	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	C1 Deconstruction and demolition	C2 Transport	C3 Waste processing	C4 Disposal	D Reuse-Recovery-Recycling
Canada	Zero carbon building	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Finland	Whole-life carbon assessment of buildings	X	X	X	✓	✓			X	X		✓	✓	✓	✓	✓
France	EQUER	X	X	X	X	✓				X	X		X	X	✓	X
Germany	Carbon Neutral building standard (DGNB) Framework. Carbon neutral building throughout life cycle ambition	X	X	X			✓	X		X				X	X	X
Norway	Zero-emission building: ZEB: OM ambition	X	X	X				✓		✓						
	ZEB:COM ambition	X	X	X	X	✓		✓		✓						
	ZEB: COME ambition	X	X	X	X	✓		✓		✓		✓	✓	✓	✓	✓^{1}
Sweden	NollCO2	✓	✓	✓	X	X		✓	✓	✓	✓	✓	✓	✓	✓	✓^{1}
	Local Roadmap Malmö	✓	✓	✓	X	X	✓	✓	✓	✓		n/c	n/c	n/c	n/c	
United Kingdom	Net zero carbon construction	✓	✓	✓	✓	✓										
	Net zero carbon whole life	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
USA	Zero Carbon Building	✓	✓	✓	✓											✓

X – included with details, ✓ - included without details, n/c- not clear, ^{1}only as additional information

Table 3.7: Main LCA data source and approach to the “time” factor in building assessment approaches

Country	Standard and performance level	Reference to LCA calculation standard, tool, or database source	Approach to ’time” factor
Canada	Zero carbon building	No specific recommendations, however, the Athena Impact Estimator and Tally LCA tools are mentioned	Static
Finland	Whole-life carbon assessment of buildings	Reference to the national method of whole life cycle carbon assessment of buildings and generic LCA database (under development).	Static
France	EQUER	Ecoinvent data base	Static
Germany	Carbon neutral building throughout life cycle ambition	ÖKOBAUDAT, GEMIS and other possible data sources, such as environmental product (EPD) declarations following EN 15804 standard are referred.	Static
Norway	Zero-emission building:	Specific (EPD) data from EPD-Norge. When EPDs are not available, generic Life Cycle Inventory (LCI) data from Eco invent is used.	Static, except PV modules, where a 50% reduction of embodied emissions during replacement phase is assumed
Sweden	NollCO2	Generic national database (under development) and EPD declarations	The method assumes that all life cycle activities 2050 will be carbon neutral; that’s why the impact of the end-of-life module (C1-C4) is considered equal to zero
	Local Roadmap Malmö		Not clear
United Kingdom	Net zero carbon construction and whole life	RICS Professional Statement “Whole life carbon assessment for the built environment” 2017, (tools not specified yet, OneClick LCA is expected to be recommended in future)	Static
United States of America	Zero Carbon Building	Carbon data should be sourced from EPDs verified as outlined in ISO 14025 Standard. Approved LCA tools: Athena Impact Estimator, eTool, One Click LCA, Tally, Environment Agency’s Carbon Calculator	Static

3.3.4 Verification of net-zero GHG emissions performance

Most of the reviewed building assessment approaches mandate the verification of net-zero GHG emissions performance of designed buildings using on-site metered data during the first year of building operation. It can be argued that this is insufficient; verifying the energy performance of a building is more complex than just measuring the consumption, which depends on climatic variation (the actual heating bill may be higher than estimated because of a colder year) and on occupants' behaviour (the actual heating bill may be higher because of a high thermostat set point rather than because of a poor building performance). Appropriate protocols (e.g. International Performance Measurement and Verification Protocol) have been defined and tools have been developed (e.g. see (Ligier et al., 2017). However, verification of embodied GHG emissions calculation using actual bills of quantities of construction materials and products, as well as, metered energy used for the actual on-site construction process, is not common among the building assessment approaches. The detailed information is presented in Table 3.8.

Table 3.8: Overview of verification requirements in analysed GHG emissions-based building assessment approaches

Country		**Verification requirements**				
	Building assessment approach and performance level	**Energy performance by on-site measurements**	**Indoor climate**	**Construction material inventory**	**LCA**	**Other**
Australia	Carbon neutral: whole buildings operation	X	n/c			
	Carbon neutral: base building operation	X	n/c			
Canada	Zero carbon building	X	n/c	X		Airtightness and peak demands
Finland	Method for the whole-life carbon assessment of buildings					
France	EQUER	X				Tool for energy performance verification
Germany	Carbon Neutral building standard (DGNB) Framework	X	X	X		User satisfaction, mobility, economic quality
Norway	Zero-emission building: ZEB: O-EQ level	X	X			
	Zero-emission building: ZEB:O, ZEB: OM, ZEB: COM and ZEB: COME level	X	X	X	X	
New Zealand	Carbon Zero Building Operations pilot scheme as a part of Zero Carbon Road Map for Aotearoa's Buildings	X				
South Africa	Net-zero and net positive carbon building: Level 1 (Base building emissions)	X	X			
	Net-zero and net positive carbon building: Level 2 (Occupant emissions)	X	X			
Sweden	NollCO2	X	X	X	X	Complementary commercial certification
	Local Roadmap Malmö	n/c				
United Kingdom	Net-zero carbon: operational energy and whole life	X				
USA	LEED zero carbon	X	X			

	Zero Carbon Building	X	X	X

3.3.5 Options and principles of GHG emissions balancing and offsetting

The overview of the allowed options for GHG emissions balancing and/or offsetting by analysed building assessment approaches is presented in Table 3.9.

Table 3.9: Options for balancing and/or offsetting allowed in analysed building assessment approaches.

Type of reduction and compensation options following the broad categories of Table 2.4		Potentially "avoided" GHG emissions elsewhere from exported part of renewable energy generation Type A.a					Type A.b	Type B	Type C	
Country	**Name of building assessment approach**	**On building area**	**On-site from on-site renewables**	**On-site from off-site renewables**	**Off-site generation**	**Off-site supply**		**Technical reduction**	**Technical removal**	**Timing of GHG emissions balancing and/or offsetting**
Australia	Carbon neutral	X	X	X	X[2]	X[2]		X		Annually
Canada	Zero carbon building	X	X	X	X	X		X		Annually
Finland	Whole-life carbon assessment of buildings	X	X	X						Annually
France	EQUER	X	X	X	X	X				Building lifetime
Germany	Carbon Neutral building standard (DGNB) Framework	X	X	X						Annually
Norway	Net Zero-emission building	X	X	X						Building lifetime
New Zealand	A Zero Carbon Road Map for Aotearoa's Buildings	X	X	X	X	X		X[1]	X[2]	Annually
South Africa	Net-zero and net positive carbon buildings	X	X	X	X[3]	X[3]		X[3]		Annually
Sweden	NollCO2	X	X	X	n/c	n/c		X[4]	X	Building lifetime
	Local Roadmap Malmö	X	X	X					X[5]	Building lifetime
United Kingdom	Net-zero carbon	X	X	X	X[3]	X[3]		X[3]		Annually
USA	LEED Zero Carbon	X	X	X	X	X		X		Annually
	Zero Carbon Building	X	X	X	X	X		X[6]	X[7]	Annually

X – Allowed option,

[1] Carbon reduction programs in developing countries

[2] Reforestation, carbon sequestration investments

[3] The on-site renewable generation is prioritised,

[4] Life cycle GHG emissions can be offset by implementing energy efficiency measures in other existing buildings,

[5] Carbon capture and storage,

[6] Renewable energy projects, and landfill gas-to-energy projects, where the methane would otherwise be released to the atmosphere.
[7] Reforestation projects

The building assessment approaches in Australia, Canada, France, New Zealand, South Africa and UK allow balancing the lifecycle GHG emissions by potentially "avoided" GHG emissions outside the system boundaries of the buildings life cycle from the generation of renewable energy from both on-site and off-site levels of system boundaries in line with. However, in the case of Australia, UK and South Africa, the building assessment approaches suggest prioritising the on-site energy generation. By contrast, according to the building assessment approaches from Finland, Germany, Norway and Sweden, the production of renewable energy must be located on-site, with the additional possibility of using the off-site renewables (e.g. biofuels) for production energy on-site.

According to available information in the, all approaches used in the selected frameworks, the exported energy-related benefits, namely avoided GHG-emissions outside the system boundaries become a part of the GHG-emissions balance and contribute to net-zero-emissions approach, which is in line with A.a approach (Lützkendorf & Frischknecht, 2020). This approach is not in line with current standards, which requires that environmental benefits and loads coming from exported energy should be included as additional information in module D. Consequently, there is a need to address these methodological issues.

Recognised removal offset possibilities (Type C from Table 2.4) mainly include reforestation programs and carbon sequestration investments. In the case of building assessment approaches, which allow offset of GHG emissions through reduction projects, the focus is on either implementing energy efficiency measures in existing, surroundings buildings or the purchase of off-set credits, with the priority given to carbon credits units traded in the national market.

4. Discussion and Recommendations

The previous section showed large differences in all the thematic areas examined in this A72 survey. This complicates the comparison of approaches and statements. General recommendations which should be included in the further development of the country-specific assessment approach or definition of net-carbon/emission buildings are presented below:

- **To ensure transparency in published results**: the respective assessment method of (net) zero GHG emissions must describe the definitions, system boundaries, data bases, rules for calculation, emission balancing, emission offsetting via emission reduction or CO_2 removal, and verification rules in a transparent and comprehensive manner. This information should be public and freely accessible. Since net zero GHG emissions is a benchmark, the above preconditions make its achievement provable. To assist in this direction, a checklist adapted from ISO 21678:2020 to also include 'net zero' benchmarks is shown in Table 4.1. In this sense, this standard should be supplemented in future further developments. Moreover, as far as possible, the suggestions made here for classification in a typology should be adopted.
- **To ensure a wider adoption of the (net) zero GHG emissions target**: the current, voluntary and new (net) zero GHG emissions building assessment approaches should be integrated into national and local policy frameworks (Passer et al., 2020) with the aim to significantly increase the share of (net) zero GHG emissions buildings in the building stock. This action should be supported by voluntary building certification schemes, which should recognise the (net) zero GHG emission concept as the next and more ambitious goal. Focusing on operation is no longer sufficient, comprehensive (i.e. life-cycle-based) (net-) zero-emission building targets are needed by 2025, if 2050 emission targets are to be achieved (Lützkendorf and Frischknecht 2020).
- **To establish minimum levels of ambition and increase the effectiveness in terms of the contribution to the fulfilment of the Paris Agreement:** it is advised that the complete scope of the B6 modules (B6.1, B6.2, and B6.3) impacts is included in a net zero emission building approach at the minimum to be able to represent the self-consumed share of the energy generated on-site in a more complete fashion. Additionally, the building design and construction should follow the minimum requirements for the embodied emissions part based on national benchmarks being developed. At the moment, various net-zero carbon/GHG emissions building definitions show different approaches in terms of the performance target level and the selected scope for the system boundary. The difference in performance levels should be transparently reflected in the naming of the net zero emission buildings.
- **To verify the benchmark fulfilment at post-construction:** for the operational part, the real performance assessment of declared net-zero GHG emissions buildings during use stage should be mandatorily verified during building operation by on-site energy monitoring system. The verification shall be realised on annual basis and not only the first year of operation. Dynamic GHG emission factors of energy sources of the highest resolution possible and available by the specific energy provider should be used. In case of life cycle-based net zero emissions benchmarks, it is also important to verify the material quantities in the embodied emissions calculations in the "as-built" condition. Finally, the GHG emission offsets purchased or invested in shall be verified and compared against the carbon footprint of the building. Up to the point of verification of at least the first years of real operation and the offsetting of real upfront emissions, one can only talk about a 'net zero' in progress than an actual 'net zero' status.
- **To avoid excess use of offsetting measures:** the following prioritisation of measures shall be followed for both new and existing buildings: (1) implementation of operational energy efficiency measures controlled through setting energy use intensity targets (EUI) as well as low embodied carbon measures controlled through benchmarks. These requirements should prevent buildings which are highly energy inefficient and have not performed all the necessary actions to reduce their overall carbon footprint from achieving the net-zero carbon/GHG emissions performance target level by applying above-average offsetting measures; (2) implementation of on-site renewable energy sources; (3) purchase of low

emission off-site renewable energy services and construction products and (4) offsetting measures. Additionally, in the case of net zero solutions, it is suggested to indicate the parts of the balance - in the sense of +10/-10 kg CO_2eq/m²a or +50 /-50 kg CO2 eq/m²a. Therefore, the two sides of the balance should be always provided separately. This is also in line with ISO 16475-1 (2017). Additionally, the type of balancing and offsetting should be clearly stated.

- **To prevent from choosing the low-hanging fruit:** The building assessment approaches should allow for a variety of balancing and offsetting solutions, and not only focus on on-site renewable generation solutions, as this strategy is mainly suitable for new and relatively small buildings. A clear priority ‘order’ of balance, reduction and removal solutions shall be provided. When on-site renewable generation is not sufficient to cover the operational energy needs of a building, off-site renewable energy generation with additionality and bundled EACs shall be prioritized over other off-site options (if at all allowed). It shall be clearly stated how the potentially avoided emissions by third parties as a result of exported energy shall be handled. Additionality principles shall be clearly stated, as well as a central list of suppliers providing additionality shall be collected and provided. Offsetting shall be limited to the most hard-to-reduce areas, such as Scope 3 emissions, to encourage a focus on emissions reduction. A list of allowable and acceptable offset possibilities in a definition of net zero GHG emission buildings shall be provided. To compensate for residual/unavoidable GHG emissions (after all reduction possibilities on the building itself have been exercised), it is advisable to prioritise carbon removal offsets over reduction offsets over balancing approaches via avoided GHG emissions to the extent possible.
- **To adapt the definition to future changing conditions**: resilience of net zero GHG emissions buildings design should be a key design asset, taking into consideration the future scenarios assuming a constant reduction of GHG emissions intensities of electricity mixes towards (nearly) zero and increased use of intermittent renewable sources of energy, like solar or wind.
- **To enlarge system boundary from building to urban district:** there is a need to move the object of assessment in the form of a single building to broader scope including neighbourhood, city or even national building stock to facilitate GHG emissions reductions at a larger scale. This is important since it allows neighbourhoods / cities / nations to make exceptions for specific building cases which cannot achieve a net zero GHG emission level in a technically feasible manner if other buildings can compensate.

Table 4.1: Checklist for the documentation and communication of benchmarks. Note: Rows A.03 + A.04 cover the functional equivalent description; Row B.05 is only relevant for budget-based benchmarks, while B.06-09 are only relevant for net zero benchmarks (see also Lützkendorf et al. 2022).

PART A	**Basic information**	**Example**
A.01	Name of the indicator	*Greenhouse gas (GHG) emissions*
A.02	Level(s) in the benchmark system	*Target value*
A.03	Type of building (function and new, refurbished or in-use)	*Office buildings, New construction*
A.04	More detailed specification if applicable (period and pattern of use)	*Period and pattern of use 5 days/week, 10 hours/day*
A.05	Reference unit	*(kg CO_2eq./m^2) x year* *m^2 based on Gross Internal Floor Area* *'year' based on the number of years defined in the reference study period (RSP)*
A.06	Region/Climate zone of validity	*Germany/ Climate zone III*
A.07	Period of validity	*From 2020 to 2025*
PART B	**System boundaries and methods**	**Example**
B.01	Explanation of methods and data bases	*Following the calculation rules of standard XX* *Data base: Ökobaudat 2017a for construction products, energy services and transport services*
B.02	Building elements/ parts covered (i.e. building model completeness)	*All building elements and services*
B.03.a	Life cycle stages covered (i.e. life cycle model completeness based on the modular structure in EN 15978:2021)	*A1-C4*
B.03.b	Parts of operational energy use covered in detail (B6.1, B6.2 & B6.3)	*B6.1 (heating, cooling, ventilation, hot water supply, lighting)*
B.04.a	Assumptions, defaults, and choices for A4-5 (if covered)	*Average transport distance of 100 km*
B.04.b	Assumptions, defaults, and choices for B1 (if covered)	*e.g. F-gases ignored or included or there are specific rules for selection of products in place*
B.04.c	Assumptions, defaults, and choices for B2-3 (if covered)	*based on date for single processes based on maintenance plan or default values*
B.04.d	Assumptions, defaults, and choices for B4-5 (if covered)	*Reference study period 50 years* *25 years assumed service life for windows, PV panels, etc.* *No technological progress considered (e.g. in relation to future production efficiency of products, etc.)*
B.04.e	Assumptions, defaults, and choices for B6.1	*Average, national annual supply electricity mix (static)*
B.04.f	Assumptions, defaults, and choices for B6.2-3 (if covered)	*Average, national annual supply electricity mix (static)*
B.04.g	Assumptions, defaults, and choices for B7 (if covered)	*average or specific data for LCA for water supply and wastewater treatment*
B.04.h	Assumptions, defaults, and choices for B8 (if covered)	*scenarios for mobility of users*

B.04.i	Assumptions, defaults, and choices for C1-2 (if covered)	*based on process related data or default values*
B.04.j	Assumptions, defaults, and choices for C3-4 (if covered)	*Taking into account current average situation*
B.04.k	Assumptions, defaults, and choices for D1 (if reported)	*Same as above*
B.04.l	Other assumptions and choices (e.g. biogenic carbon, discounting of future emissions, etc.)	*-1/+1 for biogenic carbon,* *No physical discounting*
B.05	Assumptions and choices only relevant for top-down budget-based target values	*Global budget chosen* *Effort-sharing principle chosen to derive the country budget* *Effort-sharing principle chosen to derive the sector budget*
B.06	Allowable types of balancing and/or offsetting (as per Table 5.2 in Lützkendorf et al. 2022) for the different life cycle stages and modules incl. the hierarchy	*Type Aa for B6.1-3* *Type C for A1-5, B4 and C*
B.07	Timing of balancing and/or offsetting for the different life cycle stages and modules	*A1-5, C1-4: Offsetting at practical completion based on actual bill of materials and product-specific emission factors for A1-5 (for C1-4 modelled data are used)* *B1-5: Annually in use offsetting* *Upstream impacts (Scope 3) of B6.1-3, B7: Annually in use offsetting*
B.08	Side requirements for allowable renewable energy procurement options incl. the hierarchy	*Only physical or corporate PPAs in the case of off-site RE generation – if this requirement is fulfilled provider-specific emission factors can be used*[6]
PART C	**Source and type of information**	**Example**
C.01	Source of data if bottom-up (incl. sample size and age)	*Calculated data based on design stage analyses (modelled building variants)* *100 buildings* *Data from 2016-2018*
C.02	Statistical values chosen for the representation of the benchmark (if bottom-up)	*95th Percentile as a target value*
C.03	Source of target if top-down (standard/ political goal/ global goal or budget)	*Not applicable*

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[6] If green electricity is connected to the grid, one should think of using the residual mix.

5. Conclusions

During the past few years, the attention given to reducing operational energy demand and resulting environmental impacts in the construction sector has increased significantly. In many countries, national governments have established mandatory policy frameworks, introducing nearly-zero energy buildings in operation as their main building-stock ambition. The government incentives are often supported by voluntary certification schemes, which are meant to push building ambitions to reach a (net) zero-energy building level in operation where the total amount of operational energy used by the building is covered mainly by renewable energy generation typically on an annual basis.

However, in order to achieve carbon neutrality in the construction and real estate sector by 2050 or earlier, and at the same time, meeting climate Paris Agreement Goals, there is a need for accelerating decarbonisation in the area of action “buildings” by developing and implementing the net-zero GHG emissions buildings (operation or life cycle-related) approach which introduces GHG emissions as one of the primary performance indicators and formulates requirements for climate neutrality in the whole lifecycle.

Based on the current review of 35 building assessment approaches, this report identifies 13 voluntary frameworks in 11 countries, which are characterised by net-zero carbon/GHG emissions performance targets. There is a significant variance in methodological principles and approaches between these frameworks. In order to rule out interpretation misunderstanding and greenwashing, key methodological factors from building assessment approaches are identified, explained and analysed.

Particularly, the results of the survey identified that the definition type, scope of system boundaries, choice of an average vs marginal emission factor for the electricity mix, approach to the aspect of “time” and options for offsetting are the most important issues, which should be carefully considered before developing and defining a harmonised (net) zero GHG emissions building framework.

Most likely, variations found in the existing schemes in ways of thinking about a common theme - (net) zero greenhouse gas emissions buildings – will continue to exist. These variations raise some important questions on how this concept is evolving. At the minimum, a typology of system boundaries and other dimensions, as presented in this report, can foster transparency and, consequently, the credibility of current approaches.

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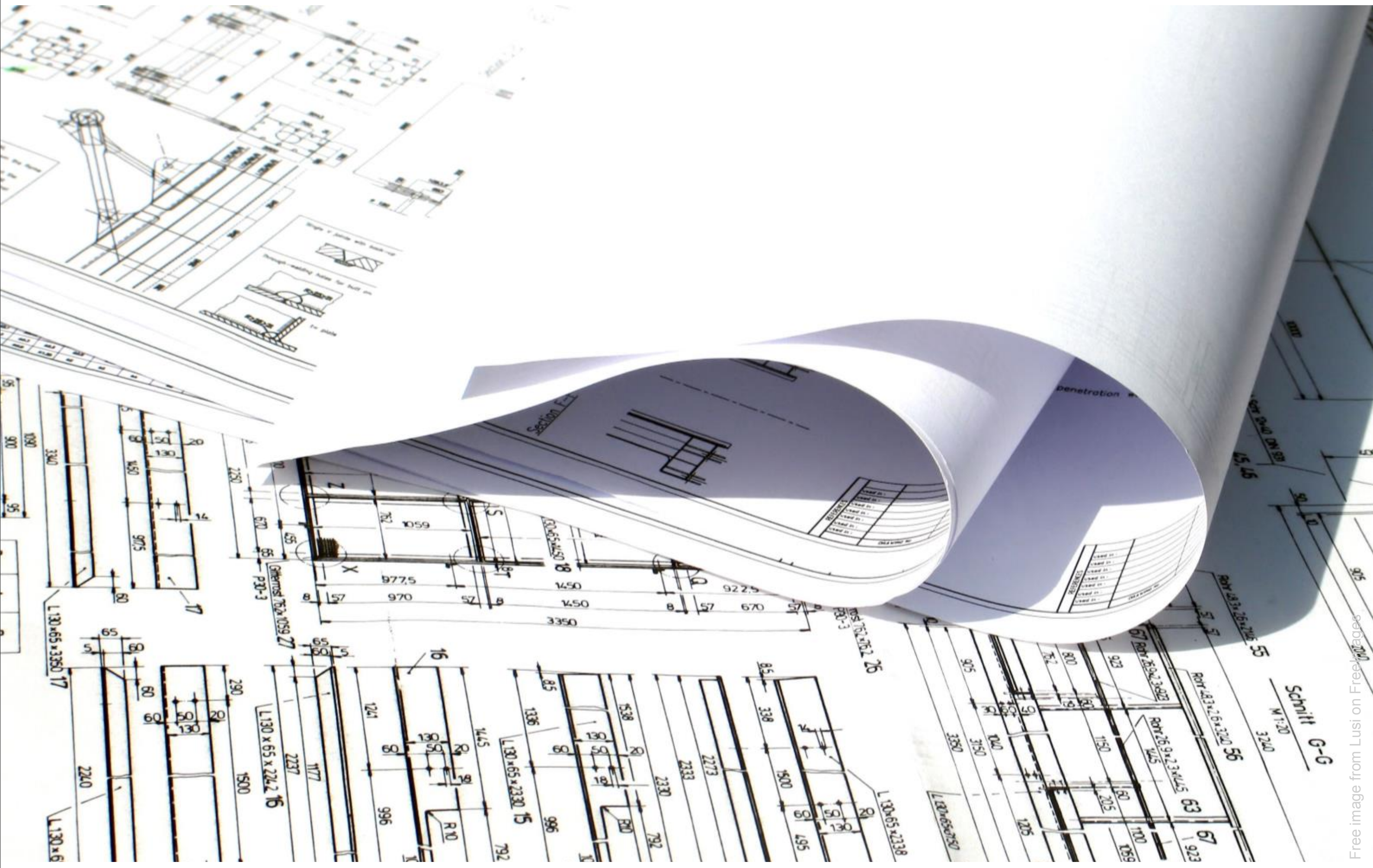
Potentials and requirements for implementing LCA across different design steps, project phases and life cycle stages

A Contribution to IEA EBC Annex 72
Part 1 - Common definition of design steps & project phases

April 2023



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International Energy Agency

Potentials and requirements for implementing LCA across different design steps, project phases and life cycle stages

A Contribution to IEA EBC Annex 72
Part 1 - Common definition of design steps & project phases

April 2023

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Abbreviations and Glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_2eq	CO_2 equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period

ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines
ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]

Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process
Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Introduction

To provide a common basis for the related activities of the different subtasks, this report presents:

- a set of terms and definitions of project management phases and building design steps in relation to life cycle stages of construction works as well as milestones from perspective of building design professionals based on the current plans of work and definitions used in the participating countries. This includes the specification and description of terms and definitions as well as additional insights into the national situation of selected countries.

Objectives

This document relates to a joint activity of ST1 and ST2. It serves to offer terms and definitions of phases in the project management process as well as steps[1] in the building design process for new construction and retrofit/refurbishment projects. Those terms and definitions shall provide the basis for:

- an assignment of methodological questions, rules and recommendations for action in individual design steps, with particular attention to earlier and later project phases (pre-/post-design) as well as the tasks related to the documentation and handover of buildings (in the context of ST1)
- a discussion of different approaches for integrating environmental assessment along the design process, including questions of responsibilities, flow of information and information exchange requirements as well as possible ways of presenting results (in the context of ST2)
- an allocation of environmental assessment tools and workflows to individual design steps (in the context of ST 2)
- an assignment of case studies to individual project phases and/or design steps where necessary and sensible (in the context of ST3)
- a discussion on the suitability of data and databases for calculation and evaluation tasks in different design steps (in the context of ST 4).

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[1] Also known as design stage (like early design stage) or design phase

1. Basic concepts

1.1 Project management, design process, building life cycle – different perspectives on one object of assessment

An important basis for understanding the potentials and requirements for implementing environmental performance assessments (such as the use of LCA) along the design and decision-making process is an appropriate definition of the design steps and milestones (decision-situations). Such a definition of the design steps and milestones enables the assignment of related tasks, available information and data, useful tools and deliverables from the perspective of specific professionals. The starting point of such considerations is the choice of a perspective and system boundaries. If considering the full life cycle of a building from a project-management perspective, post-design life cycle stages such as the use phase (building operation, maintenance and replacement), building retrofit or refurbishment, as well as decommissioning at the end of the service life, have to be addressed. If, on the other hand, the focus is put exclusively on the design and construction process, e.g., from the perspective of architects and engineers as well as construction companies, it may suffice to address exclusively the design steps. The perspective chosen here is a combination of both approaches. It should allow addressing the initial design process as well as design interventions embedded along the life cycle of a building, such as, re-design or extension, refurbishment and, as well as – eventually – the design and management for a controlled decommissioning process towards re-use and recycling.
Figure 1 shows the phase model of a project management process parallel to the design process and physical life cycle of a building. It becomes clear that the development of the design task (project identification/clients brief), the building design and its realization (i.e., construction, use stage) are part of one overall process.

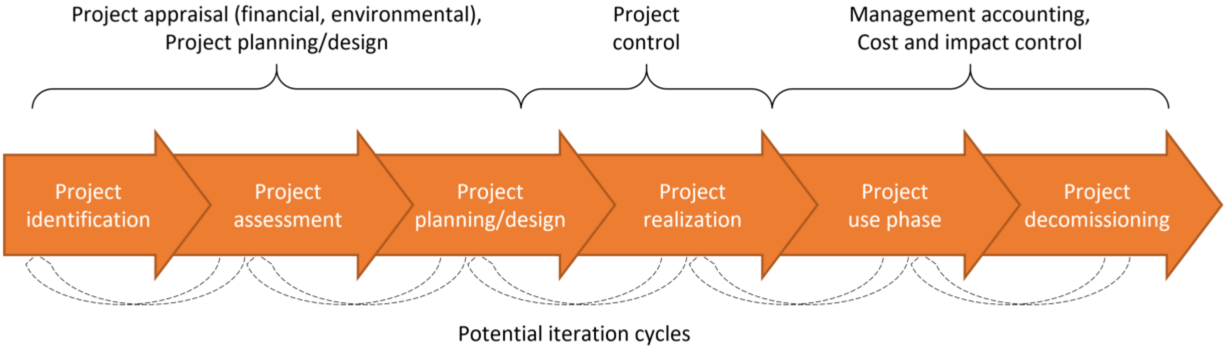

Figure 1: Project management process and building life cycle

1.2 Methodology for developing a common definition

The definition of a generic model of steps in building design and phases / milestones in the management process, which offers a common basis for the participating Annex countries, followed a four-iteration approach:

1) A survey amongst participating Annex countries asking to document the structure and definition of design steps and milestones as well as related tasks and deliverables for their respective country;
2) An analysis of existing and well-established definitions of design steps and project phase models;
3) The synthesis of 1) and 2) to propose a generic definition as a common reference for Annex 72;
4) The option for Annex countries to review their definitions with reference to the common model for future refinement and revision towards increased harmonization.

2. Common definition of design steps, tasks and milestones

2.1 Survey amongst Annex participants

Using a spreadsheet-based survey, the design and project step[2] definitions were compiled for 13 countries. Respondents from participating countries were asked to provide the definitions in their respective country, including a detailed description of the tasks and deliverables. Furthermore, participants reported on the presence and timing of relevant milestones, which provide a potential for the implementation of environmental target setting, environmental performance assessment and reporting of environmental performance assessment results. Five milestones were suggested for allocation:

(1) Definition of environmental performance targets
(2) Architectural design competition
(3) Building permit application
(4) Procurement of construction works
(5) Hand over and commissioning
(6) Decommissioning and deconstruction

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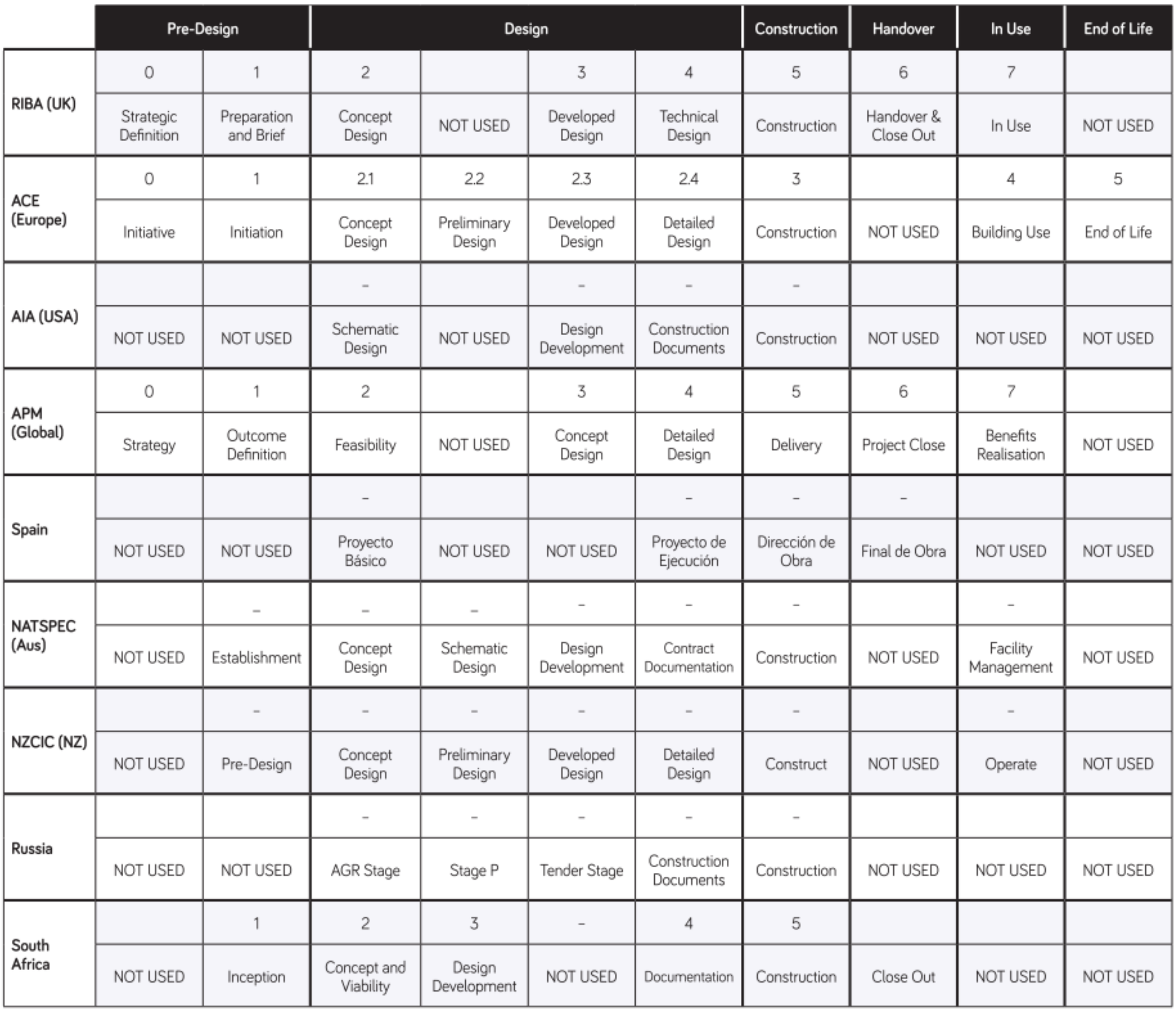
[2] Often called design phases in the national definitions

2.2 Analysis of existing definitions



	Pre-Design		Design				Construction	Handover	In Use	End of Life
RIBA (UK)	0	1	2		3	4	5	6	7	
	Strategic Definition	Preparation and Brief	Concept Design	NOT USED	Developed Design	Technical Design	Construction	Handover & Close Out	In Use	NOT USED
ACE (Europe)	0	1	2.1	2.2	2.3	2.4	3		4	5
	Initiative	Initiation	Concept Design	Preliminary Design	Developed Design	Detailed Design	Construction	NOT USED	Building Use	End of Life
AIA (USA)			-		-	-	-			
	NOT USED	NOT USED	Schematic Design	NOT USED	Design Development	Construction Documents	Construction	NOT USED	NOT USED	NOT USED
APM (Global)	0	1	2		3	4	5	6	7	
	Strategy	Outcome Definition	Feasibility	NOT USED	Concept Design	Detailed Design	Delivery	Project Close	Benefits Realisation	NOT USED
Spain			-			-	-	-		
	NOT USED	NOT USED	Proyecto Básico	NOT USED	NOT USED	Proyecto de Ejecución	Dirección de Obra	Final de Obra	NOT USED	NOT USED
NATSPEC (Aus)		-	-	-	-	-	-		-	
	NOT USED	Establishment	Concept Design	Schematic Design	Design Development	Contract Documentation	Construction	NOT USED	Facility Management	NOT USED
NZCIC (NZ)		-	-	-	-	-	-		-	
	NOT USED	Pre-Design	Concept Design	Preliminary Design	Developed Design	Detailed Design	Construct	NOT USED	Operate	NOT USED
Russia			-	-	-	-	-			
	NOT USED	NOT USED	AGR Stage	Stage P	Tender Stage	Construction Documents	Construction	NOT USED	NOT USED	NOT USED
South Africa		1	2	3	-	4	5			
	NOT USED	Inception	Concept and Viability	Design Development	NOT USED	Documentation	Construction	Close Out	NOT USED	NOT USED

Figure 2: Comparison of international plans of work (RIBA 2020 [Royal Institute of British Architects (RIBA), 2020]).

The responses from Annex participants were reviewed in comparison with the well-established building design step? definition of the Royal Institute of British Architects (RIBA). The RIBA Plan of Work (RIBA 2020 [Royal Institute of British Architects (RIBA), 2020]) was considered well suited for the purpose of providing a generic definition of design phases or steps, core objectives and related tasks of individual design professionals in the various design steps. In the 2020 version of its Plan of Work, RIBA presents a comparison with other international building design and project phase definitions (Figure 2). These checkpoints have been further integrated in the 2020 version.

The 2020 RIBA Plan of Work itself defines eight design and project phases, and for each phase the expected outcomes, core tasks as well as exchange requirements, among other aspects (See Appendix Figure A5).

2.3 Synthesis: Proposal for harmonized terms and definitions

2.3.1 Mapping of design step and project phase definitions

As highlighted in the initial phase / step model concept (Figure 1), the various decisions relevant for improving the performance of buildings across their life cycle are not limited to design steps. They include other relevant stages of the building life cycle, such as the construction stage, the use stage – including maintenance and interventions, such as modernizations and refurbishments – as well as, eventually, the decommissioning of the building for recycling and end-of life treatment.

The survey showed that most countries are structuring design steps,project phases and related tasks based on a more refined structure than initially suggested. Based on the findings of the survey as well as the review of existing definitions from RIBA, this report hence proposes a generic definition of five design steps, including the pre-design (0-5) and three post-design steps (6-8) incl. definition of related key tasks (Figure 3).

0	1	2	3	4	5	6	7	8
Strategic definition	Preliminary studies	Concept design	Developed design	Technical design	Manufacturing and construction	Handover and comissioning	Operation and management	End of use, re-cycling
Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, Construction and supervision	As-built documentation, hand over, comissioning and testing	Facilities Management and Asset Management, Evaluation and improvement of building performance	Decommissioning of the building, deconstruction, reuse and recycling

Figure 3: Common definition of design steps and project phases with related key tasks.

Based on the responses to the survey amongst Annex participants, a mapping of the generic definition of design steps and project phases with the national definitions was prepared (Figure 4). This mapping aims at providing a visual overview for Annex countries to relate their national situation and definitions to the general definitions and recommendations formulated in the works of IEA EBC Annex 72.

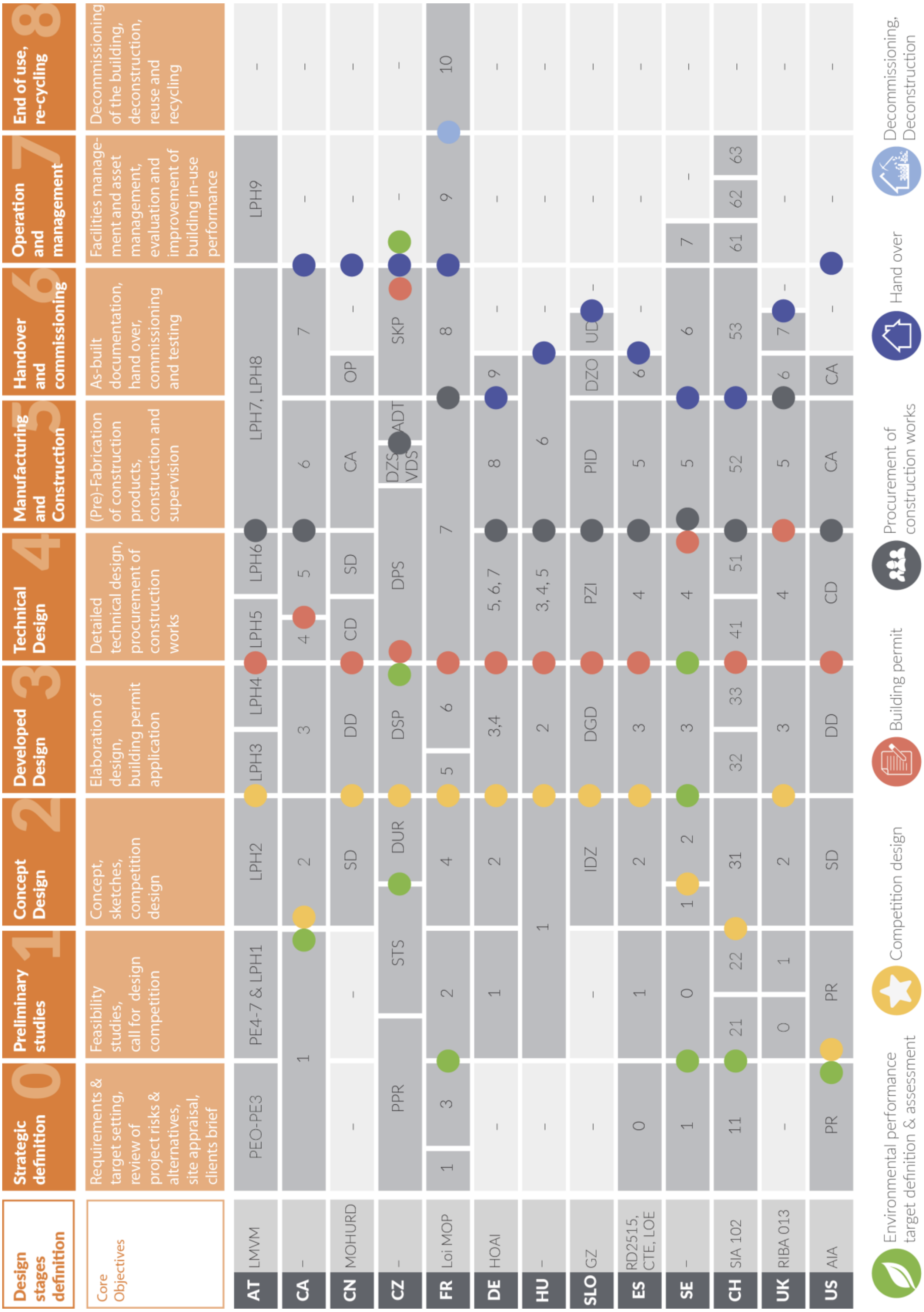


Figure 4: Overview and mapping of the common definition of design steps and project phases and typical tasks in relation to specific design tasks and milestones in the participating Annex countries.

2.3.2 Milestones for improving environmental performance

The milestones proposed in the survey were localised within the mapping of the common and national definitions from Annex countries (Figure 4). The majority of participating countries stated and allocated existing milestones related to '*design competition*', '*building permit application*', '*procurement of construction works*' as well as '*hand over and commissioning*'. At the same time, only very few countries to-date explicitly specify milestones for '*environmental target definition*' as well as '*decommissioning and deconstruction*'.

In order to implement environmental target setting, assessment and reporting (e.g., energy performance, carbon performance) along building design and project phases in the future, a set of milestones and related tasks are proposed (Table 1).

Table 1: Milestones and related tasks for implementing environmental performance assessment into the design-, decision making-, and facility management process of

Milestone	**Description of proposed tasks**
Environmental performance target definition	• Initial definition of the design task, related environmental performance targets by the client, as well as identification of related environmental requirements by laws and standards
Architectural design competition	• Definition of environmental targets (e.g., carbon budgets) as part of the call for design proposal • Requirement for design competition entries to provide an assessment of environmental impacts (screening assessment) • Sustainability assessment "new construction vs. refurbishment"
Building permit application	• Environmental assessment (pre check) based on a defined energy and material concept (type of structure, estimation of main construction material quantities and energy consumption for building operation) - based on a design for environment and design for deconstruction approach • Evaluation of environmental target fulfilment through public authorities as part of the building permit application process
Procurement of construction works	• Tender to include environmental requirements for construction products and building systems in-line with the specified environmental targets
Hand over and commissioning	• Commissioning / bringing into service, monitoring and refinement of the building's environmental performance in use
Use, operation management	• Continuous assessment and improvement based on monitoring, user satisfaction surveys, sustainability assessment "in use"
Decommissioning and deconstruction	• Pre-deconstruction audit, plan for deconstruction • Decommissioning and deconstruction of the building towards re-use and recycling as well as end-of-lie treatment in-line with life cycle scenarios underlying previous environmental assessments

The coherent definition of environmental targets by example of 'carbon budgets' has been the subject of a recent article by Habert et al. [Habert et al., 2020] with multiple contributions on the topic presented in the related special issue of Buildings & Cities (https://bit.ly/32sohGP).

3. Conclusions and recommendations

The definition of the design steps,milestones and related tasks, as well as deliverables may differ across building design and construction projects, as they are subject to agreement amongst the project partners. The presented generic terms and definitions offer a common understanding of the relevant steps, project phases, milestones and tasks for fostering the implementation of environmental assessment along the building design process and project phases in the participating Annex countries.

The common definition of the design steps and project phases as well as related core tasks should serve as guidance for the description and development of building assessment workflows and tools (ST2). Furthermore, it provides a framework for discussing the available information and appropriate assessment methods, and how these affect the inherent uncertainty of conducting environmental performance assessments in specific design steps and project phases (ST1).

This definition of the design steps and milestones represents a common systematic for structuring the building project cycle, that goes beyond the mere design process. It provides an overview of the core tasks as well as relevant milestones for implementing environmental targets in the process of an environmental performance assessment. Furthermore, the common understanding of the design process, specific milestones in the decision-making process and related tasks enables participants but also other actors to relate the current practice in their countries to a common structure. It supports learning from experiences in other countries, enabling the exchange of expertise and providing a common basis for future research, as well as for the clarification and further development of national definitions.

References

Habert G, Röck M, Steininger K, Lupisek A, Birgisdottir H, Desing H, et al.: Carbon budgets for buildings: Harmonizing temporal, spatial and sectoral dimensions. Build Cities 2020;1–24.

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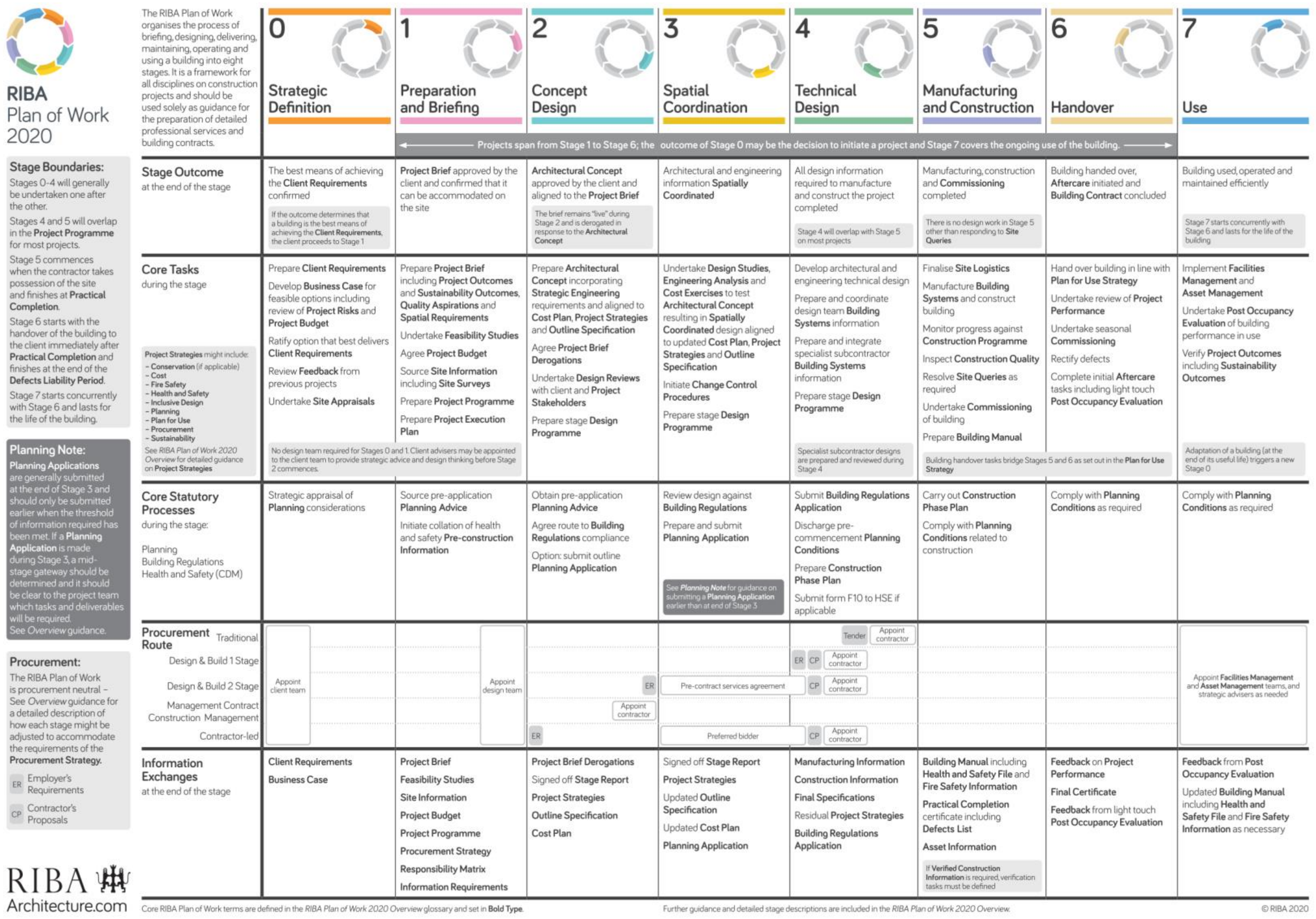
Royal Institute of British Architects (RIBA): RIBA Plan of Work 2020 2020; DOI: 10.4324/9780429346637-2

Appendix



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Stage Boundaries:

Stages 0-4 will generally be undertaken one after the other.

Stages 4 and 5 will overlap in the **Project Programme** for most projects.

Stage 5 commences when the contractor takes possession of the site and finishes at **Practical Completion**.

Stage 6 starts with the handover of the building to the client immediately after **Practical Completion** and finishes at the end of the **Defects Liability Period**.

Stage 7 starts concurrently with Stage 6 and lasts for the life of the building.

Planning Note:

Planning Applications are generally submitted at the end of Stage 3 and should only be submitted earlier when the threshold of information required has been met. If a **Planning Application** is made during Stage 3, a mid-stage gateway should be determined and it should be clear to the project team which tasks and deliverables will be required. See *Overview* guidance.

Procurement:

The RIBA Plan of Work is procurement neutral – See *Overview* guidance for a detailed description of how each stage might be adjusted to accommodate the requirements of the **Procurement Strategy.**

ER Employer's Requirements

CP Contractor's Proposals

The RIBA Plan of Work organises the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages. It is a framework for all disciplines on construction projects and should be used solely as guidance for the preparation of detailed professional services and building contracts.	0 Strategic Definition	1 Preparation and Briefing	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing and Construction	6 Handover	7 Use
		← Projects span from Stage 1 to Stage 6; the outcome of Stage 0 may be the decision to initiate a project and Stage 7 covers the ongoing use of the building. →						
Stage Outcome at the end of the stage	The best means of achieving the **Client Requirements** confirmed If the outcome determines that a building is the best means of achieving the **Client Requirements**, the client proceeds to Stage 1	**Project Brief** approved by the client and confirmed that it can be accommodated on the site	**Architectural Concept** approved by the client and aligned to the **Project Brief** The brief remains "live" during Stage 2 and is derogated in response to the **Architectural Concept**	Architectural and engineering information **Spatially Coordinated**	All design information required to manufacture and construct the project completed Stage 4 will overlap with Stage 5 on most projects	Manufacturing, construction and **Commissioning** completed There is no design work in Stage 5 other than responding to **Site Queries**	Building handed over, **Aftercare** initiated and **Building Contract** concluded	Building used, operated and maintained efficiently Stage 7 starts concurrently with Stage 6 and lasts for the life of the building
Core Tasks during the stage **Project Strategies** might include: – **Conservation** (if applicable) – **Cost** – **Fire Safety** – **Health and Safety** – **Inclusive Design** – **Planning** – **Plan for Use** – **Procurement** – **Sustainability** See *RIBA Plan of Work 2020 Overview* for detailed guidance on **Project Strategies**	Prepare **Client Requirements** Develop **Business Case** for feasible options including review of **Project Risks** and **Project Budget** Ratify option that best delivers **Client Requirements** Review **Feedback** from previous projects Undertake **Site Appraisals** No design team required for Stages 0 and 1. Client advisers may be appointed to the client team to provide strategic advice and design thinking before Stage 2 commences.	Prepare **Project Brief** including **Project Outcomes** and **Sustainability Outcomes**, **Quality Aspirations** and **Spatial Requirements** Undertake **Feasibility Studies** Agree **Project Budget** Source **Site Information** including **Site Surveys** Prepare **Project Programme** Prepare **Project Execution Plan**	Prepare **Architectural Concept** incorporating **Strategic Engineering** requirements and aligned to **Cost Plan**, **Project Strategies** and **Outline Specification** Agree **Project Brief Derogations** Undertake **Design Reviews** with client and **Project Stakeholders** Prepare stage **Design Programme**	Undertake **Design Studies**, **Engineering Analysis** and **Cost Exercises** to test **Architectural Concept** resulting in **Spatially Coordinated** design aligned to updated **Cost Plan**, **Project Strategies** and **Outline Specification** Initiate **Change Control Procedures** Prepare stage **Design Programme**	Develop architectural and engineering technical design Prepare and coordinate design team **Building Systems** information Prepare and integrate specialist subcontractor **Building Systems** information Prepare stage **Design Programme** Specialist subcontractor designs are prepared and reviewed during Stage 4	Finalise **Site Logistics** Manufacture **Building Systems** and construct building Monitor progress against **Construction Programme** Inspect **Construction Quality** Resolve **Site Queries** as required Undertake **Commissioning** of building Prepare **Building Manual** Building handover tasks bridge Stages 5 and 6 as set out in the **Plan for Use Strategy**	Hand over building in line with **Plan for Use Strategy** Undertake review of **Project Performance** Undertake seasonal **Commissioning** Rectify defects Complete initial **Aftercare** tasks including light touch **Post Occupancy Evaluation**	Implement **Facilities Management** and **Asset Management** Undertake **Post Occupancy Evaluation** of building performance in use Verify **Project Outcomes** including **Sustainability Outcomes** Adaptation of a building (at the end of its useful life) triggers a new Stage 0
Core Statutory Processes during the stage: Planning Building Regulations Health and Safety (CDM)	Strategic appraisal of **Planning** considerations	Source pre-application **Planning Advice** Initiate collation of health and safety **Pre-construction Information**	Obtain pre-application **Planning Advice** Agree route to **Building Regulations** compliance Option: submit outline **Planning Application**	Review design against **Building Regulations** Prepare and submit **Planning Application** See ***Planning Note*** for guidance on submitting a **Planning Application** earlier than at end of Stage 3	Submit **Building Regulations Application** Discharge pre-commencement **Planning Conditions** Prepare **Construction Phase Plan** Submit form F10 to HSE if applicable	Carry out **Construction Phase Plan** Comply with **Planning Conditions** related to construction	Comply with **Planning Conditions** as required	Comply with **Planning Conditions** as required
Procurement Route Traditional	Appoint client team	Appoint design team			Tender Appoint contractor			Appoint **Facilities Management** and **Asset Management** teams, and strategic advisers as needed
Design & Build 1 Stage					ER CP Appoint contractor			
Design & Build 2 Stage			ER	Pre-contract services agreement	CP Appoint contractor			
Management Contract Construction Management			Appoint contractor					
Contractor-led			ER	Preferred bidder	CP Appoint contractor			
Information Exchanges at the end of the stage	**Client Requirements** **Business Case**	**Project Brief** **Feasibility Studies** **Site Information** **Project Budget** **Project Programme** **Procurement Strategy** **Responsibility Matrix** **Information Requirements**	**Project Brief Derogations** Signed off **Stage Report** **Project Strategies** **Outline Specification** **Cost Plan**	Signed off **Stage Report** **Project Strategies** Updated **Outline Specification** Updated **Cost Plan** **Planning Application**	**Manufacturing Information** **Construction Information** **Final Specifications** Residual **Project Strategies** **Building Regulations Application**	**Building Manual** including **Health and Safety File** and **Fire Safety Information** **Practical Completion** certificate including **Defects List** **Asset Information** If **Verified Construction Information** is required, verification tasks must be defined	**Feedback** on **Project Performance** **Final Certificate** **Feedback** from light touch **Post Occupancy Evaluation**	**Feedback** from **Post Occupancy Evaluation** Updated **Building Manual** including **Health and Safety File** and **Fire Safety Information** as necessary

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Core RIBA Plan of Work terms are defined in the *RIBA Plan of Work 2020 Overview* glossary and set in **Bold Type**.

Further guidance and detailed stage descriptions are included in the *RIBA Plan of Work 2020 Overview*.

Figure A5: Overview of design phases and related tasks acc. RIBA Plan of Work (RIBA 2020 [Royal Institute of British Architects (RIBA), 2020]).

Table A2: Description of 'Sustainability Checkpoints' in the RIBA plan of work 2013 [Royal Institute of British Architects (RIBA), 2013]

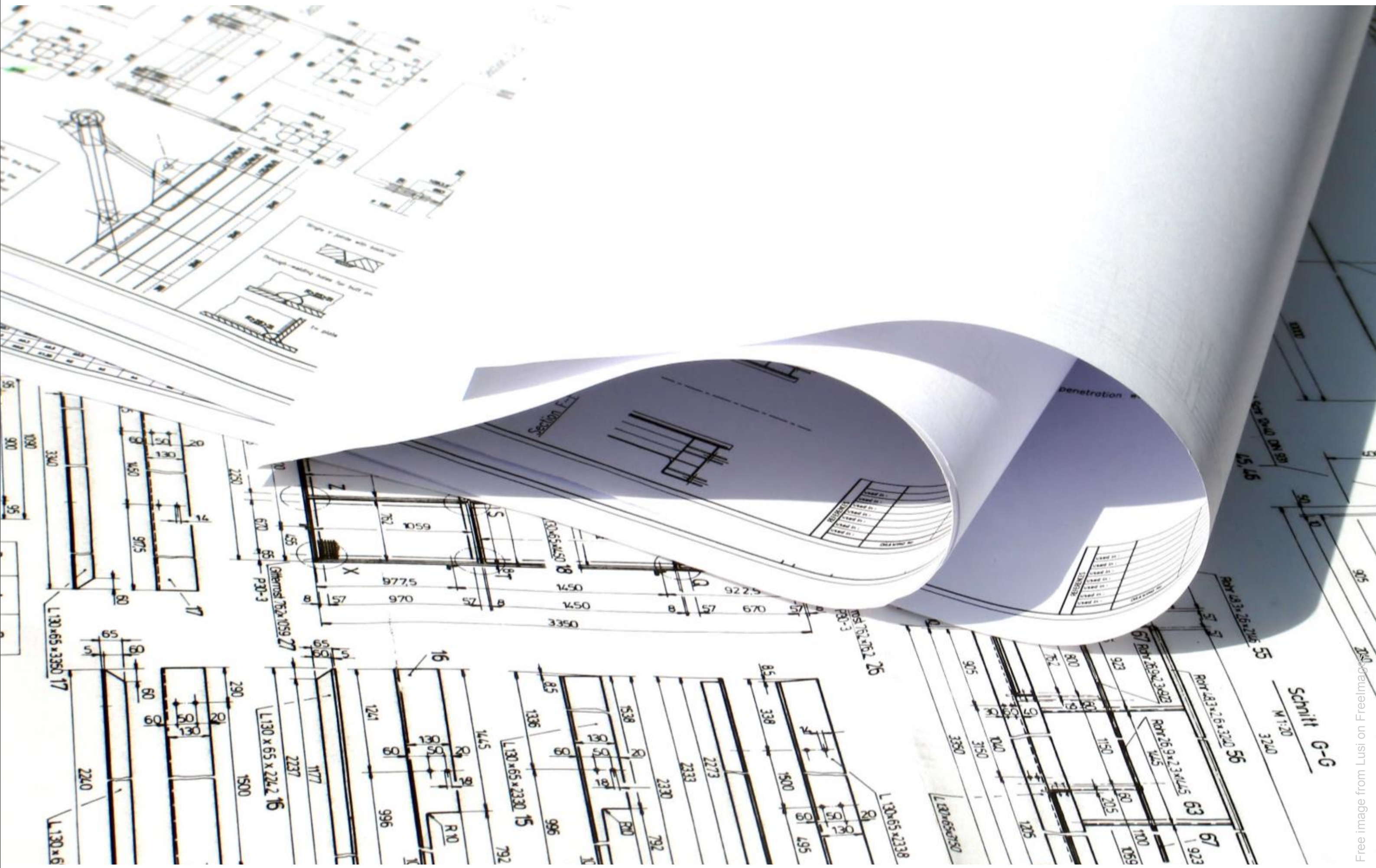
Design step	Core Objectives	Sustainability Checkpoints
Strategic definition	Identify client's Business Case and Strategic Brief and other core project requirements.	• Ensure that a strategic sustainability review of client needs and potential sites has been carried out, including reuse of existing facilities, building components or materials.
Preliminary studies	Develop Project Objectives, including Quality Objectives and Project Outcomes, Sustainability Aspirations, Project Budget, other parameters or constraints and develop Initial Project Brief. Undertake Feasibility Studies and review of Site Information.	• Confirm that formal sustainability targets are stated in the Initial Project Brief. Confirm that environmental requirements, building lifespan and future climate parameters are stated in the Initial Project Brief. Have early steps consultations, surveys or monitoring been undertaken as necessary to meet sustainability criteria or assessment procedures? Check that the principles of the Handover Strategy and post-completion services are included in each party's Schedule of Services. Confirm that the Site Waste Management Plan has been implemented.
Concept Design	Prepare Concept Design, including outline proposals for structural design, building services systems, outline specifications and preliminary Cost Information along with relevant Project Strategies in accordance with Design Programme. Agree alterations to brief and issue Final Project Brief.	• Confirm that formal sustainability pre-assessment and identification of key areas of design focus have been undertaken and that any deviation from the Sustainability Aspirations has been reported and agreed. Has the initial Building Regulations Part L assessment been carried out? Have 'plain English' descriptions of internal environmental conditions and seasonal control strategies and systems been prepared? Has the environmental impact of key materials and the Construction Strategy been checked? Has resilience to future changes in climate been considered?
Developed Design	Prepare Developed Design, including coordinated and updated proposals for structural design, building services systems, outline specifications, Cost Information and Project Strategies in accordance with Design Programme.	• Has a full formal sustainability assessment been carried out? Have an interim Building Regulations Part L assessment and a design step carbon/energy declaration been undertaken? Has the design been reviewed to identify opportunities to reduce resource use and waste and the results recorded in the Site Waste Management Plan?
Technical Design	Prepare Technical Design in accordance with Design Responsibility Matrix and Project Strategies to include all architectural, structural and building services information, specialist subcontractor design and specifications, in	• Is the formal sustainability assessment substantially complete? Have details been audited for airtightness and continuity of insulation? Has the Building Regulations Part L submission been made and the design step carbon/energy declaration been updated and the future climate impact assessment prepared? Has a non-technical user guide been drafted and have the format and content of the Part L log book

	accordance with Design Programme.	been agreed? Has all outstanding design step sustainability assessment information been submitted? Are building Handover Strategy and monitoring technologies specified? Have the implications of changes to the specification or design been reviewed against agreed sustainability criteria? Has compliance of agreed sustainability criteria for contributions by specialist subcontractors been demonstrated?
Construction	Offsite manufacturing and onsite Construction in accordance with Construction Programme and resolution of Design Queries from site as they arise.	• Has the design step sustainability assessment been certified? Have sustainability procedures been developed with the contractor and included in the Construction Strategy? Has the detailed commissioning and Handover Strategy programme been reviewed? Confirm that the contractor's interim testing and monitoring of construction has been reviewed and observed, particularly in relation to airtightness and continuity of insulation. Is the non-technical user guide complete and the aftercare service set up? Has the 'As-constructed' Information been issued for post-construction sustainability certification?
Handover and close out	Handover of building and conclusion of Building Contract.	• Has assistance with the collation of post-completion information for final sustainability certification been provided?
In use	Undertake In Use services in accordance with Schedule of Services.	• Has observation of the building operation in use and assistance with fine tuning and guidance for occupants been undertaken? Has the energy/carbon performance been declared?

Potentials and requirements for implementing LCA across different design steps, project phases and life cycle stages

A Contribution to IEA EBC Annex 72
Part 2- National reports on definition of design phases

April 2023



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International Energy Agency

Potentials and requirements for implementing LCA across different design steps, project phases and life cycle stages

A Contribution to IEA EBC Annex 72
Part 2- National reports on definition of design phases

April 2023

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Table of content - L2

Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_2eq	CO_2 equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines

ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process

Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Introduction

This report offers a summary of short-reports on the definition of design phases, milestones and steps related to the environmental assessment and use of LCA along the design process. The short-reports were provided by Annex experts of the respective countries.

The short-reports on the situation in Annex countries address, e.g.:

- National definition of design phases, milestones and deliverables: From perspective of building design professionals, which standards/guidelines are relevant for your country (might be multiple for different building design professionals) and what tasks, decisions and deliverables do they describe? Here, you will later on be able to use the figure provided for your country (see example figure of Germany below (draft)).
- Steps related to assessment and improvement of environmental performance: Description of the current state of environmental performance requirements (environmental benchmarks) and assessment in design practice, addressing in which design phases and what type of environmental performance assessment (e.g. LCA) is conducted (referring to relevant standards, guidance documents, if available). Is there any (formal) description of how environmental performance of a building project should be assessed and improved at different phases of the project?
- Other relevant aspects: If environmental assessment is not (yet) applied in practice, please describe the current state of (life cycle) cost estimation in building design practice incl. the related tasks along the design process (referring to relevant standards, guidance documents, if available).

Objectives

This document relates to a common activity of ST1 and ST2. It serves to offer a common definition of phases in the building design process for new construction and modernization projects. This definition should provide the basis for

- An assignment of methodological questions, rules and recommendations for action in individual design phases, with particular attention to earlier and later project phases (pre-/post-design) as well as the tasks related to the documentation and handover of buildings (ST1)
- A discussion of different approaches for integrating environmental assessment along the design process, including questions of responsibilities, information and exchange requirements as well as possible ways of presenting results (ST2)
- An allocation of environmental assessment tools and workflows to individual design phases (ST 2)
- An assignment of case studies to individual design phases where necessary and sensible (ST3)
- A discussion on the suitability of data and databases for calculation and evaluation tasks in different design phases (ST 4).

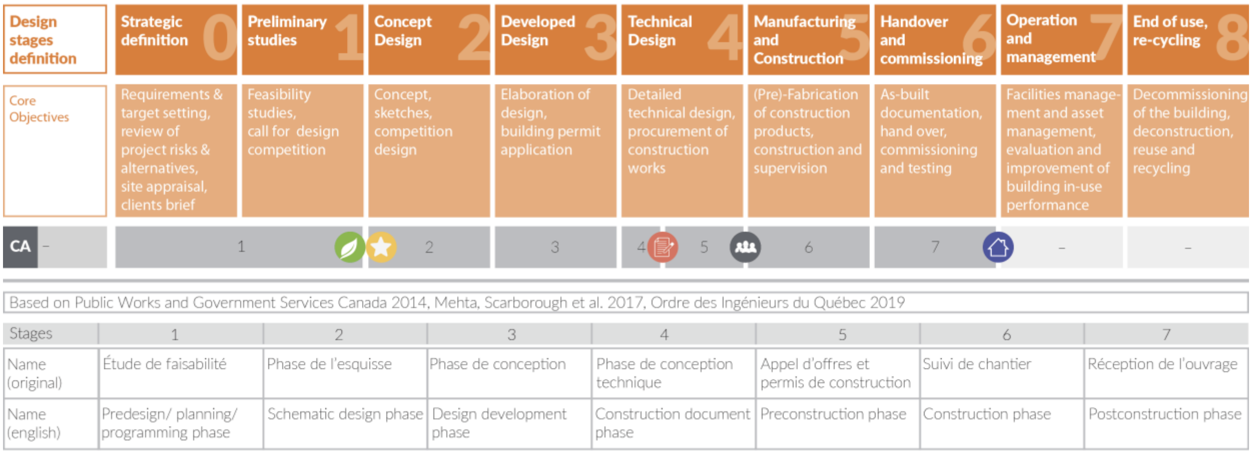
1. National report for Canada

Author(s): Vincent Roy, Martin Michaud, Claudiane Ouellet-Plamondon (Ecole de Technologie Superieure)

1.1 Introduction

Even if it has often been proven that using LCA in early design stages of buildings is highly beneficial for its environmental performance, no mandatory requirement exists in Canada for regular building construction until now. For most public and private contracts, the lowest bidder rule is still the norm. Projects like LCA^2 by National Research Council Canada aim at developing and eventually incorporate LCA in procurement. Started in 2019, this initiative will end in 2022. Beside standards like LEED, Envision and others, there are no incentive yet for landlords and builders. Existing environmental regulations for construction focus on aspects like soil and contamination, flora and fauna and energy efficiency while excluding embodied carbon.

1.2 National definition of design phases, milestones and deliverables



Design stages definition	Strategic definition 0	Preliminary studies 1	Concept Design 2	Developed Design 3	Technical Design 4	Manufacturing and Construction 5	Handover and commissioning 6	Operation and management 7	End of use, re-cycling 8
Core Objectives	Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, construction and supervision	As-built documentation, hand over, commissioning and testing	Facilities management and asset management, evaluation and improvement of building in-use performance	Decommissioning of the building, deconstruction, reuse and recycling
CA –	1	2	3	4 5	6	7	–	–	

Based on Public Works and Government Services Canada 2014, Mehta, Scarborough et al. 2017, Ordre des Ingénieurs du Québec 2019

Stages	1	2	3	4	5	6	7
Name (original)	Étude de faisabilité	Phase de l'esquisse	Phase de conception	Phase de conception technique	Appel d'offres et permis de construction	Suivi de chantier	Réception de l'ouvrage
Name (english)	Predesign/ planning/ programming phase	Schematic design phase	Design development phase	Construction document phase	Preconstruction phase	Construction phase	Postconstruction phase

Figure 1: Detailed overview of design phases and milestones – Canada

Multiple definitions exist regarding design phases in Canada. Depending on the location and the type of professional, project and contract, phases vary. As an example, tasks and their timing can be quite different if the client chooses a fast track delivery mode for his project instead of the traditional mode or design-build mode. Depending on the various professional associations' standards in Canada, answers in the table below could slightly vary. Nonetheless, the table presents an accurate big picture for the definitions, milestones and deliverables of the different phases in Canada (and more globally North America). From a project's developer, owner or landlord view, there could be two additional phases regarding maintenance and operation and building's end of life which are, in most cases, completely excluded from the engineers or architects' scope of work in traditional projects. Table content is based on the engineer's association official document, government procurement guide (Public Works and Government Services Canada 2014) and academic resource (Mehta, Scarborough et al. 2017).

Table 1 : Building delivery phases based on (Public Works and Government Services Canada 2014, Mehta, Scarborough et al. 2017, Ordre des Ingénieurs du Québec 2019)

PHASE	TASKS	DELIVERABLES	MILESTONES
Predesign/ planning/ programming phase	• Details of the project's program. • Economic feasibility assessment, including the project's overall budget and financing. • Site assessment and selection, including the verification of the site's appropriateness, and determining its designated land use. • Governmental constraints assessment, for example, building code and zoning constraints and other legal aspects of the project. • Sustainability ratings—whether the owner would like the project to achieve sustainability rating, such as the Leadership in Energy and Environmental Design (LEED) certification at some level. • Design team selection.	Building or project programs delivered. This includes defining the activities, functions, and spaces required in the building, along with their approximate sizes and their relationships with each other. Preparing the program is the first step in the project delivery process. It should be spelled out in writing and in enough detail to guide the design, reduce the liability risk for the architect, and avoid its misinterpretation.	Building or project program completed and design team chosen (if not already)
Schematic design phase	• Schematic design: overall design concept with documentation primarily for owner (not contractor). Emphasis on design.	Schematic design documents completed and approved by owners and other necessary authorities	Schematic drawings and probable costs
Design development phase	• Design development: Schematic design developed to greater details for cost, time and constructability considerations. Documentation primarily for the design team. Emphasis on solving design decisions.	Design development documents completed and approved by owners and other necessary authorities	More detailed drawings and costs
Construction document phase	• Construction documents: Design finalized to nuts and bolts details. Documentation for the construction team.	Construction documents completed and approved by owners and other necessary authorities	Construction plans completed
Preconstruction phase	• Bid package: Preparation of package comprising construction drawings and specifications, procurement and contracting requirements and addenda. • General contractor qualification: surety bonds (bid, performance and payment). • Contractor and project delivery type selection: methods differ depending on the project and owner (private vs. public).	Bid package documents and final contracts	General contractor's contract awarded and noticed to proceed with construction works
Construction phase	• Product sample, mockups, shop drawings and performance data submission for approval by the design team. • Construction progress documentation and inspection of work by contractor and design team. • Payment certifications and change orders.	Any required inspection approval sheet for different types of work (rebar, concrete, welding, etc.)	Certificate of occupancy secured by the contractor
Postconstruction phase	• Contractor provides all necessary warranties and guarantees from manufacturers and subcontractors. • Substantial completion inspection done by the design team (liability transfers to the owner) • Final inspection by the design team once all deficiencies are corrected. • As built documents	Substantial completion inspection, final inspection and As built drawings	As built drawings and documentation

1.3 Steps related to assessment and improvement of environmental performance

As mentioned, actual mandatory environmental performance assessments are not related to embodied carbon. Each province has its own generic law regarding environmental quality. As an example, in the province of Quebec, builders must comply with the law on environmental quality (Québec 2020). In order to receive a construction permit, they must assure that they are building on a proper site (industrial, residential, institutional, etc.). If soil on site is too contaminated to build, they must decontaminate it. Also, if they are in a fragile zone (e.g., wetlands), more studies need to be done in order to deliver permit and mitigation measures must be put in place by builders. Other regulations linked to building construction are related to energy efficiency. They are included to the national building code and specify different directives regarding building component thermal resistance value, construction of specific elements like weather stripping, how to eliminate thermal bridges and others (Canada 2010).

Despite not being mandatory, the Canada Green Building Council launched the Zero Carbon Building Standard (Canadian Green Building Council 2019). In order to obtain that standard, one of the main requirements is to conduct a LCA including modules A1-5, B1-5 and C1-4. After minimizing carbon emissions during design and construction, the projects will be required to offset their embodied carbon in order to obtain the certification (offset does not include Module D's embodied carbon). To foster material reuse, LCA shall only include new material from envelope and structural elements, including footings and foundations, and complete structural wall assemblies (from cladding to interior finishes, including basement), structural floors and ceilings (not including finishes), roof assemblies, and stairs. Parking structures are to be included; however, excavation and other site development, partitions, building services (electrical, mechanical, fire detection, alarm systems, elevators, etc.), and surface parking lots are excluded. Projects that wish to evaluate their embodied carbon more fully may elect to include materials beyond the structure and envelope at their discretion provided they are reported as a separate line item. For example, the fit-up of interior spaces may provide opportunities for embodied carbon reductions. To provide an opportunity to influence design, the standard requires that the LCA analysis begin at the schematic design phase. Project teams are encouraged to set a reduction goal as early as pre-design. The embodied carbon report submitted must include a list of recommendations that were considered and/or implemented to reduce the embodied carbon of the project and must be based on the final design. The LCA must assume a building service life of 60 years. This service life is chosen to ensure standardized reporting throughout the program and may not reflect the service life the project is designed for. If the service life of a product used in initial construction is longer than the building's assumed service life, the impacts associated with the product may not be discounted to reflect its remaining service life. Embodied carbon must be reported in kilograms of carbon dioxide equivalent (kg CO2 e) as a total value, as well as broken down in two different ways: 1. A life-cycle stage analysis including totals for stages A, B, C, and D (if available); and, 2. A contribution analysis broken out by either material type or by building assembly. The LCA must demonstrate an embodied carbon reduction using the life-cycle stages A, B, & C. Projects that wish to expand the scope of the analysis to look for reductions elsewhere may do so provided both the baseline and the proposed building use the same scope. For building equivalence, baseline building must be equivalent to the proposed building. The following must be constant in both the baseline and proposed building: (1) Operational energy use (2) Gross floor area (3) Functional use of space (4) Building shape and orientation. Retrofit projects that use an existing structure for 50 per cent or more of the final gross floor area are deemed compliant and are not required to model a baseline building.

1.4 Other relevant aspects

As mentioned above, phase definition can slightly vary depending from which point of view we are looking at. The table 1 contains a holistic representation covering most of the phases in a more architectural point of view. Indeed, the architect is often the main responsible for environmental performance improvements on building construction projects. The schematic, design development and construction design phases are typical to architects. It has been discussed that these different points of view or definitions between stakeholders can reduce efficiency and information flows within the project substantially (Michaud, Forgues et al. 2019). To illustrate this aspect, please refer to figure 1. Indeed, not having a common understanding or design process fosters silo mentality instead of collaboration. One major issue regarding this fact is professional responsibility. Indeed, professional association regulates according to specific tasks and those rarely account for new design or delivery methods. Laws and regulations tend to follow technical innovation, but not the opposite. Also, another issue regards who pilots the project first. As an example, traditional procurement method would usually imply an architectural team first with the landlord. Then, engineering team would be chosen and finally the contractor. For other projects, landlords also act as a real estate developer. While doing public consultation, the developer could already fix different environmental targets to make the project socially acceptable before choosing a design team and contractor. In other contexts, contractors also act as a real estate developer making the situation even more complicated. Nevertheless, in most cases environmental aspects are covered in the first phase of the project for every type of professional regarding requirements and second phase for environmental design for engineers and architects. A positive development is BIM process being slowly widely adopted for economic and time concern. This adoption could enable more collaboration in the early stages of the project regarding environmental concerns. One suggestion would also be to have a representative of every party in the early stages in order to set realistic targets for everyone, reducing costs associated with design and contract changes since no party faces a *fait accompli*. Starting with a common understanding and appropriate regulations would improve environmental and overall project performance.

1.5 Outlook

Having a common language will certainly foster collaboration at an early stage of the project. Indeed, processes like BIM will indirectly solve some of these issues even if the focus is more on time and money. By including common environmental requirements, professional associations could also quickly improve that process. New regulations and initiative like the LCA^2 will foster LCA use on a national scale. Public instances must lead by example and include embodied carbon in procurement for their future projects. New standardization procedures may arise in Canada from the LCA^2 initiative. More information about the initiative can be found here[1].

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[1] Website: https://nrc.canada.ca/en/research-development/research-collaboration/programs/low-carbon-assets-through-life-cycle-assessment-initiative

2. National report for France

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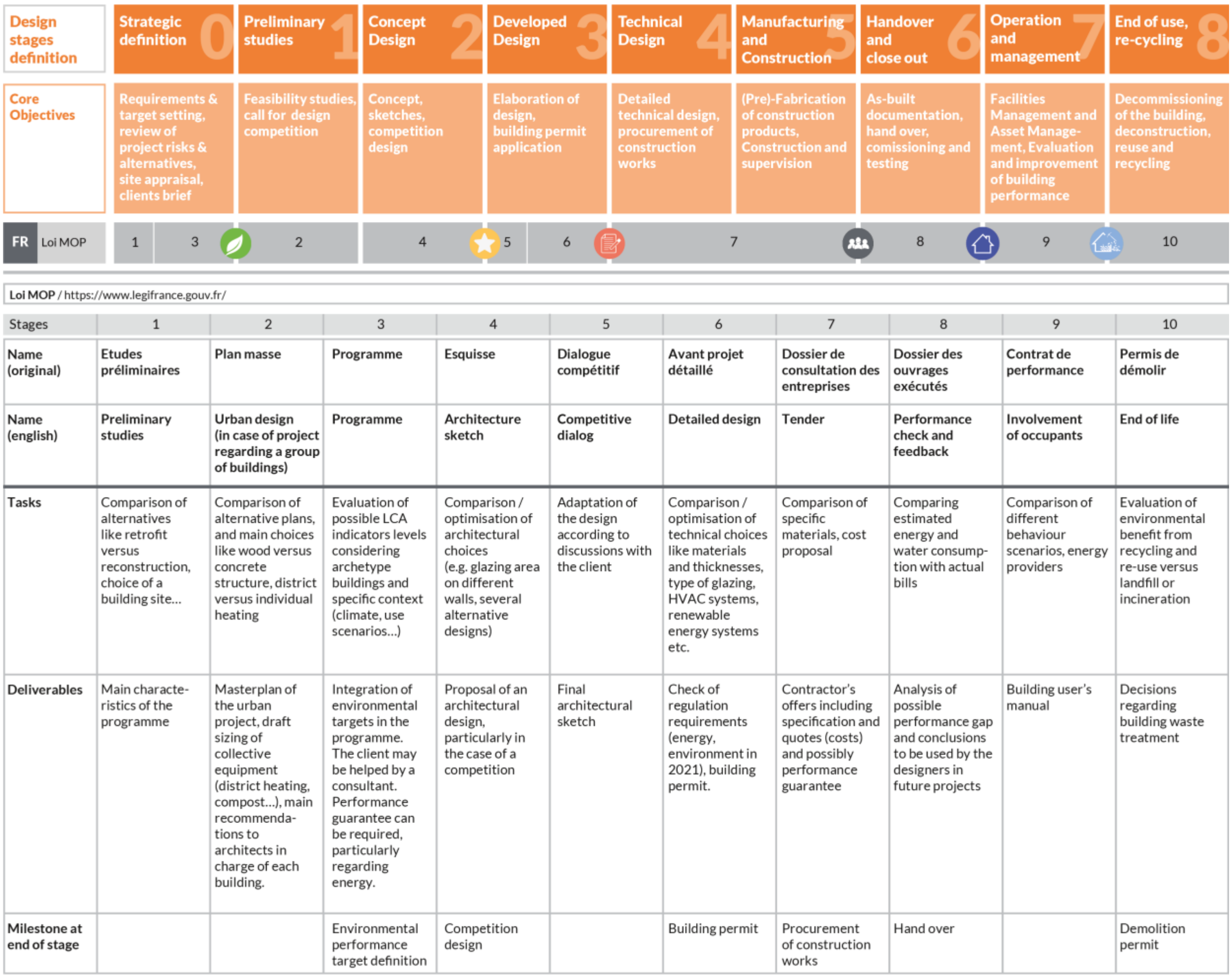
2.1 Introduction

Using LCA is more useful at early phases of a project, when the decisions made have the largest influence on environmental performance. But in most cases the resources are too limited at early phases. An interesting approach is to have one year called “competitive dialog” just after the competition. For instance three design teams are selected (each including an architect, a contractor and possibly engineers), and discuss with the clients in order to improve their project, being paid by the client who finally selects one of the teams. Each project is unique in terms of context and functional unit, so that designers in general prefer to use their own intelligence rather than just to follow a standard procedure. What is important is the result: performance should be checked by measurements (e.g. energy and water bills) and the designers can largely gain from this feedback for future projects.

2.2 National definition of design phases, milestones and deliverables



Design stages definition	Strategic definition 0	Preliminary studies 1	Concept Design 2	Developed Design 3	Technical Design 4	Manufacturing and Construction 5	Handover and close out 6	Operation and management 7	End of use, re-cycling 8
Core Objectives	Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, Construction and supervision	As-built documentation, hand over, comissioning and testing	Facilities Management and Asset Management, Evaluation and improvement of building performance	Decommissioning of the building, deconstruction, reuse and recycling
FR Loi MOP	1 3	2	4	5 6	7		8	9	10

Loi MOP / https://www.legifrance.gouv.fr/

Stages	1	2	3	4	5	6	7	8	9	10
Name (original)	**Etudes préliminaires**	**Plan masse**	**Programme**	**Esquisse**	**Dialogue compétitif**	**Avant projet détaillé**	**Dossier de consultation des entreprises**	**Dossier des ouvrages exécutés**	**Contrat de performance**	**Permis de démolir**
Name (english)	**Preliminary studies**	**Urban design (in case of project regarding a group of buildings)**	**Programme**	**Architecture sketch**	**Competitive dialog**	**Detailed design**	**Tender**	**Performance check and feedback**	**Involvement of occupants**	**End of life**
Tasks	Comparison of alternatives like retrofit versus reconstruction, choice of a building site…	Comparison of alternative plans, and main choices like wood versus concrete structure, district versus individual heating	Evaluation of possible LCA indicators levels considering archetype buildings and specific context (climate, use scenarios…)	Comparison / optimisation of architectural choices (e.g. glazing area on different walls, several alternative designs)	Adaptation of the design according to discussions with the client	Comparison / optimisation of technical choices like materials and thicknesses, type of glazing, HVAC systems, renewable energy systems etc.	Comparison of specific materials, cost proposal	Comparing estimated energy and water consumption with actual bills	Comparison of different behaviour scenarios, energy providers	Evaluation of environmental benefit from recycling and re-use versus landfill or incineration
Deliverables	Main characteristics of the programme	Masterplan of the urban project, draft sizing of collective equipment (district heating, compost…), main recommendations to architects in charge of each building.	Integration of environmental targets in the programme. The client may be helped by a consultant. Performance guarantee can be required, particularly regarding energy.	Proposal of an architectural design, particularly in the case of a competition	Final architectural sketch	Check of regulation requirements (energy, environment in 2021), building permit.	Contractor's offers including specification and quotes (costs) and possibly performance guarantee	Analysis of possible performance gap and conclusions to be used by the designers in future projects	Building user's manual	Decisions regarding building waste treatment
Milestone at end of stage			Environmental performance target definition	Competition design		Building permit	Procurement of construction works	Hand over		Demolition permit

Figure 2: Detailed overview of design phases, milestones and tasks - France

The phases differ according to the project, for instance the process is simpler for smaller buildings. In the case of a renovation project, the architecture sketch is generally not needed.

Design phases	**Milestones**	**Deliverables**
Preliminary studies	Comparison of alternatives like retrofit versus reconstruction, choice of a building site…	Main characteristics of the programme
Urban design (in case of project regarding a group of buildings)	Comparison of alternative plans, and main choices like wood versus concrete structure, district versus individual heating	Masterplan of the urban project, draft sizing of collective equipment (district heating, compost…), main recommendations to architects in charge of each building.
Programme	Evaluation of possible LCA indicators levels considering archetype buildings and specific context (climate, use scenarios…)	Integration of environmental targets in the programme. The client may be helped by a consultant. Performance guarantee can be required, particularly regarding energy.

Architecture sketch	Comparison / optimisation of architectural choices (e.g. glazing area on different walls, several alternative designs)	Proposal of an architectural design, particularly in the case of a competition
Competitive dialog	Adaptation of the design according to discussions with the client	Final architectural sketch
Detailed design	Comparison / optimisation of technical choices like materials and thicknesses, type of glazing, HVAC systems, renewable energy systems etc.	Check of regulation requirements (energy, environment in 2021), building permit.
Tender	Comparison of specific materials, cost proposal	Contractor's offers including specification and quotes (costs) and possibly performance guarantee
Performance check and feedback	Comparing estimated energy and water consumption with actual bills	Analysis of possible performance gap and conclusions to be used by the designers in future projects
Involvement of occupants	Comparison of different behaviour scenarios, energy providers	Building user's manual
End of life	Evaluation of environmental benefit from recycling and re-use versus landfill or incineration	Decisions regarding building waste treatment

2.3 Steps related assessment and improvement of environmental performance

The phases considered and the main actions to be done are summarized in the table given in annex (Peuportier B., 2015) but they should be adapted in line with the project, see also the ADEME guide aimed at building contractors and stakeholders (Bornarel A. et al., 2002).

Examples of LCA applications at various design phases can be found in the literature, e.g.

- Comparison of building sites (Polster B. et al., 1996)
- Comparison between retrofit and rebuilding (Palacios-Munoz B. et al., 2019)
- Design of an urban project (Roux C. et al., 2016), (Herfray G. et al., 2011)
- Design of a new construction (Oyarzo J. et al., 2014), (Thiers S. et al., 2012), (Recht T. et al., 2016)
- Renovation project (Peuportier B., 2002)
- Comparison of users behaviours (Polster B. et al., 1996)

2.4 Other relevant aspects

Performing LCA should include checking functional requirements when comparing alternatives. This induces the use of other tools in the design phase (e.g. thermal simulation, lighting and acoustic calculations to check comfort, structure calculation etc.). Cost calculation is of course also part of the design work.
An important aspect in eco-design is to identify main contributions in environmental impacts. This objective requires choosing an appropriate reference study period (RSP). Some LCA practitioners consider a 50 years period whereas a structure may last more than 200 years (Palacios-Munoz B. et al., 2019). Considering a shorter RSP gives more importance to products fabrication and end of life. Focusing on products leads to limit e.g. the use of insulation and solar systems, with the risk of higher energy consumption and higher impacts over the whole life cycle. In a design tool, the user should be allowed to choose the RSP according to the use of the building and the context even if the RSP is fixed in a regulation. Calculation according to the regulation are performed at the end of the design.

2.5 Outlook

The new regulation in preparation, following the E+C- experimentation, will probably impose a CO2 equivalent threshold on products and lower performance requirements regarding energy consumption (as the primary energy factor and CO2 emissions have been decreased for electricity with poor scientific justification). The risk is to limit the use of energy efficient or renewable techniques, leading to higher energy consumption during operation. It will be useful to compare the same building designed according to this regulation and the previous one, in order to know the variation of environmental impacts (which will probably increase). Eco-design should therefore be based upon more physical assessment and not just respecting regulation thresholds.

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Use the "Insert Citation" button to add citations to this document.

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Appendix

Steps related to assessment and improvement of environmental performance, from (Peuportier B., Eco-design for buildings and neighbourhoods, 2015).

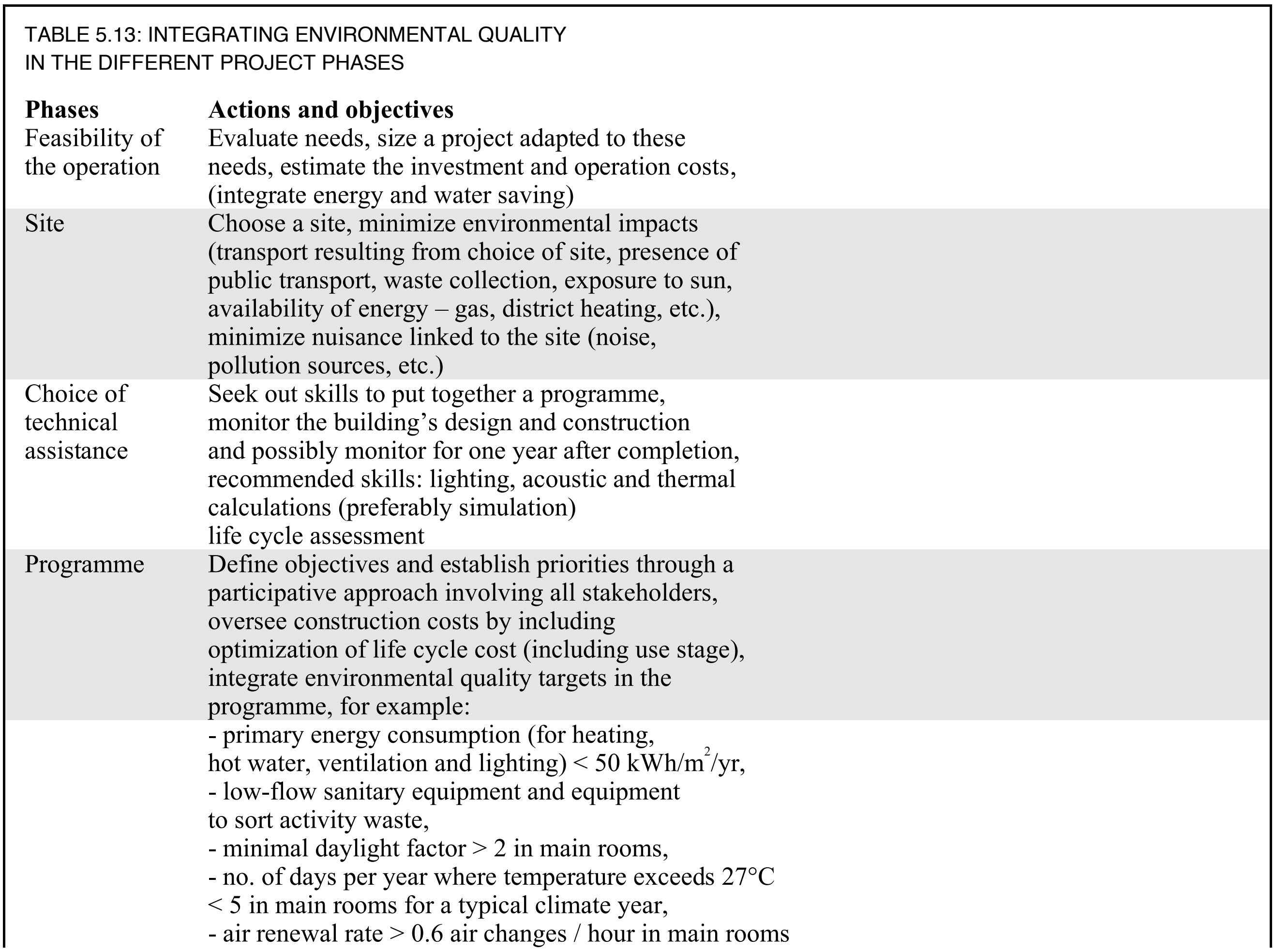


TABLE 5.13: INTEGRATING ENVIRONMENTAL QUALITY IN THE DIFFERENT PROJECT PHASES

Phases	**Actions and objectives**
Feasibility of the operation	Evaluate needs, size a project adapted to these needs, estimate the investment and operation costs, (integrate energy and water saving)
Site	Choose a site, minimize environmental impacts (transport resulting from choice of site, presence of public transport, waste collection, exposure to sun, availability of energy – gas, district heating, etc.), minimize nuisance linked to the site (noise, pollution sources, etc.)
Choice of technical assistance	Seek out skills to put together a programme, monitor the building's design and construction and possibly monitor for one year after completion, recommended skills: lighting, acoustic and thermal calculations (preferably simulation) life cycle assessment
Programme	Define objectives and establish priorities through a participative approach involving all stakeholders, oversee construction costs by including optimization of life cycle cost (including use stage), integrate environmental quality targets in the programme, for example:
	- primary energy consumption (for heating, hot water, ventilation and lighting) < 50 kWh/m^2/yr, - low-flow sanitary equipment and equipment to sort activity waste, - minimal daylight factor > 2 in main rooms, - no. of days per year where temperature exceeds 27°C < 5 in main rooms for a typical climate year, - air renewal rate > 0.6 air changes / hour in main rooms

Estimation of costs	Refine estimated construction cost, preferably taking a life cycle cost approach (including usage, maintenance, possibly "external" costs (environmental and social)
Design competition and choice of winner	Require skills from building project teams, in particular: lighting, acoustic and thermal calculations (preferably by simulation), life cycle assessment, pre-select teams taking into account their references (performance of previous constructions) and their note of intention Set up a jury and a technical commission that takes environmental criteria on board in their appraisal, set out selection criteria in a transparent manner, including explicit environmental criteria Select the winning team after analyzing "enhanced preliminary sketch": preliminary sketch accompanied by a note describing the main technical choices so that the most significant performances can be quantified (energy and water consumption, daylight factors, acoustic insulation, summer comfort, environmental impacts, life cycle cost), enhanced preliminary sketches constitute an intermediate level between the preliminary sketch and the basic preliminary design
Sketch	Define the general part of the construction (morphology), fit the building into the site, anticipate outside equipment (compost or waste sorting, bicycle garage, etc.), optimize ground waterproofing to manage rainwater, organize main functions, make key technical choices, respect economic constraints Optimize environmental quality by taking advantage of building's exposure, compactness, balance between glazed and opaque surfaces depending on direction of surfaces and spaces, reduce consumption of matter (e.g. lightweight surfaces in zones that do not require thermal mass): the tools described in chapter 3 can be used from this stage to refine and validate a sketch
Basic Preliminary Design	Describe the project with plans (1/200, possibly details at 1/100) showing each premises (including technical areas, circulation, etc.), justify technical measures, calculate a provisional estimate of the provisional cost of the work, Evaluate more precisely, using the tools described above, energy and water consumption, comfort levels (thermal, visual and acoustic), environmental impacts, life cycle cost, refine some parameters (insulation thickness, materials, glazing quality, etc.) to optimize environmental quality
Detailed Preliminary Design	Describe the project in a detailed manner (plans at 1/100, details at 1/50), write up precise technical notes (thermal, acoustic, lighting simulation), optimize equipment, e.g. ventilation (air flow ensuring satisfactory air quality, heat recovery, possibly night-time ventilation to cool in summer, hygro-adjustable or time-set ventilation, etc.), sanitary equipment (reduced flow), heating equipment (e.g. condensing, high-efficiency, or low NOx emission boilers, solar systems, control, emitters), lighting systems (low-energy lamps and efficient light fittings, control), compare different energies to reduce environmental impact and costs (gas, wood, district heating, etc.), provide final estimate of provisional cost of the work

Tendering Package	Draw up the Special Technical Terms and Conditions by lot, preparing the order for contractors, and including detailed plans (1/50 or 1/20, in particular to deal with thermal bridges and air-tightness of the envelope), technical specifications (e.g. choice (of glazing and joinery) and block diagram schemes explaining how systems function Size installations (heating, ventilation, hot water, air conditioning), avoid over-sizing which can reduce performances (e.g. efficiency of boilers or air-conditioning units) Choose, for the same functionality, materials and Components (insulation, masonry, coatings, joinery, etc.) offering the highest environmental quality possible (c.f. life cycle assessments, environmental and health declaration sheets, FSC wood certification), consider recycled, renewable or re-used materials that are easy to recycle, take into account impacts from cleaning products (especially when choosing coatings) Motivate partner companies (e.g. sub-contractors) by informing them of the quality approach and objectives, especially the “green worksite” approach (waste sorting, limited nuisances – noise, dust, liquid waste, etc.)
Assistance to building contracts	Select contractors based on responses to tendering package, taking into account environmental aspects in the responses (commitment to green worksite charter, choice of products, techniques proposed such as using recycled materials for foundations, reduction of thermal bridges, etc.), and possibly company references, oversee additional costs of eco-techniques reassuring companies about manufacturers’ guarantees, facility of implementation and any references
Worksite	Prepare the worksite to limit nuisances to local residents (select access areas to manage traffic, limit noise and dust), reduce risks of accidents and pollution (collect used oil, polluting waste), anticipate storage zones to sort waste and for backfill, Inform stakeholders about environmental quality objectives at worksite meetings, inform local residents, Ensure that worksite operations conform to green worksite charter commitments (the presence of an environment monitor is required on-site), ensure that workers are trained (efficiency of sorting waste, appropriate pictograms, air-tightness), identify waste recuperation channels and control relationships between contractors Verify some technical parameters (reduction of thermal bridges, insulation thickness, air permeability, etc.)
Acceptance and follow-up	Check whether the construction conforms with initial programme and special terms & conditions (e.g. quality of windows, sanitary equipment, lighting systems, etc.), verify correct operation of the building, its components (windows, solar protection, etc.) and its equipment (heating, hot water, ventilation, lighting), carry out tests (blower door for air tightness, infra-red thermography) Send future occupants notices, plans and information on managing and maintaining the building, inform them about environmental quality objectives and their role in the building’s actual performance

	(temperature settings, ventilation, water and energy consumption, waste sorting, building maintenance, etc.) Monitor the building’s performance during the first year (full guarantee of perfect completion for the year): note energy consumption (measurements may be perturbed in year 1 as some components dry out and controls are refined, and measuring during the second year is recommended), measure water consumption, temperatures, lighting levels, noise levels, and other more qualitative parameters with a satisfaction survey of occupants
Interior and exterior furnishings	Choose interior furnishings and equipment not included in the actual construction (light fittings, domestic and office appliances, etc.), taking into account water and energy savings (energy label for domestic appliances, priority for classes A & B), potential emissions from these appliances (e.g. formaldehyde or other VOCs linked to some glues or varnishes used on furniture), reduced packaging, easier maintenance and impacts generated at this stage, use of recycled or renewable materials, re-used or recyclable products Install appliances that generate electro-magnetic flows so as to limit human exposure (avoid placing this kind of appliance close to beds, work stations, etc.) Choose plantations for green areas so as to limit impacts from maintenance and the need for watering
Building management	Ensure occupants’ comfort and the building’s smooth running while limiting environmental impacts, especially: - adjust temperatures over time so as to avoid over-heating and reduce heating during unoccupied periods, - reduce ventilation during unoccupied winter periods, increase it in summer if night cooling is necessary, - inform occupants of their role in managing the building (managing lighting, water consumption, sorting waste, car-pooling or use of public transport, cycling, etc.), - maintain the building so as to increase the lifespan of components (e.g. regularly paint woodwork, maintain equipment for heating, hot water, ventilation, etc.) , - maintain the building so as to limit health risks (check domestic hot water installation, clean filters and vents, clean premises using products with low environmental impact, etc.), - measure energy and water consumption to detect excesses (fault in the boiler or heating control, water leak, etc.), - link up the building’s equipment with municipal management (waste sorting), - choose consumables with low environmental impact (e.g. recycled paper)
Retrofit	Retrofit operations follow a fairly similar process to new construction projects: at the feasibility phase, an audit can evaluate requirements by consulting inhabitants and making technical assessments (e.g. energy audit); resources that can be mobilized are evaluated (common equity, loan repaid in line with rents, grants, etc.). It is not common for this operation to be open to competition since the building’s architecture is rarely called into question. An architect is however involved in designing the façades. Analysis tools (for heat, lighting, acoustics, life cycle) can be used to compare

	alternatives and optimize choices, from basic preliminary design to special terms and conditions. Subsequent phases are similar to those of a new construction (company contracts, worksite, acceptance, management)
Deconstruction	Ensure that the building’s deconstruction is necessary (possibly compare with a retrofit scenario) Prefer deconstruction to demolition, i.e. dismantling all components that can be separated, e.g. windows, possible re-use of components, sorting and recycling of waste Manage the worksite taking a green approach (c.f. worksite phase), with even more emphasis on waste management (volume and cost).

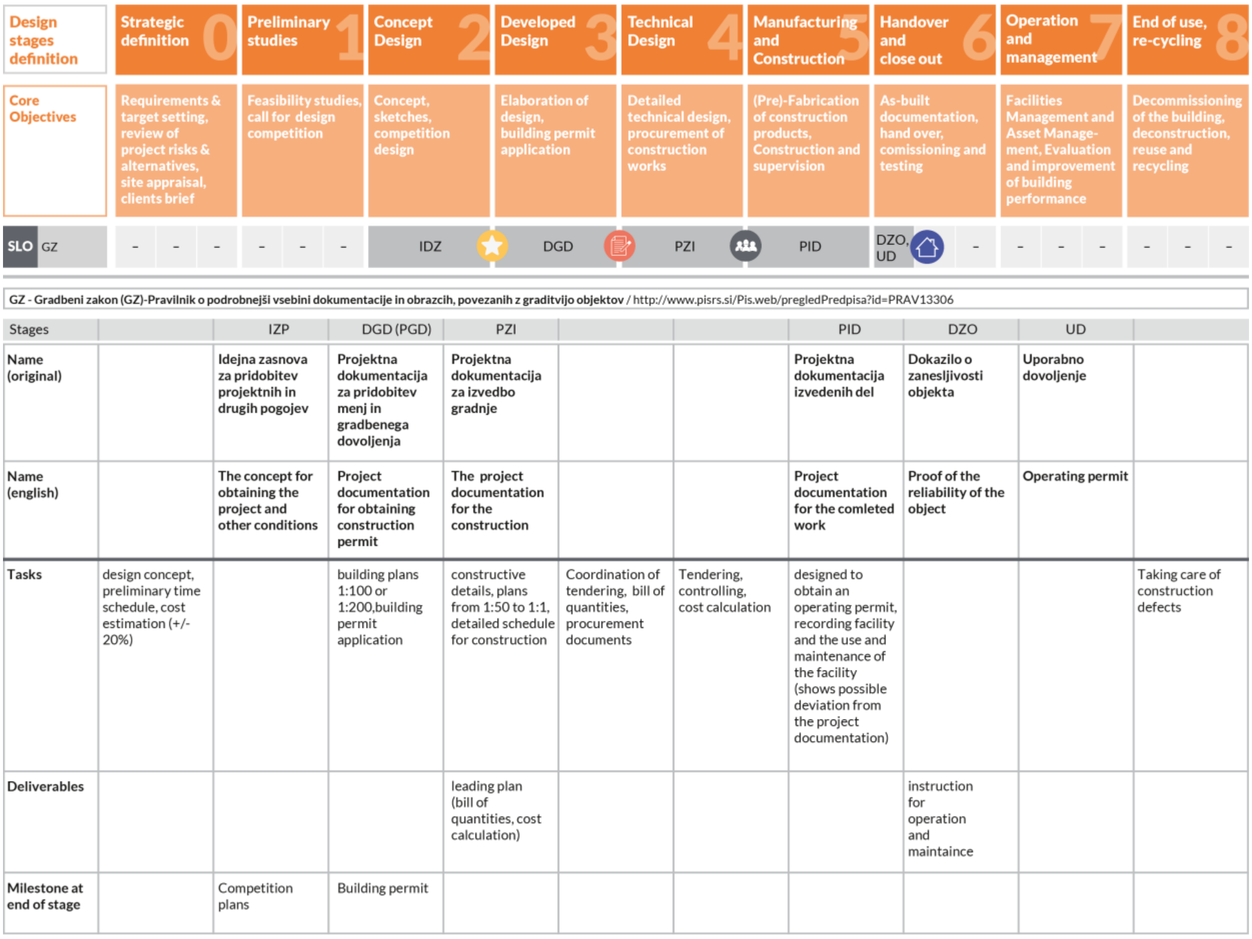
3. National report for Slovenia

Author(s): Tajda Potrc Obrecht (Zavod za gradbeništvo (ZAG))

3.1 Introduction

The design phases are defined with Rules on the detailed content of documentation and forms related to construction (Pravilnik o podrobnejši vsebini dokumentacije in obrazcih, povezanih z graditvijo objektov) which have to be followed in the design process of construction works.
The Rules specify the detailed content, form and method of preparation of documentation for complex, less demanding and non-demanding construction. It is used for particular types of buildings, civil engineering structures and other constructions.

3.2 National definition of design phases, milestones and deliverables



Design stages definition	Strategic definition 0	Preliminary studies 1	Concept Design 2	Developed Design 3	Technical Design 4	Manufacturing and Construction 5	Handover and close out 6	Operation and management 7	End of use, re-cycling 8
Core Objectives	Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, Construction and supervision	As-built documentation, hand over, comissioning and testing	Facilities Management and Asset Manage-ment, Evaluation and improvement of building performance	Decommissioning of the building, deconstruction, reuse and recycling
SLO GZ	- - -	- - -	IDZ	DGD	PZI	PID	DZO, UD -	- - -	- - -

GZ - Gradbeni zakon (GZ)-Pravilnik o podrobnejši vsebini dokumentacije in obrazcih, povezanih z graditvijo objektov / http://www.pisrs.si/Pis.web/pregledPredpisa?id=PRAV13306

Stages		IZP	DGD (PGD)	PZI			PID	DZO	UD	
Name (original)		Idejna zasnova za pridobitev projektnih in drugih pogojev	Projektna dokumentacija za pridobitev menj in gradbenega dovoljenja	Projektna dokumentacija za izvedbo gradnje			Projektna dokumentacija izvedenih del	Dokazilo o zanesljivosti objekta	Uporabno dovoljenje	
Name (english)		The concept for obtaining the project and other conditions	Project documentation for obtaining construction permit	The project documentation for the construction			Project documentation for the comleted work	Proof of the reliability of the object	Operating permit	
Tasks	design concept, preliminary time schedule, cost estimation (+/-20%)		building plans 1:100 or 1:200,building permit application	constructive details, plans from 1:50 to 1:1, detailed schedule for construction	Coordination of tendering, bill of quantities, procurement documents	Tendering, controlling, cost calculation	designed to obtain an operating permit, recording facility and the use and maintenance of the facility (shows possible deviation from the project documentation)			Taking care of construction defects
Deliverables				leading plan (bill of quantities, cost calculation)				instruction for operation and maintaince		
Milestone at end of stage		Competition plans	Building permit							

Figure 3: Detailed overview of design phases, milestones and tasks - Slovenia

According to the purpose of use, the documentation is classified into:

1. Concept design- Idejna zasnova za pridobitev projektnih in drugih pogojev (IZP) ,
2. Approval design- Projektna dokunetacija za pridobitev mnenj in gradbenega dovoljenje (DGD),
3. Detailed design- Projektna dokumentacija za izvedbo gradnje (PZI),
4. Project Documentation of Completed Works- Projektna dokumentacija izvedenih del (PID),
5. Proof of the Reliability of the object- Dokazilo o zanesljivosti objekta (DZO)

1. Concept design- Idejna zasnova za pridobitev projektnih in drugih pogojev (IZP)

INTENT: obtain project idea and other conditions for the execution of construction and use of the facility.

DELIVERABLES: the details of the participants, general information on the facilities and location views

MILESTONES: Competition design

2. Approval design- Projektna dokumetacija za pridobitev mnenj in gradbenega dovoljenje (DGD)

INTENT: the compliance of the documentation and plans with the regulations

DELIVERABLES: information on the participants, a statement by the designer and the project manager general information on the facilities the technical report, graphical representations.

MILESTONES: Building permit

3. Detailed design- Projektna dokumentacija za izvedbo gradnje (PZI)

INTENT: provide information about the execution of the construction work

DELIVERABLES: the master plan and plans.

MILESTONES: Procurement

4. Project Documentation of Completed Works- Projektna dokumentacija izvedenih del (PID)

INTENT: to obtain the operating permit, evident all the change happened during the construction process

DELIVERABLES: plans with highlighted changes that happened during the construction process

MILESTONES: /

5. Proof of the Reliability of the object (DZO)

INTENT: documentation that proves that the construction project fulfils all the requirements, basis for issuing the operation permit

DELIVERABLES: proofs of building quality collected, instruction for operation and maintenance

MILESTONES: Hand over

3.3 Steps related to assessment and improvement of environmental performance

The Approval design has to provide information about energy efficiency of the project. It has to deliver data about the methods used; calculation that prove that construction is aligned with the legislative requirements, annual primary energy consumption for the technical systems in the building; CO2 emissions that are emitted by the use of the technical equipment in the building.

In the Detailed design- Projekt za izvedno (PZI) the bill of quantities are delivered. These can be than used to make an LCA calculation, but LCA ins not mandatory in Slovenia.

3.4 Outlook

Within a project the certification process for sustainable buildings will be developed in within this project it is foreseen that the use of LCA in building should be implemented.

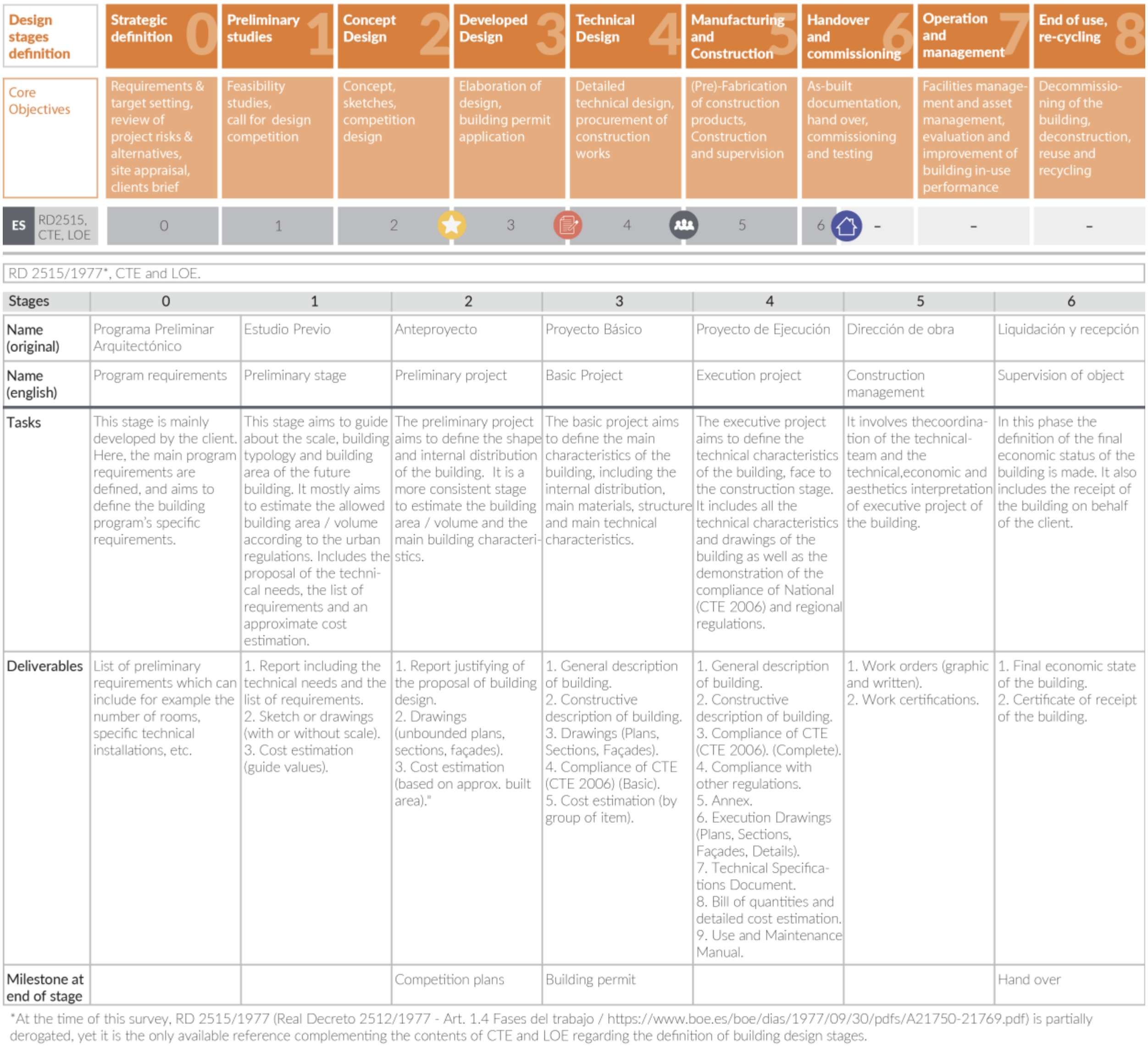
4. National report for Spain

Author(s): Antonio García-Martínez, Carmen Llatas, Juan Carlos Gómez de Cózar, Bernardette Soust-Verdaguer (University of Seville, Seville)

4.1 Introduction

In the Spanish context, the architects are responsible of the project and construction management of building construction and civil engineering works including (such as urban services: streets, sidewalks, lighting, distribution networks, gardening, etc., hydraulic constructions for lighting and water supply to towns, sewerage works, neighbourhood and private utility roads; bridges, reservoirs, canals, irrigation ditches and bracelets for private service and urban development of the underground) The design stages of the projects are defined in the RD. 2512/1977 [1] , the phase of the work are: Preliminary stage (*Estado previo*), Preliminary Project (*Anteproyecto*), Basic project (*Proyecto Básico*), Execution Project (*Proyecto de Ejecución*), Construction Management (*Dirección de obra*) and Reception and Settlement (*Liquidación y recepción de obra*). However, based on current practice a stage before the Preliminary stage can be identified, which is called Preliminary architectural program or Program requirements (*Programa Preliminar Arquitectónico).* Regarding these design stages, little requirements, experience and regulations about the integration of building environmental performance assessment and LCA application at the phases of a project in current practice are detected.

4.2 National definition of design phases, milestones and deliverables



Design stages definition	Strategic definition 0	Preliminary studies 1	Concept Design 2	Developed Design 3	Technical Design 4	Manufacturing and Construction 5	Handover and commissioning 6	Operation and management 7	End of use, re-cycling 8
Core Objectives	Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, Construction and supervision	As-built documentation, hand over, commissioning and testing	Facilities management and asset management, evaluation and improvement of building in-use performance	Decommissioning of the building, deconstruction, reuse and recycling
ES RD2515, CTE, LOE	0	1	2	3	4	5	6 -	-	-

RD 2515/1977*, CTE and LOE.

Stages	0	1	2	3	4	5	6
Name (original)	Programa Preliminar Arquitectónico	Estudio Previo	Anteproyecto	Proyecto Básico	Proyecto de Ejecución	Dirección de obra	Liquidación y recepción
Name (english)	Program requirements	Preliminary stage	Preliminary project	Basic Project	Execution project	Construction management	Supervision of object
Tasks	This stage is mainly developed by the client. Here, the main program requirements are defined, and aims to define the building program's specific requirements.	This stage aims to guide about the scale, building typology and building area of the future building. It mostly aims to estimate the allowed building area / volume according to the urban regulations. Includes the proposal of the technical needs, the list of requirements and an approximate cost estimation.	The preliminary project aims to define the shape and internal distribution of the building. It is a more consistent stage to estimate the building area / volume and the main building characteristics.	The basic project aims to define the main characteristics of the building, including the internal distribution, main materials, structure and main technical characteristics.	The executive project aims to define the technical characteristics of the building, face to the construction stage. It includes all the technical characteristics and drawings of the building as well as the demonstration of the compliance of National (CTE 2006) and regional regulations.	It involves thecoordination of the technical-team and the technical,economic and aesthetics interpretation of executive project of the building.	In this phase the definition of the final economic status of the building is made. It also includes the receipt of the building on behalf of the client.
Deliverables	List of preliminary requirements which can include for example the number of rooms, specific technical installations, etc.	1. Report including the technical needs and the list of requirements. 2. Sketch or drawings (with or without scale). 3. Cost estimation (guide values).	1. Report justifying of the proposal of building design. 2. Drawings (unbounded plans, sections, façades). 3. Cost estimation (based on approx. built area)."	1. General description of building. 2. Constructive description of building. 3. Drawings (Plans, Sections, Façades). 4. Compliance of CTE (CTE 2006) (Basic). 5. Cost estimation (by group of item).	1. General description of building. 2. Constructive description of building. 3. Compliance of CTE (CTE 2006). (Complete). 4. Compliance with other regulations. 5. Annex. 6. Execution Drawings (Plans, Sections, Façades, Details). 7. Technical Specifications Document. 8. Bill of quantities and detailed cost estimation. 9. Use and Maintenance Manual.	1. Work orders (graphic and written). 2. Work certifications.	1. Final economic state of the building. 2. Certificate of receipt of the building.
Milestone at end of stage			Competition plans	Building permit			Hand over

*At the time of this survey, RD 2515/1977 (Real Decreto 2512/1977 - Art. 1.4 Fases del trabajo / https://www.boe.es/boe/dias/1977/09/30/pdfs/A21750-21769.pdf) is partially derogated, yet it is the only available reference complementing the contents of CTE and LOE regarding the definition of building design stages.

Figure 4: Detailed overview of design phases, milestones and tasks - Spain

The main regulatory framework for architects in Spain is the CTE (*Código Técnico de la Edificación*) [2], the document contains the main requirements that the buildings should comply in security and habitability, defined in the Law 38/1999 *de 5 de noviembre, de Ordenación de la Edificación* (LOE). The documnet is composed by the following parts:

1. *Royal Decree* and Part 1
2. Structural security
3. Fire security
4. Utility and accessibility security
5. Energy savings (energy and environmental aspects)
6. Noise protection
7. Healthiness
8. Legal provisions (*Disposiciones legales*)

4.3 Steps related to assessment and improvement of environmental performances

In current practice, the building environmental performance requirements are provided by the CTE [2]. There, general and the regional specific requirements of the buildings during the design stages, are mostly focused on the operational energy. The energy demand of the building is estimated and certified along the design stages.

For research purposes, the assessment of the environmental performance of the building is based on the LCA application. According to the information provided, the uncertainties during the design stages falls as the level of definition of the building information increase. Thus, during the “Preliminary Project”, “Basic Project” and “Executive Project” design phases the environmental impacts produced by the building can be estimated by using for example BIM-based LCA methods [3–8]. Due to the fact that the design process mostly includes 3D models of the building, these methods can adapt the workflow and available data from the BIM model to the LCA application. The studies mostly focused the LCA application at an approx. LOD 300 because at this level the most relevant building elements and components has been already defined [9]. The “Concept stage” needs another method to deal with these uncertainties, especially to estimate the environmental impacts of buildings. In the Spanish context it is possible to estimate the cost of the building adapted to regional characteristics by using a simplified method [10] developed by the associations of architect (COA). Thus, a similar method to estimate the environmental impacts of buildings can be developed.

4.4 Other relevant aspects

Another recent contribution (for research purposes) to calculate the CO2 emissions of building sector, during the concept stage of design in Spain is the CO2 tool [11]. In the Open Educational Resource OERCO2 [11] the calculations of CO2 emissions at each phase of the building are unified to get an overall picture about footprint from the concept stage and decide on each construction variable.

4.5 Outlook

The current national regulations are mostly focused on the operational energy demand based on simplified calculation tools (called HULC) CTE [2]. Hoverer, differences has been detected in the environmental requirements (the use of other tools or sources) and specific regulations along the different regions and “Autonomous Communities” in Spain. In design practice, lack of knowledge and maturity, and little requirements related to the environmental performance of the building in design stages are detected. In spite of the fact that progress has been detected in research works, there are several aspects that require attention, such as the a lack of harmonisation in the data sources related to the environmental impact categories such as CO2 emission and the energy consumption (contained in commercial tools e.g., BEDEC, CYPE).

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Appendix

In the Spanish context the design stages of an architectural project can be organized according to the following criteria (Source RD. 2512/1977 [1]):

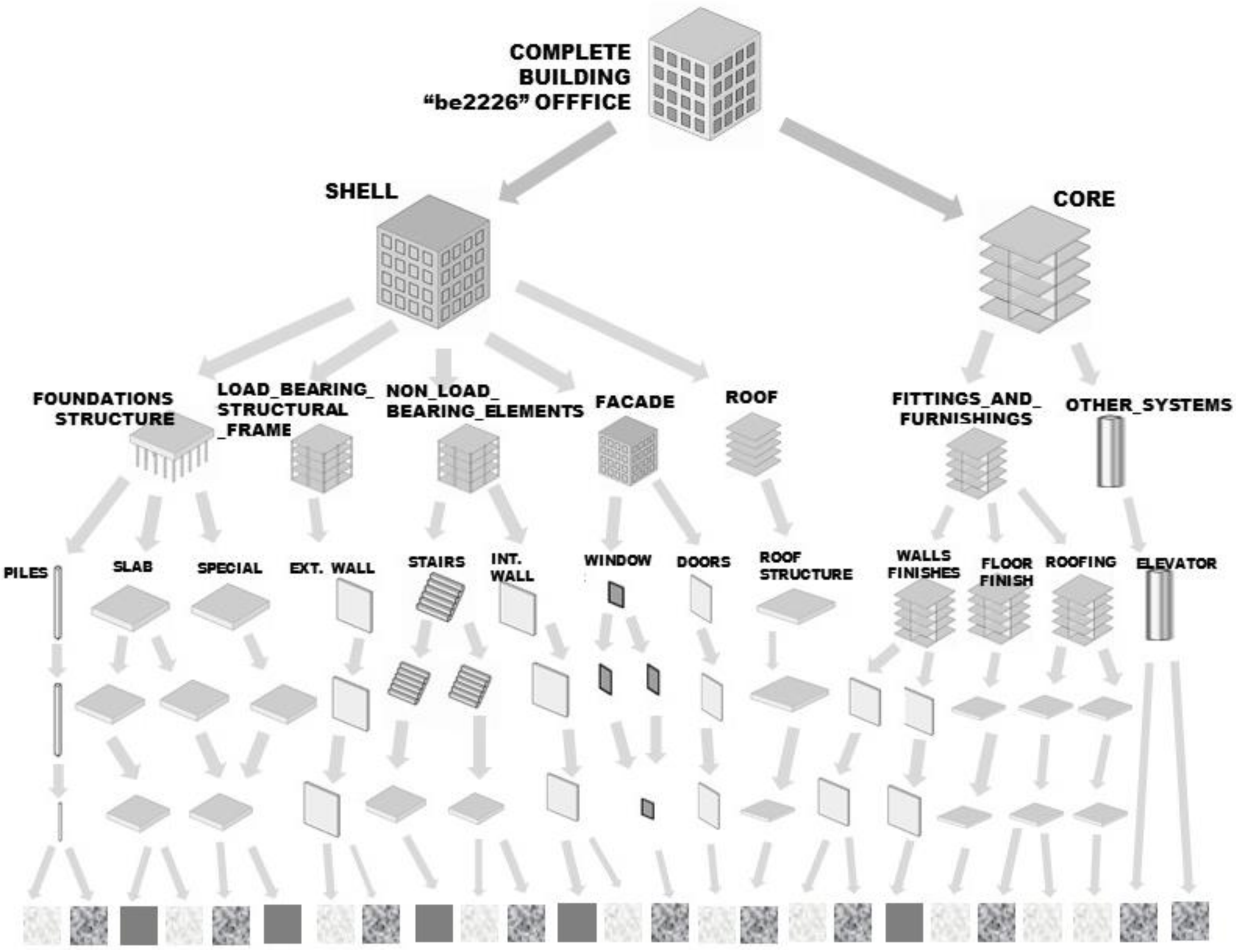
DESIGN STAGE	**Preliminary architectural program or Program requirements (Programa Preliminar Arquitectónico)**	**Preliminary stage (*Estado previo*)**	**Preliminary project *(Anteproyecto)***	**“Basic Project” (*Proyecto Básico*)**	**“Execution project” (*Proyecto de Ejecución*)**	**Construction management (*Dirección de obra*)**	**Reception and settlement (*Liquidación y recepción de obra*)**
Definition	This stage is mainly developed by the client. Here, the main program requirements are defined, and aims to define the building program’s specific requirements.	This concept stage aims to guide about the scale, building typology and building area of the future building. It mostly aims to estimate the permitted building area / volume according to the urban regulations and to quick estimate the building costs.	The preliminary project aims to define the shape and internal distribution of the building. It is a more consistent stage to estimate the building area / volume and the main building characteristics.	The basic project aims to define the main characteristics of the building, including the internal distribution, main materials, structure and main technical characteristics.	The executive project aims to define the technical characteristics of the building, face to the construction stage. It includes all the technical characteristics and drawings of the building as well as the demonstration of the compliance of National [2] and regional regulations.	The architect coordinates the construction management of the building, the technical, economic and aesthetic interpretation of the “Execution project”.	The architect determinate the “final economic state” of the building construction works, by using the prices of the real products and real measurements. The reception of the building is also performed in the name of the client, according to the documents and technical specifications contained in the “Execution project” and the rest of the documents included during the construction works.
Content	The contents and scope of this primary estimation are not regulated by National regulations.	The contents and scope of this primary estimation are not regulated by National regulations.	The contents and scope of this primary estimation are not regulated by National regulations.	The contents and scope of this design stage are established by the associations of architect (“Colegios de Arquitectos”) and complies with National [2] and regional regulations for buildings.	The contents and scope of this design stage are established by the associations of architect (“Colegios de Arquitectos”) and complies with National [2] and regional regulations for buildings.	The contents and scope of this stage complies with National [2] and regional regulations for buildings construction works.	The contents and scope of this stage complies with National [2] and regional regulations for buildings construction works.

Deliverable	List of preliminary requirements which can include for example the number of rooms, specific technical installations, etc.	Documents and drawings are needed during the decision-making, mostly to guide the client. - Report including the list of requirements - Drawings and schemes (without scale) - Cost estimations	Documents and drawings are needed during the decision-making, mostly to guide the client. - Report and justification of the decisions - Plans, facades and sections (without scale) - Cost estimations (updated)	These documents and drawings are needed to the building permit application. The main content of the "Basic project" are: 1. Description of the building. 2. Constructive description of the building. 3. Drawings (Plans, Sections, Façades). 3. Compliance of the CTE [2] (Basic). 4. Cost estimations (updated).	The main content of the "Executive project" are: 1. Description of the building. 2. Constructive description of the building. 3. Compliance of the CTE [2]. (Complete). 4. Compliance with other regulations. 5. Annex. 6. Drawings for the execution (Plans, Sections, Façades, Details). 7. Technical Specifications Document 8. Measurements and cost estimations (updated). 9. Usage and Maintenance Manual.	The main contents of this phase are: - "Orders of Construction Works", graphics and specifications. - "Construction attestation"	The main contents of this phase are: - Final Economic state of the building construction works - Hand over minute.
Milestone			Competition Plan	Building permit 1rst step Tendering	Building permit 2nd step	Construction attestation	Hand over

Systematic building decomposition for implementing LCA

A Contribution to IEA EBC Annex 72

April 2023



International Energy Agency

Systematic building decomposition for implementing LCA

A Contribution to IEA EBC Annex 72

April 2023

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Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO$_2$eq	CO$_2$ equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
LCCO$_2$	Life Cycle CO$_2$ equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines

ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process

Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

The Life Cycle Assessment (LCA) technique applied to buildings involves the compilation and organization of a large amount of data. Thus, the systematic decomposition is considered a suitable practice to organise and classify building elements and materials. It is considered as a structure that can help to solve specific difficulties when completing the life cycle inventory, as well as allow to obtain reliable and transparent results. The present section provides an overview about the use of systematic building decomposition to conduct LCA to buildings, analyse the implications of taking such approach when integrating LCA in BIM and describe the results of a comparison among different national standards/guidelines that are used to conduct LCA for building decomposition. The study is based on the comparison of national classification systems/standards/guidelines used by twelve Annex participant countries. Moreover, as a common basis of comparison, the “be2226” reference office building was used as a case study to apply the different national standards/guidelines for building decomposition. Results shows that there are differences among the levels of decomposition, grouping and taxonomy principles. It allows us to identify the consequences of using such different systems/standards to conduct LCA, how these differences affect the LCI structures, the LCA databases and the communication of results. To conclude a set of recommendations and challenges based on these findings are proposed.

Keywords: Life Cycle Assessment; Building Information Modelling; Systematic Building Decomposition; Classification System.

Introduction

In the context of the application of LCA in buildings, the use of a systematic structure to decompose the building is needed for several purposes such as to simplify the processes of data collection and its organization (Cheng & Tong, 2017). It allows dividing or decomposing the building into a number of 'portions', 'component groups', 'elements', products, materials, typologies and fabricants (e.g., systems, parts, elements, components, materials or specific manufacturers) and should be performed following specific criteria or structure (Cheng & Tong, 2017; Soust-Verdaguer et al., 2020). For this purpose, a *taxonomy,* defined as 'a *system for naming and organizing things'* (Cambridge Dictionary, 2016) is a suitable term that can describe the main objective of this structure. The concepts of *taxonomy* and *classification systems* applied to buildings can provide a reliable description of the building, organise and relate the different parts, as well as a common reference to name the different systems, elements, and components, among others. It allows to describe and decompose the building elements for different purposes, such as cost estimation, library organization, and environmental assessment, among others.

In this context and based on the literature (Röck et al., 2018a; Shipra Singh Ahluwalia, 2008; Soust-Verdaguer et al., 2020) a variety of classification systems for the building decomposition are detected. Most of them are based on ISO 12006-2 Building Construction - Organization of Information about Construction Works - Part 2: Framework for Classification, which defines a global framework for the development of built environment classification systems (ISO, 2012a).

Objectives

The current report focuses on providing a basis for the understanding and the analysis of the topic. It starts from the definition and introduction of the main aspects related to the taxonomy and classification systems of buildings applied for the systematic building decomposition. The main section identifies and compares the different standards and guidelines that are used by the participating countries for that purpose, and is illustrated by a case study application to a reference building. The present report focuses on detecting the challenges, limitations, and opportunities for its implementation, as well as the current status on the integration national standards and guidelines for systematic building decomposition in BIM. Finally, its implications in on conducting an LCA with a focus on LCA-BIM coupling are analysed.

1. General Context

1.1 Systematic building decomposition to conduct building LCA

The application of systematic decomposition is needed to describe the building elements when conducting LCA, which allows one to identify possible levels of decomposition such as groups of elements, elements, components, products, materials, typologies, and manufacturers (see Figure 1) (Hoxha, 2015). In this vein, the systematic building decomposition in a comprehensible and standardized way according to national standards or guidelines is needed to provide results of building LCA studies at all levels of hierarchy (e.g., building, element, material). Also, though the use of a systematic building decomposition hierarchically conceived, the process of revising assessed components can be facilitated (Shipra Singh Ahluwalia, 2008). A systematic decomposition in a comprehensible and standardized way can also improve, among others, the overview of the completeness of the Life Cycle Inventory (LCI). Regarding the results communication, it also improves the understanding of hot spots for environmental impacts, when presented on various levels (per Life Cycle Stage, materials, elements, etc.). Moreover, the use of a systematic approach can support assessment at various design stages of the building (e.g., using element information early on and material level at a later stage) and supports consideration of uncertainties occurring on different hierarchical levels and at different design stages.

A study conducted by Cavalliere, Habert, Dell'Osso & Hollberg, (2019) investigated the potential of using a hierarchical systematic decomposition of the building, based on a classification system. It relates the design stages (in BIM) with the levels of hierarchy that organize the Bauteilkatalog (Holliger Consult, n.d.) which is based on the Swiss code (CRB, 2009) for the construction works classification system. Some of the advantages of using a classification system when conducting LCA are that it can support the comparability of results for both studies within one country and studies across different countries (one-time mapping of standardized decomposition systems enables comparison). It can also improve transparency in the communication of results in LCA, considering the existing differences in building classification systems. In the context of the IEA EBC Annex 72 (IEA EBC, 2017) project, a wide variety of classification systems applied in different countries to building decomposition were identified when conducting LCA (Soust-Verdaguer et al., 2020). The present chapter is focused on providing a general description of the standards and guidelines used for the systematic decomposition of buildings, mainly used in the Annex countries participants, as well as on comparing their main aspects and illustrating the relevance of their consideration when conducting building LCA.

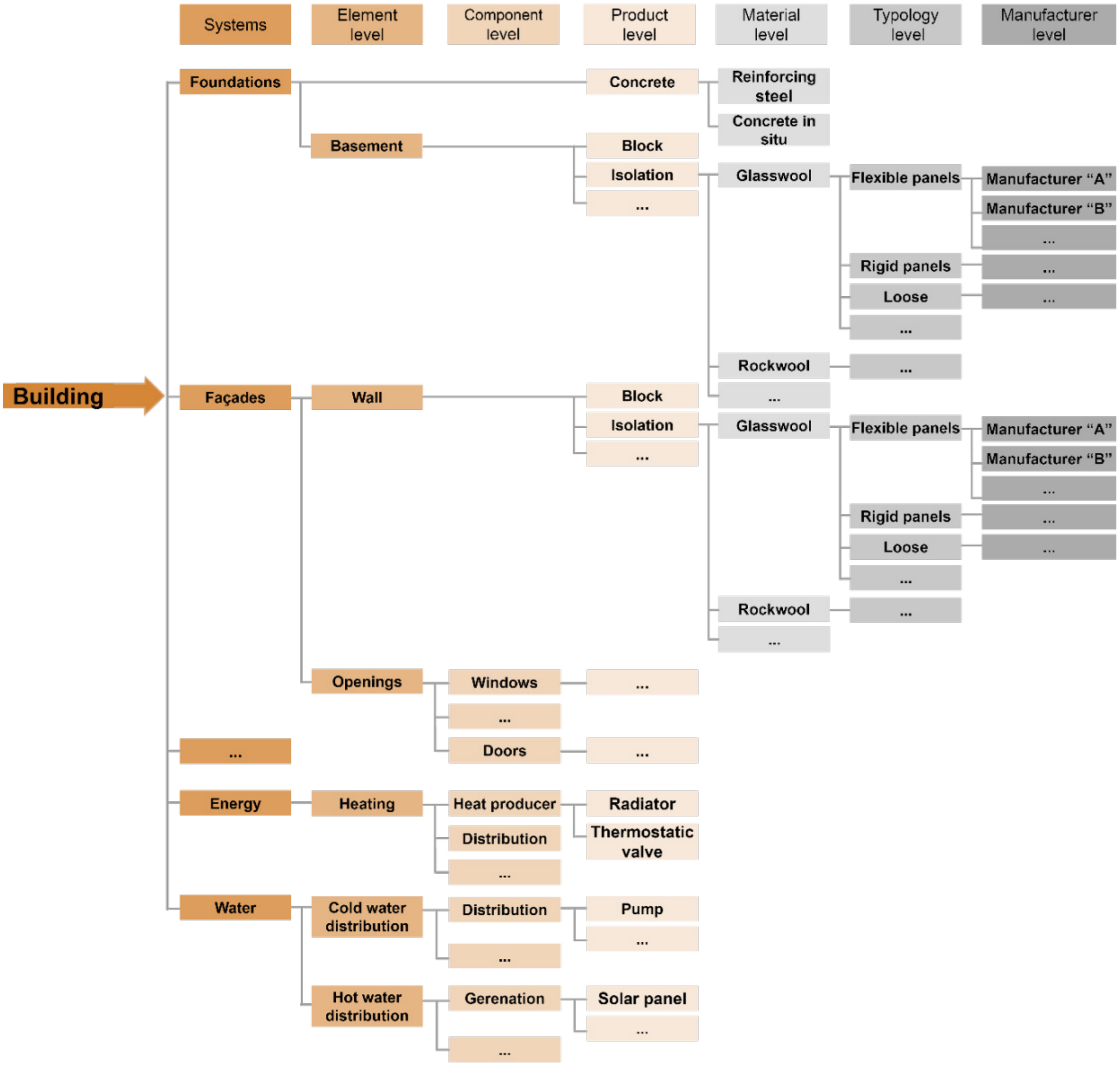

Figure 1: Example of the building decomposition for the building description when conducting LCA. (Source: Hoxha (Hoxha, 2015)

1.2 Systematic building decomposition and classification systems in BIM

The use of digital tools for designing and constructing buildings has changed over the last decades (Volk et al., 2014). Since the extensive use of building information modeling (BIM) tools to support design and construction is recognized, it has modified *“the way we deal with information in the construction sector, transferring the information contained in traditional documentation to ICT- handled data objects with attached information representing the construction complexes and entities, the spaces and the elements”* (International Construction Information Society, 2017). In this context, the integration of structures/tables focus on the description, organization, classification, and identification of objects in the digital tools as BIM is recognized as a challenge to deal with. This integration can provide, among others, a common language, a structure for building decomposition, and ways of managing information in a more uniform and transparent way (International Construction Information Society, 2017).
Additionally, one of the main utilities of the use of classification systems in BIM is the capability to integrate naming codes to organize and manage the building elements that compose the BIM model. The ICIS report on 'Classification, identification, and BIM' underscores that 'it *is important for modeling that the same object has the same code and name in the geometry and textual parts of the information model, so these two parts can integrate and be linked together'* and also 'the *challenge is that both building models and specifications are structured in a way that data will be able to be put on the lists in a coordinated manner'* (International Construction Information Society, 2017). This means that, depending on the level of object definition and needed specifications, from early stage design generic objects can be used followed by detailed objects at detailed stages. Thus, depending on the level of detail of the model and the level of detail of the LCA application, the amount and precision of the information and the levels of decomposition will increase.

For the building construction cost estimation, the application of LCC and environmental assessment to building, similarities on the modelled system structures are detected (Naneva et al., 2020) and demonstrated by the growing combination of both techniques in BIM (Bierer et al., 2015; Santos et al., 2019; Santos, Aguiar Costa, et al., 2020; Santos, Costa, et al., 2020). However, when comparing both methods performed in BIM, the level of maturity in the application of the cost estimation can be considered higher than for the environmental assessment based on LCA (International Construction Information Society, 2018a).

Otherwise, the use of BIM methodology to conduct LCA has been growing (Seyis, 2020; Soust-Verdaguer et al., 2017). Similar as the cost estimation the LCA requires to conduct an inventory, the quantification of the building elements, components, materials, products, and the use of classification systems to identify and organise this information. But, here unlike the cost estimation in BIM the LCA application in BIM, in some cases, lacks fluent workflows, specific databases, standardised or harmonised comprehension of the building elements, materials, products, components, as well as guarantees to obtain comparable results.

2. Problem statement and goal

In this chapter, we aim to provide a general description of the main concepts and criteria to the building decomposition, especially focus on conduction buildings LCA, its integration into design tools such as BIM methodology and the design workflow. Firstly, it includes a review of the main concepts and current standards in the field of taxonomy and classification systems applied to the construction works. Secondly, an overview of the use of systematic building decomposition to conduct LCA in the context of the Annex participants is presented. It discusses and compares them in theory, the main aspects of the classification systems to decompose building elements and its application in the context of digital design tools (such as BIM). Thirdly, a comparison in practice of the different standards/guidelines is performed by applying the case study to the 'be2226' reference building. Finally, challenges, open questions, and recommendations are proposed.

3. Building decomposition and classification main concepts

3.1 Taxonomy and classification systems

Given that systematic building decomposition implies the organization of the building elements, components and materials, etc., following certain criteria, the concepts of ***taxonomy*** and ***classification systems*** provide a valuable basis to the understanding of how this organization can be performed. In general terms, the taxonomy is considered as "*the science of classification*" (Encyclopedia Britannica, n.d.). It is conceived as a *"list of words that provides a classification of some larger topic"* (Inmon et al., 2019)*,* and has originally been applied to plants and animals. Nowadays, the use of the term is being adopted by other disciplines. Generally, *w*hen a taxonomy is used, categories can be proposed within a classification depending on how relationships of similarities or relationships of interdependence are defined (Currás, 2010). Thus, it will be possible to establish a classification in a horizontal direction, and a hierarchy relation is used to establish a scale from greatest *to smallest, from superior to inferior* entity, which will give a sense of collectively and generality (Currás, 2010). Although, both concepts (taxonomy and classification) are closely related, slight differences are detected when considering the **taxonomy** and **classification system**. A **classification system** is a "*systematic arrangement in groups or categories according to established criteria*" (Merriam-Webster, 2020). A taxonomy can provide a structure and tags for the classification system. Classifying things is conceived as a technique to deal with complexity and organize content in a systematic way (ISO, 2013). Hence, regarding both concepts (taxonomy and classification systems), its definition and implications in the systematic building decomposition, the **classification systems** will be considered as a key concept for the systematic comprehension and analysis of the building parts and their relations. The following sections are focused on providing a general overview of the current standards and main concepts to expose a basis for the analysis of the **classification systems** and the standards/guidelines used for the building decomposition.

3.1.1 Review of International Standards of Classification Systems to Construction Works

The main standard related to the use of classification systems is the ISO 22274 (ISO, 2013), and its adaptation to the construction works is the ISO 12006-2 - Building Construction - Organization of Information about Construction Works - Part 2: Framework for Classification. It defines a global framework for the development of built environment classification systems (ISO, 2012a). The standard is focused on the scope definition of construction classification, defines the overall conceptual model, and points out relevant classification tables for the construction industry to use. The ISO 12006-2:2015 applies to the complete life cycle of construction works, including briefing, design, documentation, construction, operation and maintenance, and demolition (ISO, 2012a). The standard was revised in 2015 to, among other aims, "move it from the area of merely classifying document-oriented information to make it more BIM- and object-focused" (International Construction Information Society, 2017). Moreover, the ISO 12006-3:2007 - Building Construction - Organization of Information about Construction Works - Part 3: Framework for Object-Oriented Information, "enables classification systems, information models, object models and process models to be referenced from within a common framework" (ISO, 2012b). It provides the specification of a taxonomy model to define concepts by means of properties, to group concepts, and to define relationships between them, where objects, collections, and relationships are the basic entities of the model (ISO, 2012b). The standard is based on the statement that "the set of properties associated with an object provide the formal definition of the object as well as its typical behaviour" (ISO, 2012b). Overall, the standard proposes a general framework to use classification systems, object models, and object processes, specifically adapted to construction works.

Focusing on the general concepts that establish the ISO 12006-2 (ISO, 2012a) standards, the purpose of a classification system is to organize concepts and terms of a domain and provide a foundation for making distinction between objects. First, it is necessary to define the purpose of the classification, secondly the properties of interest, and finally the object can be organized according to the selected classes and properties (ISO, 2012a). Considering that a class is a concept that refers to an object (ISO, 2012a), in classification, objects are grouped into different classes, where each class is a set composed of its members and determinate by properties. Attributes are concepts that represent an aspect or a singular property of an object (ISO, 2012a). In the BIM methodology an attribute is a "piece of data forming a partial description of an object or entity» (BSI, 2013), otherwise a property is a "unit of information that is dynamically defined as a particular entity instance" (ISO, 2020).

The classification allows to arrange in a hierarchy component classes (Jørgensen, 1998). There, the most general classes are at the higher levels and the most special classes are at the lower levels. A *level* is a set of classes with the same fineness or granularity (ISO, 2012a). The ISO 22274 (ISO, 2013) identify three types of classification tables: enumerative, faceted, and a combination of enumerative and faceted. Figure 2 illustrates the possible levels and relations that in general compose a classification system.

- ***Enumerative:*** *attempt to list all classes within their defined area of applicability* (ISO, 2012a).
- ***Faceted:*** *allows the assignment of multiple classification to an object* (ISO, 2012a).
- ***Combined:*** *a combination of both, in the higher levels of classification an enumerative approach can narrow down the areas of applicability of the individual classes to a manageable size, and at a lower level a faceted approach is applied to specify the nature of the concepts contained in the leaf classes of the classification system* (ISO, 2012a).

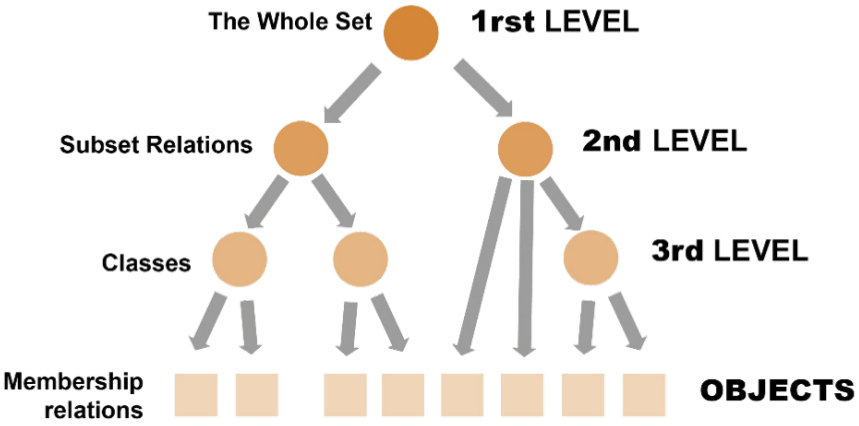

Figure 2: Structure of a classification system. (Source: based on ISO 12006-2 (ISO, 2012a) Building Construction).

3.1.1.1 Part-of relations and type-of relations

The ISO 12006-2 (ISO, 2012a) standard establishes that a classification system, apart from a level order of specializations, has a level order of composition or composition structure. Figures 3 and 4 illustrate examples of the hierarchical principles of classification and composition.

Different types of relations are identified by the different characteristic properties (International Construction Information Society, 2017). The ISO 12006-2 (ISO, 2012a) identifies different types of relations depending on the hierarchy of the classes (classes and sub-classes).

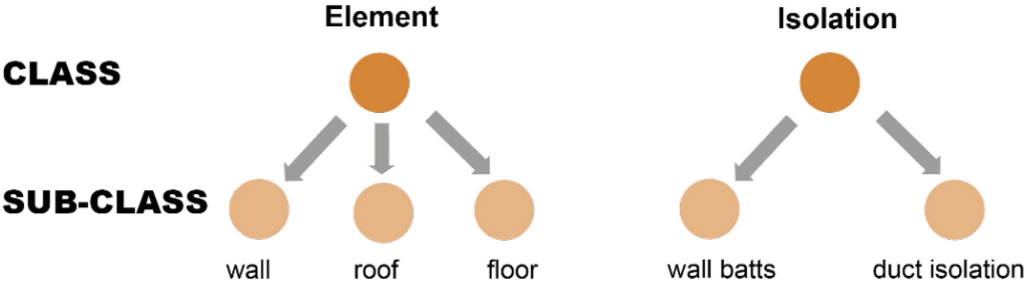

Figure 3: Classification hierarchy, subclasses are types of a superordinate class. (Source: ISO 12006-2 - Building Construction).

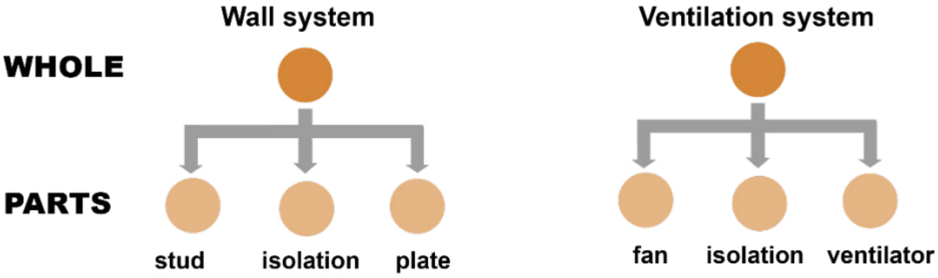

Figure 4: Composition hierarchy, subordinates are parts of a superordinate whole. (Source: ISO 12006-2 - Building Construction).

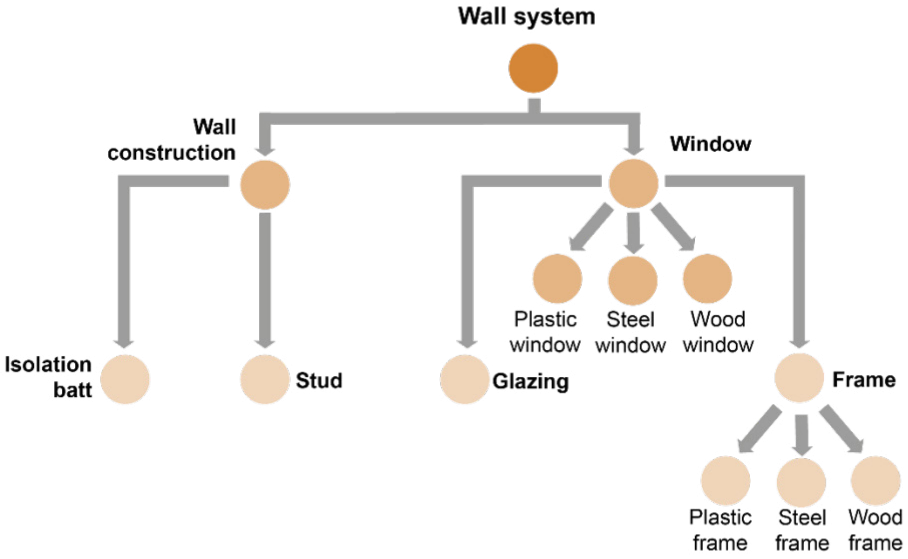

Figure 5: Combination of a composition and classification hierarchy. (Source: ISO 12006-2 - Building Construction).

In building construction, classification into subclass of a superordinate class can generally provide a horizontal decomposition or subdivision of elements (see Figure 3), and a vertical decomposition of elements (see Figure 4) generally allows classification of subordinate parts of a whole. However, horizontal decomposition can also be composed of a combination of both (Figure 5) at the lower vertical levels of decomposition.

3.1.1.2 Principles of specialization Part-of relations and type-of relations

The object of interest of the ISO 12006-2 (ISO, 2012a) standard is the "Construction Object". For this object, four main classes are defined: 'Construction Resource', 'Construction Process', 'Construction Result', and 'Property / Characteristic' (ISO, 2012a). These classes are related in a generic process model which starts with 'Construction Resources', are used in 'Construction Processes' that will result in 'Construction Results', and all these objects have 'Properties / Characteristics' (Ekholm, 2005). The EXPRESS-G schema in Figure 5 illustrates the relations between the most generic classes.

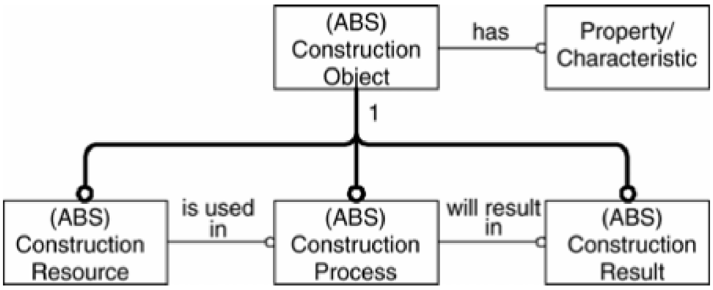

Figure 6: Main object classes and general relations between them. (Source: Ekholm et al. (Ekholm, 2005)).

However, the ISO 12006-2 (ISO, 2012a) standard does not specify any strict classification, recommends and suggests an example of specialization principles (Table 1) applied to the object classes ("Construction Resource", "Construction Process", "Construction Result", and "Property/Characteristic"). Thus, classification table are the results of the application of *principle of specialization* to divide classes into subclasses (ISO, 2012a). In classification systems, there are specific tables to organize and classify elements (on a generic way), designed element (focus on the design stages for drawings and models), Work section/Work result/Production result (for calculation and execution), and Maintenance result (for operation purposes) (International Construction Information Society, 2017).

Table 1. Example of the principles of specialization applied to object classes (Source: ISO 12006-2 (ISO, 2012a))

Class	Classified by
Classes related to sources	
Construction Information	Content
Construction product	Function or form or material, or any combination of these
Construction agent	Discipline or role or any combination of these
Construction aid	Function or form or material, or any combination of these
Classes related to process	
Management	Management activity
Construction process	Construction activity or construction process lifecycle stage or any combination of these
Classes related to result	
Construction complex	Form or function or user activity or any combination of these
Construction entity	Form or function or user activity or any combination of these
Construction element	Form or function or user activity or any combination of these
Built space	Function or form or position, or any combination of these
Work result	Work activity and resources used
Classes related to property	
Construction properties	Property type

Hence, the use of standardized classification systems can support the organization of the information about the building and provide a systematic approach to the decomposition of the buildings, among the development of tables and data structures focus on a certain propose**.** Different stakeholders are interested in different properties depending on the information of interest and their purposes, thus, all classifications are based on characteristic properties (International Construction Information Society, 2017). In this vein, tables and data structures are used to organize different aspects of the building during its life cycle and focus on different purposes such as cost estimation, management and operating activities, among others.

3.2 Synthesis of the section

A taxonomy provides the order to the list of elements, and the *classification system* defines the relations (*part-of* and *type-of*) between those elements. According to the concepts mentioned above, a classification system can define vertical and horizontal orders for building decomposition. Thus, the vertical decomposition allows for the subdivision or classification of a system into subsystems using 'part-of' relations, while the horizontal decomposition allows the order of classes in subdivision determined by 'type-of' relations. Vertical levels and horizontal subdivision decomposition were used to compare and analyse a collection of national standards and guidelines for building decomposition (Soust-Verdaguer et al., 2020). Moreover, the *principles of specialization* also provide a purpose to the organization of the building parts and can also be considered as a key concept to be integrated in the analysis.

Given that the ISO standards do not provide a unique structure or table that should be used to conduct a systematic building decomposition, differences can be detected when analysing different country approaches. The general description of the main concepts and principles used in the definition of a taxonomy for buildings and classification systems provided by this chapter will be considered by the next chapter to compare and analyse different information structures based on standards and guidelines for building decomposition by the Annex participant countries.

4. Systematic Decomposition of Buildings according to National Standards/Guidelines

4.1 Overview of the state of play in the Annex countries

In the context of the IEA EBC Annex 72 when conduction LCA, different classification standards/ guidelines and tables for the building decomposition are used to organize the information of buildings. From an internal (within the IEA EBC Annex 72) survey requesting for contributors in this topic, turned out the following Annex participants: Austria, Belgium, Brazil, Canada, Czech Republic, France, Germany, Netherlands, New Zealand, Spain, Switzerland and UK.

Following, a summary of the structures and tables used by each country is presented in Table 2. It includes the name of the standard / guideline, which is based on, a brief description of the purpose of it use and Table 3 provide a graphical reference (Sankey diagram [1]) to illustrate their main characteristic. The complete version of the tables is included in Appendix I.

Table 2 and Table 3 provide an overview of the main aspects and characteristics of the standards / guidelines / tables, and a brief description of the parameters considered was presented including:

1. Country (use): Refers to the Annex participant country that is using a certain standard/guideline.
2. Name of classification system: If exist, refers to the name of the code, standards, or regulation of the classification system used for the building decomposition.
3. Main purpose: Refers to the main purpose for which it has been developed.
4. Data structure (Sankey diagram): Graphical reference of the data structure for the building decomposition. A general overview of the organization of the data structures including the scope, hierarchy order, and number of parts considered by each of the Annex countries participants.

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[1] The Sankey diagrams were built with http://sankeymatic.com/build/.

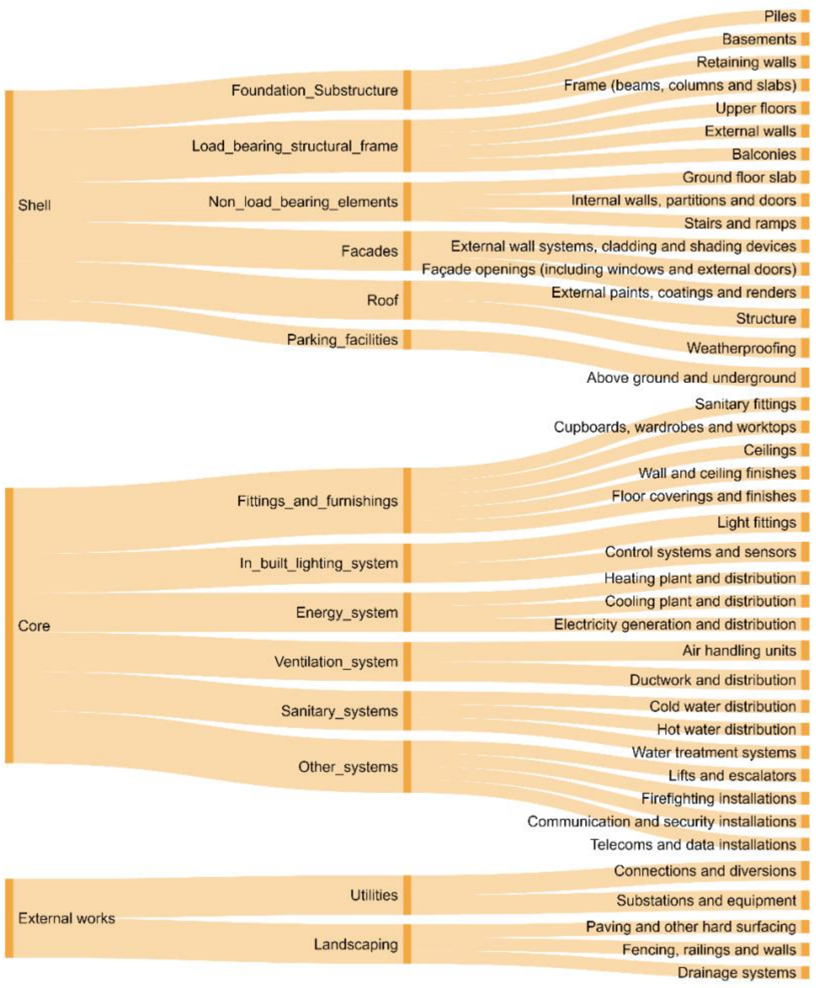
Table 2. National Classification and guidelines for building decomposition use to organise LCA information in Annex countries, including Austria, Belgium, Czech Republic, France, Germany, Netherlands, New Zealand, Spain, Switzerland and UK. (Source: Prepared by the authors based on (Afsari & Eastman, 2016) and on national regulation in classification systems).

Country	Standard or guideline based on	Main purpose
Austria	ÖNORM B1801 (ÖNORM, 2015b)	Building construction cost estimation and LCA data structure.
Belgium	BB/SfB plus (De Troyer, 2008)	Classification and coding system, building construction cost estimation and LCA data structure.
Brazil	ABNT NBR 15575 (NBR 15575-1: Edificações Habitacionais — Desempenho Parte 1: Requisitos Gerais, 2013)	Building performance (also suitable for construction cost estimation and LCA data structure)
Canada	UNIFORMAT II Elemental Classification (E1557-97) (Charette & Marshall, 1999)	Building specifications, cost estimating, cost analysis and (also LCA data structure)
Czech Republic	Not specified – *ad-hoc table*	LCA data structure
France	EQUER model (Polster et al., 1996)	LCA data structure and energy demand calculation
Germany	DIN 276 (DIN, 2008) DIN 18960 (Fröhlich & Fröhlich, 2010)	Building construction, cost estimation, (also LCA data structure).
The Netherlands	NL/SfB	Building construction, cost and LCA data structure
New Zealand	Uniclass 2015 (CPIc, 2015)	Building construction, cost estimation and LCA data structure.
Spain	CTE (CTE, 2006) (Spanish Building Technical Code) and *BCCA* (Andalusian Government, 2017)	Building construction, cost estimation, (also LCA data structure).
Switzerland	SN 506 511 (CRB, 2009)	Building construction, cost estimation and LCA data structure.
UK	SFCA (RICS & BCIS, 2012)	Building construction, cost estimation and LCA data structure.

Table 3. National Classification and guidelines for using the building decomposition to organise LCA information in Annex countries, including Austria, Belgium, Czech Republic, France, Germany, Netherlands, New Zealand, Spain, Switzerland and UK. (Source: Prepared by the authors based on (Afsari & Eastman, 2016) and on national regulation in classification systems)

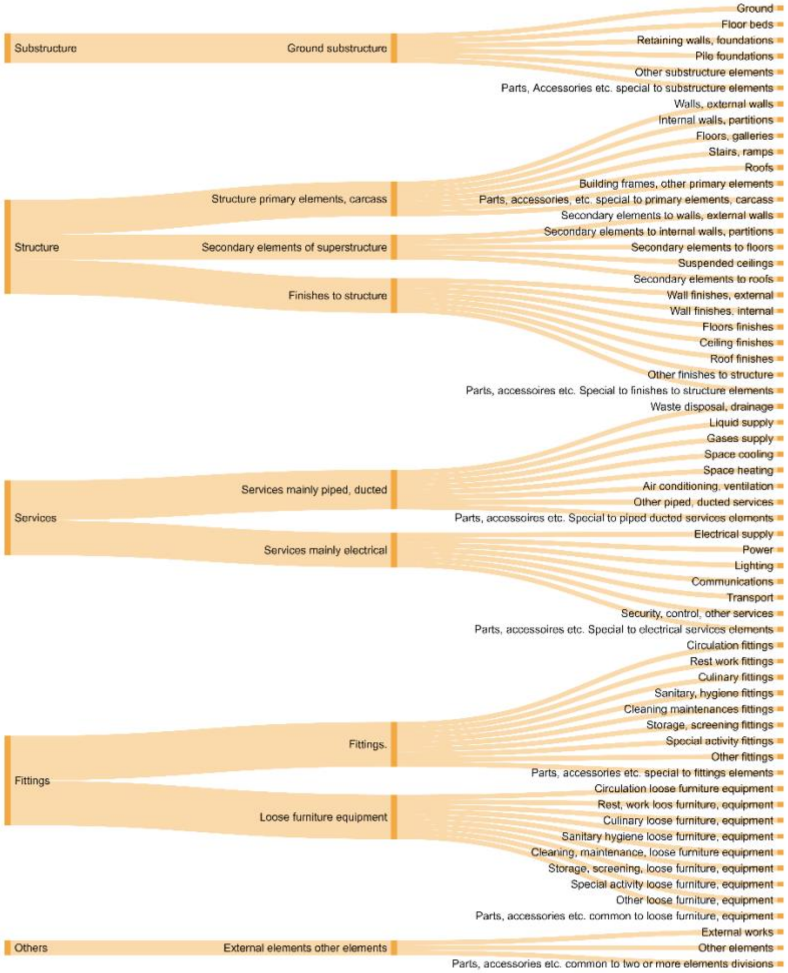
Austria (AT)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



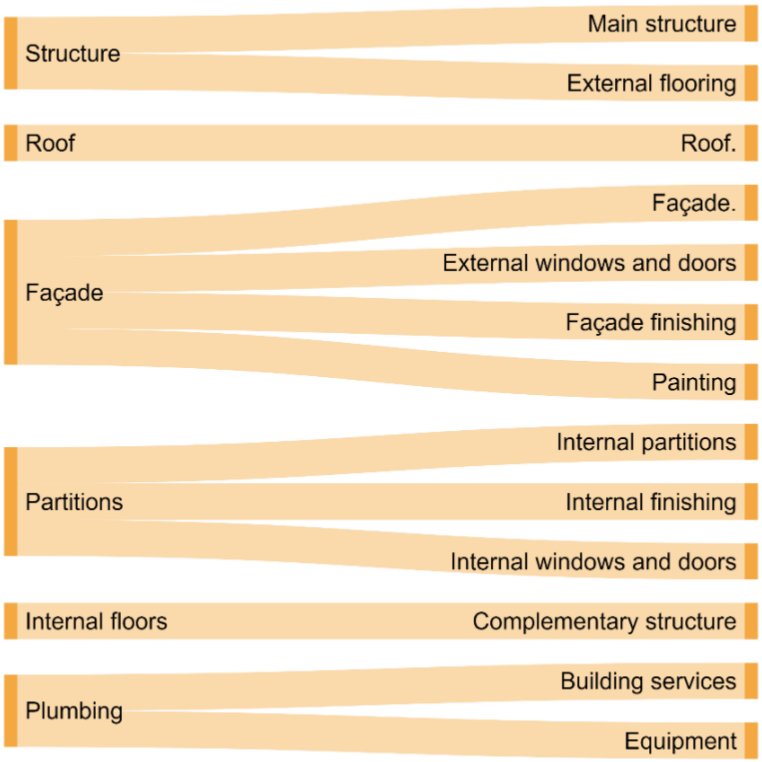
Belgium (BE)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



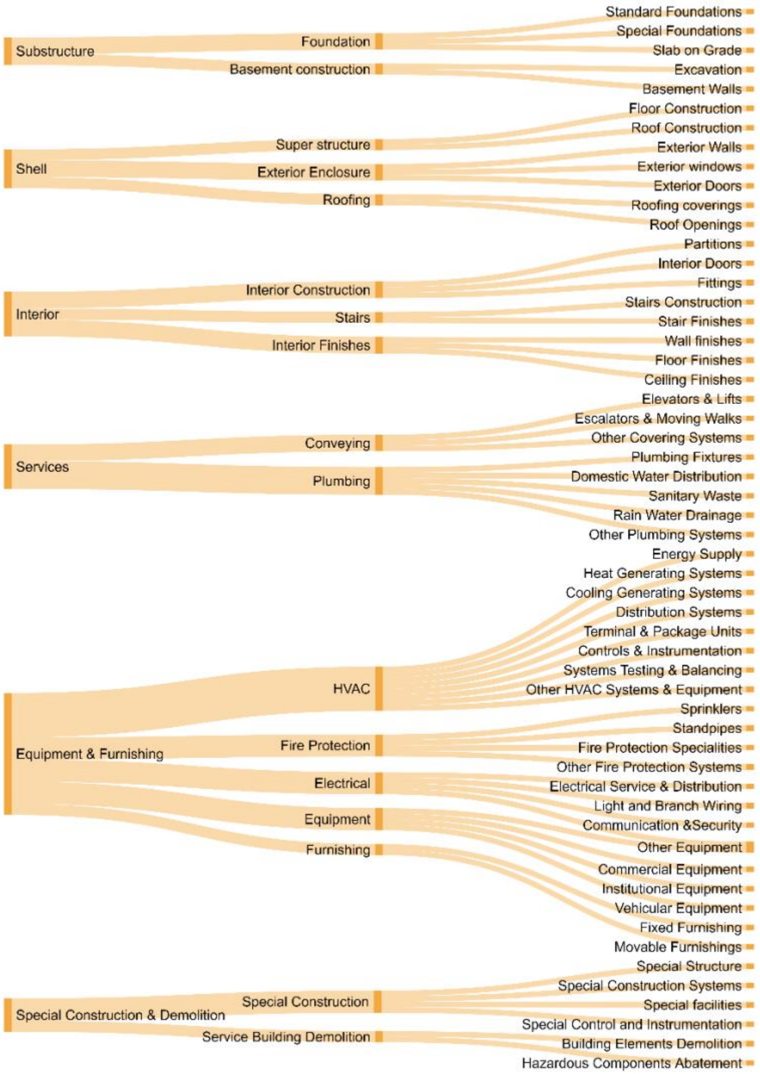
Brazil (BZ)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



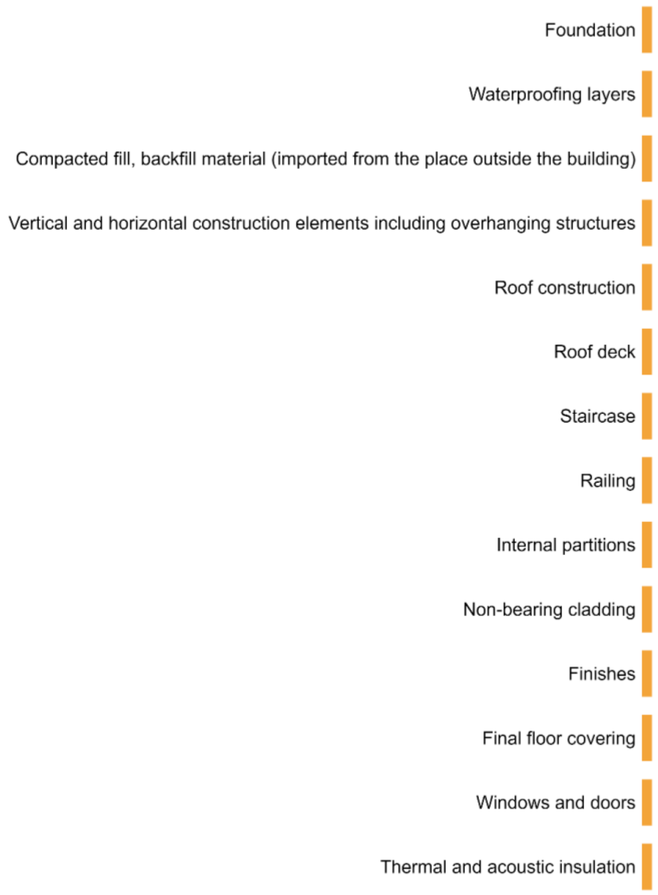
Canada (CA)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



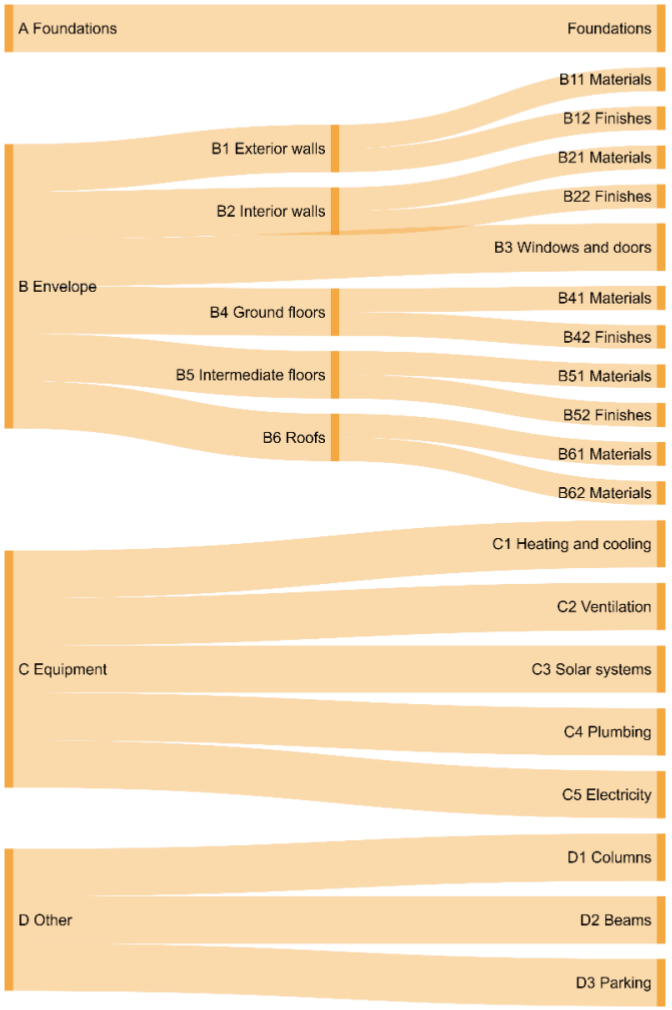
Czech Republic (CZ)

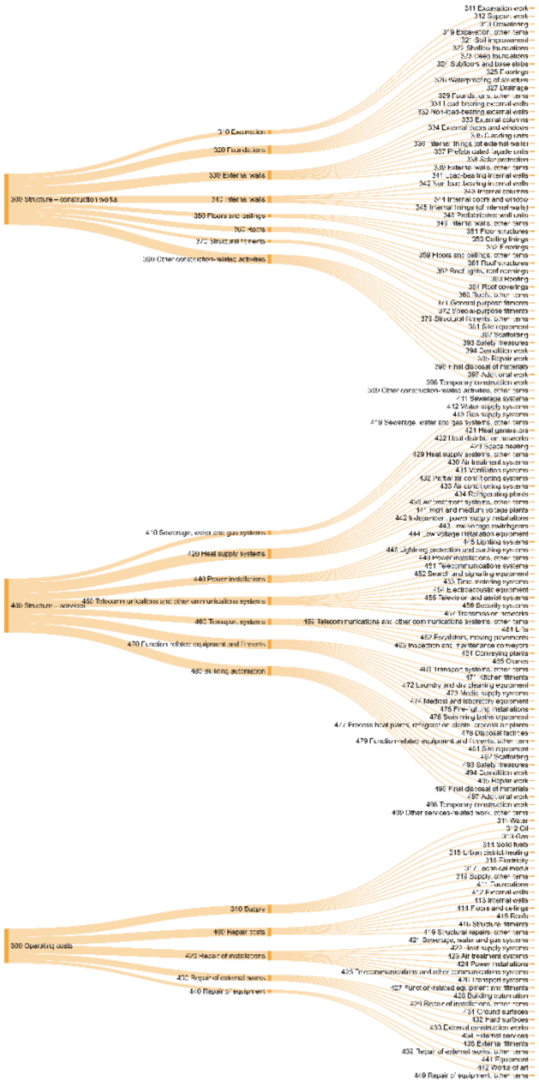
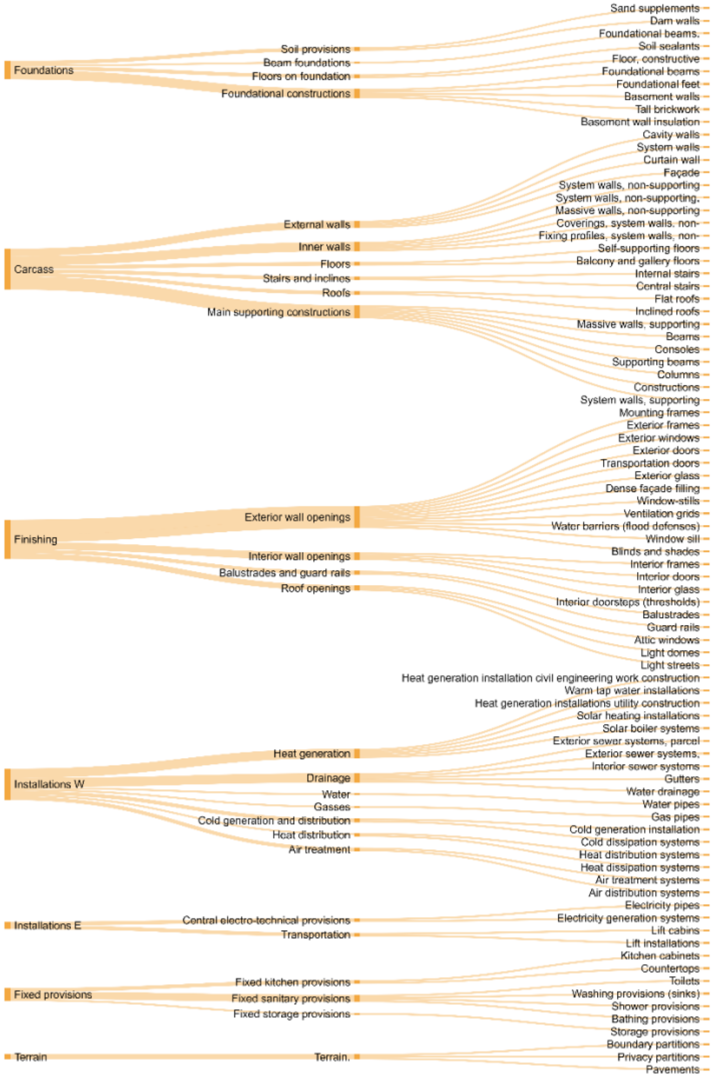
Building decomposition structure: (Ctrl+Click here to enlarge the image)



France (FR)

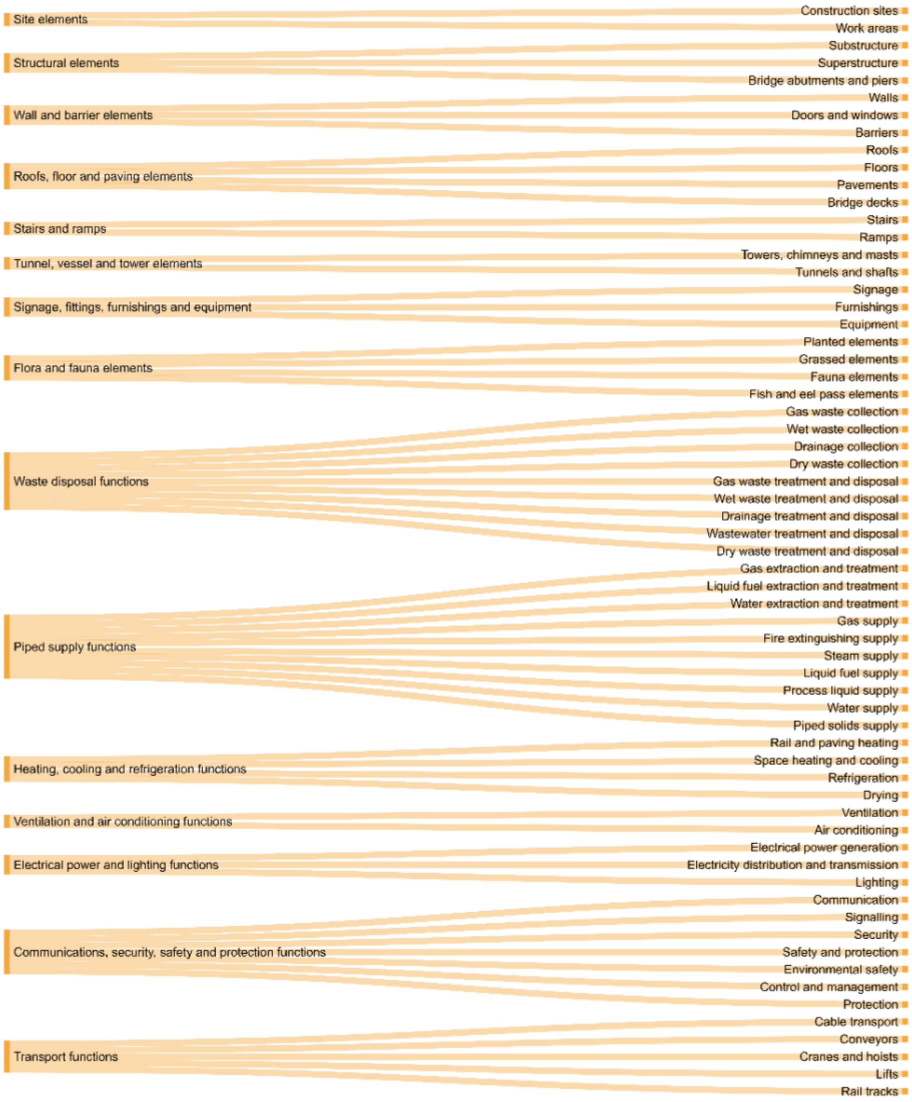
Building decomposition structure: (Ctrl+Click here to enlarge the image)



Germany (DE)		Netherlands (NL)
Building decomposition structure: (Ctrl+Click here to enlarge the image) 		*Building decomposition structure: (Ctrl+Click here to enlarge the image)* 

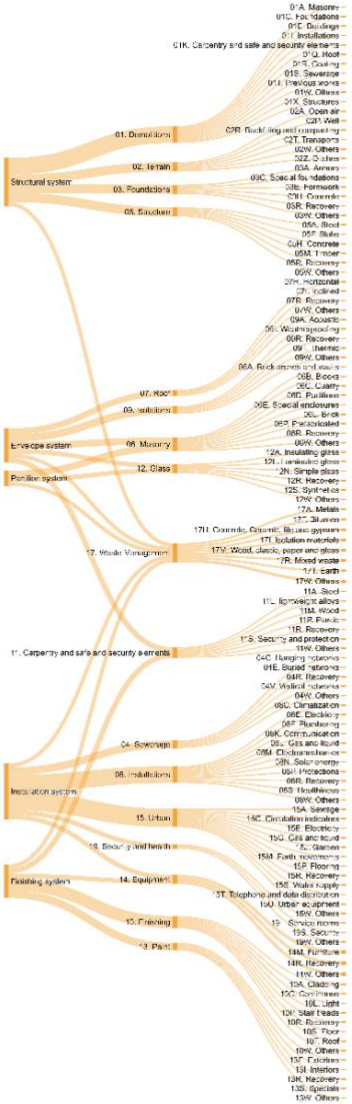
New Zealand (NZ)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



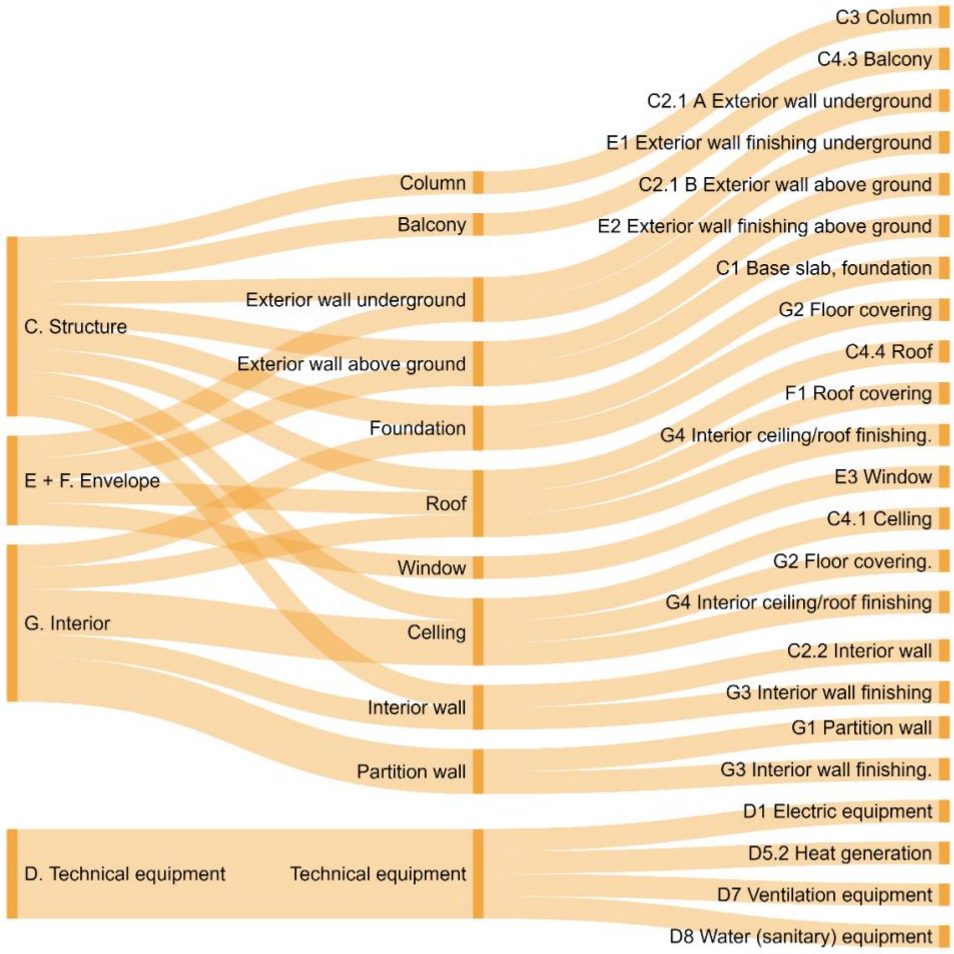
Spain (ES)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



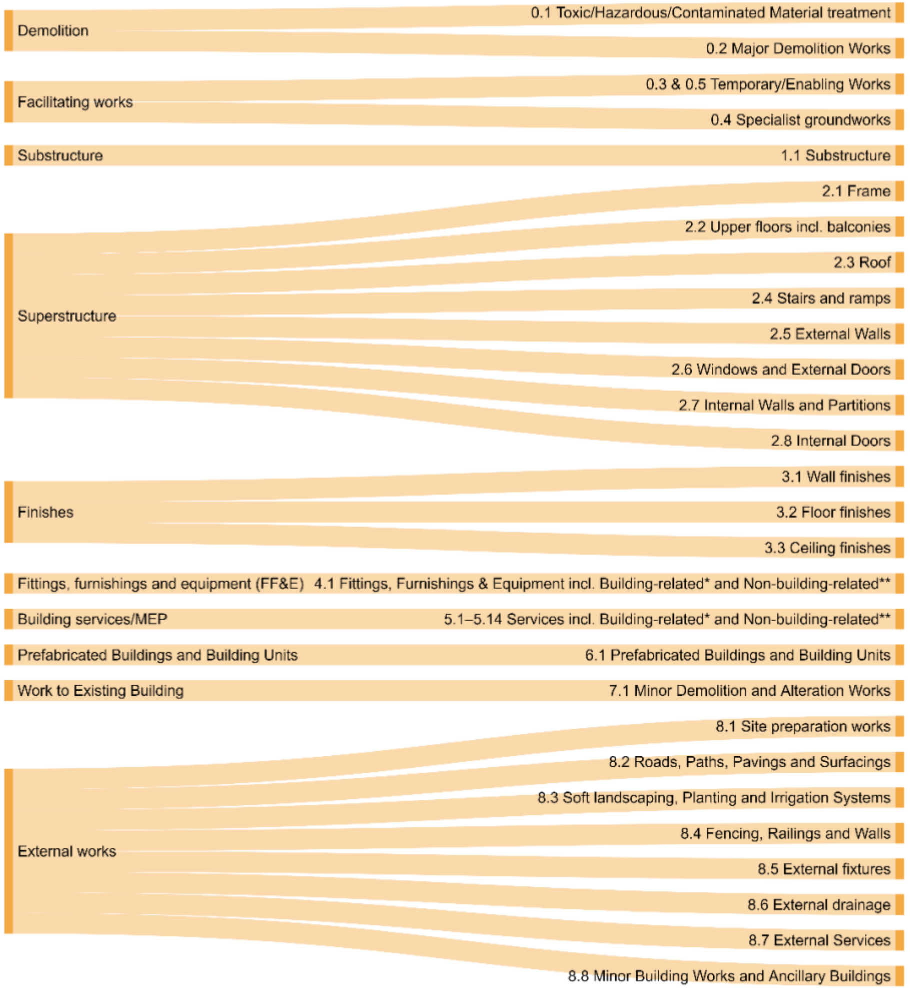
Switzerland (CH)

Building decomposition structure:
Extract of the data structure applied in (Cavalliere et al., 2019). *(Ctrl+Click here to enlarge the image)*



United Kingdom (UK)

Building decomposition structure: (Ctrl+Click here to enlarge the image)



Notice that the structures used for building decomposition are generally composed by tables based on national standards for building construction cost estimations (e.g. UK, Germany, Switzerland). In several cases, the structures belong to guidelines based on national standards to organize building parts/elements (e.g. Belgium). Other countries (e.g. France, and the Czech Republic) proposed a specific structure for the application of LCA.

Table 2 and especially Table 3 provide evidence of the heterogeneity of the different data structures used by each country. Therefore, the following section is focused on analysing and comparing the detected differences, based on the main concepts defined in Section 4.

4.2 Methods

The comparative analysis of the structures/tables/guidelines for building decomposition used by the Annex participant aims to:

- Analyse and categorize their main differences, regarding:
    - the **Vertical and Horizontal orders** to decompose the building (previously defined in Section 3.1.1.1.), (included in Section 5.3.1).
    - the main **principles of specialization** (previously defined in Section 4.1.2., Table 1), (included in Section 5.3.1).
- Analyse their implications to conduct LCA in BIM, regarding:
    - an overview of the existing classification systems for systematic building decomposition in BIM (included in Section 5.3.2).
    - the analysis of the design stages of buildings (early and detail) in BIM, (included in Section 5.3.3).

Hence, the objective of Section 5.3.1 is to characterize the main differences on the organization of the building parts and the principles and purpose of their grouping. Sections 5.3.2 and 5.3.3 are focused on the discussion of the integration of systematic building decomposition in the context of design tools.

4.3 Results and Discussion

4.3.1 Analysis of levels of decomposition and principles of specialization

This section presents from a conceptual point of view, the characterization of the differences on the structures/guidelines and tables used for systematic building decomposition, involving the following aspects:

– *Levels of decomposition:* Refers to the number or levels in which each structure/guideline and table decompose the building parts.

1. **Vertical LEVELS** (vertical order) **- COMPOSITION PRINCIPLE (Figure 3 and 4):** This principle is generally based on the use of a structure to relate the parts of a whole (building). For example, considering the structure, a vertical level of decomposition can include columns, slabs, and beams, among others. The use of a hierarchical structure to define different levels of decomposition is generally based on a first level that involves the complete building up to the division into materials/products.

2. **Horizontal SUBDIVISION** (horizontal order) - **CLASS PRINCIPLE** (Figure 3 and 4): The horizontal level generally refers to different classes and sub-classes of systems/categories /elements/objects, for example, focus on the function, materiality, etc.

– *Principles of Specialization:* These principles can provide support to the organization of the information about the building and generate a systematic approach to the decomposition of the buildings, among the development of tables and data structures focus on a certain propose **to a certain stakeholder.**

– *Taxonomy and naming codes:* Refers to the rules and convention codes used for naming the building parts.

The results of Table 3 evidence the heterogeneity of the different structures analysed. This could be due to the differences in the purpose of the classification of building elements, the criteria to organize the building elements (principle of specialization) and the naming codes (taxonomy principles). Some of the national structures for building decomposition were based on national standards for cost estimation such as the Swiss SN 506 511(CRB, 2009). Others organize building elements of the LCI such as in the France case. Thus, from the analysis of **Tables 2, 3, and 4** several findings can be extracted:

– **Levels of decomposition:** Most of case studies (such as Austria, Belgium, Germany, Netherlands, New Zealand, Switzerland, Spain and UK) integrate at least three or four vertical levels of decomposition (from the complete building level to elemental level): a first level that integrates the general classification of the building systems or categories, a second level composed by a classification of group of elements, a third level composed by an elemental classification, and a fourth level that integrates a material/product classification. However, major differences have been detected in the horizontal sub-divisions. These differences can have consequences on the LCI completeness and the LCA results, which are analysed in depth in **Section 6** by a case study application**.**

  When evaluating the level definition, differences in the scope are detected. Table 4 shows the differences on the organization of the elements (groups) and the number of elements considered, which also affect the subsequent sub-elements, components, products and materials. For example, considering the building decomposition at vertical level 1 (first classification criteria), it was detected that national regulations do not considered the same number of building groups of elements, and their sub-sequential elements/sub-elements/materials and products.

  The obtained results show that the tables used for implementing the systematic building decomposition at the vertical level are mostly limited to the classification of the building parts up to the elemental decomposition. Thus, none of the tables provide detailed specifications of the more detailed vertical levels of decomposition (such as material, typology, or manufacture levels), introduced by Hoxha (Hoxha, 2015) as the highest levels of specification to describe the building parts when conducting LCA. Several exceptions are the Spanish data structure (Andalusian Government, 2017), Belgian (De Troyer, 2008), Canadian (Charette & Marshall, 1999), French (Centre Efficacité énergétique des Systèmes de Mines ParisTech, n.d.), and Switzerland that includes several specifications about the organization of the sub-element or/and material level. For example, Switzerland uses for defining the material level the KBOB ("KBOB. Okobilanzdaten im Baubereich", n.d.) list of materials. The Spanish data structure (Andalusian Government, 2017) (developed for the cost estimation dataset and also to organise the cost estimation database) provides a complete description of the systems and processes that comprise building construction, including a description of the elements, subelement, materials, products, machinery, and labour, according to the regional technical characteristics (more detailed information is included in Appendix I). This approach can provide a complete dataset and increase transparency when conducting the detailed modelling of construction (A5), replacement (B4) or deconstruction modules

(C1), due to the fact that allows to organize the specific information about the building parts (e.g., energy consumption for installation of the items).

Despite the heterogeneity in the number of the horizontal sub-divisions (from 9 to 32 at the vertical level 2), the results show (see Table 3) that several groups of elements have been generally considered. These are foundations, façade, roofs, floors, partitions (related items coloured orange in Table 4). Hence, the main differences are related to their conception, organization, and to the number of type-of relations considered. For example, Uniformat standard (Charette & Marshall, 1999) (Canada) defines three element types in the group of foundations (“Standard Foundations”, “Special Foundations”, “Slab on Grade”), while the German standard (DIN, 2008) defines eight types (“321 Soil improvement”, “322 Shallow foundations”, “323 Deep foundations”, “324 Subfloors and base slabs”, “325 Floorings”, “326 Waterproofing of structure”, “327 Drainage”, and “329 Foundations, other items”).

- **Principle of Specialization:** Table 4 evidences that most of the structures for the building decomposition that organize the object classes related to “Construction elements” (based on Table 1 ISO 12006-2 (ISO, 2012a) examples), focus on the main class “Construction Result” (ISO, 2012a). Notice that in almost all data structures, an *elemental decomposition of the building* has been performed. However, several differences on the organization and hierarchization of the “Construction elements” are identified. For example, the French structure considered finishes at vertical level 3, and the Dutch structure integrates a category for “finishes” at vertical level 1. However, other object classes are considered, in addition to the 'Construction elements'. Germany, for example, declared the use of tables/structures to organize information about use stages, close to object classes related to 'Management activity' (see Table 1). The UK and Spain also include object classes related to 'construction aids' (such as 'Demolition' UK or 'Ground breaking' Spain).

  Moreover, the results also show that some of the analysed examples combine an *element classification* (relating to the elements that compose the building) with a classification into *system* approach (relating to the systems that compose the building) (see Figure 7). This means that some countries first perform a *classification into systems* and then a *classification of element* (e.g., Spain (Andalusian Government, 2017) first recognises the “Finishing system” and then the elements (such as external wall, ceiling, etc.) that include the finishing). In this vein, the Uniclass 2015 (CPIc, 2015) standard is the unique standard for the classification system that explicitly provides a set of classification tables focused on different purposes (systems, elements, among others). The elemental classification / decomposition generally allows to identify the most relevant elements that compose the building, such as the structure, exterior walls, partitions, etc. It also can help to track an item from the elemental to the material level (e.g., alkyd paint (material level) _paint layer (sub-element) _exterior wall 2 (element level)). In contrast, the system classification can help to group by their function the main systems that compose the building. The limitation of that approach is that the possibilities of tracking a material by the element and sub-element which belongs to, can be not possible. This means that once similar materials are identified, they can be grouped without specifying the specific element and sub-element that it came from.

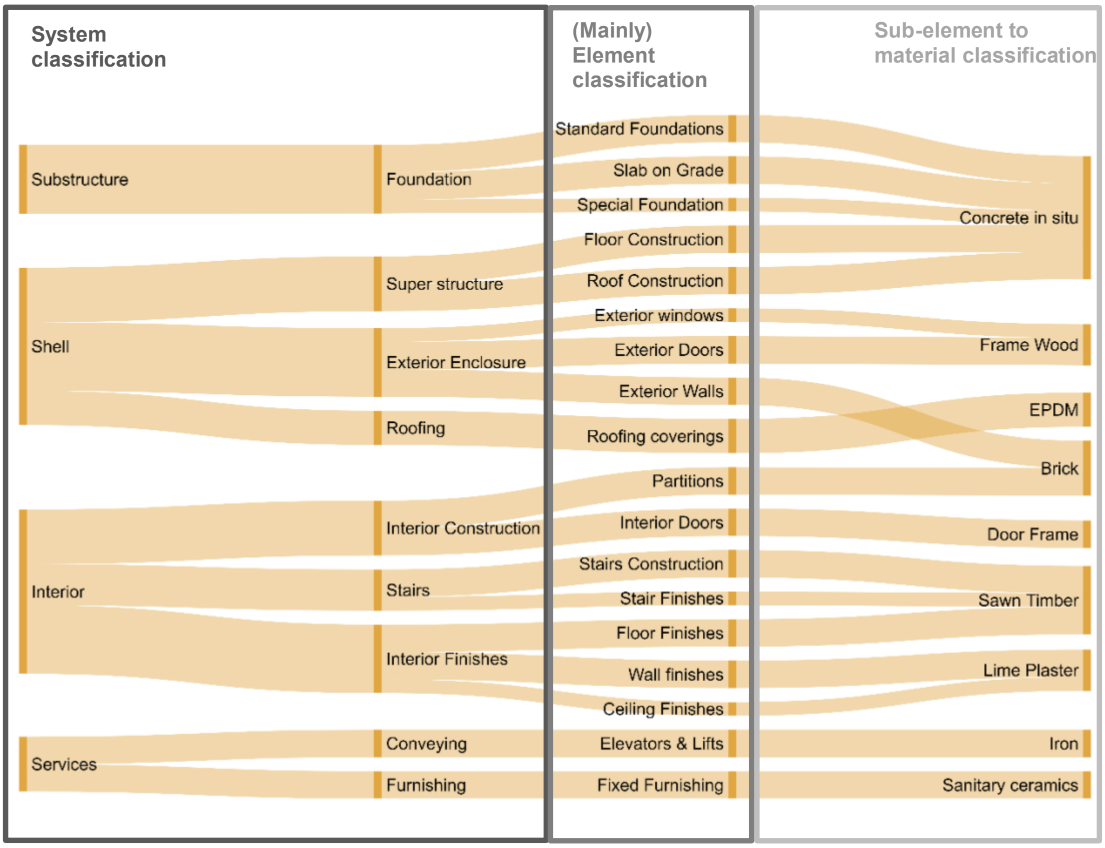


Figure 7. Example of the system and elemental approaches based on a selection of items of the Uniformat II standard. (Source: Prepared by authors)

For example, the finishing material for the walls (e.g. lime plaster interior) can be grouped together without specifying which type of wall it belongs to (interior or exterior). Notice that a classification system should allow to identify all the elements that compose the building and describe the main characteristics of those systems that transversally involve the building elements (e.g., finishing, waterproofing layers).

- **Taxonomy and naming codes:** Several differences have been noticed in naming codes and conventions, which follow different criteria on the taxonomy and organization of the different levels of decomposition. These could be due to differences in translation or meaning definition related to each country or region. For example, similar terms are used to describe similar items such as 'Shell' (Austria and Canada), 'Carcass' (The Netherlands and Belgium) and 'Envelope' (France, Spain, and Switzerland). The differences can also be related to the regional technical characteristics of each country and the traditions and technologies of building construction.

  The obtained results show that several standards provide detailed rules for introducing the naming codes when tagging elements, sub-elements and materials (e.g., Spain), while other standards or guidelines (e.g., France) introduce a less rigorous rules. Notice that the use of naming conventions and tags can provide a useful reference when tracking and organizing the data for implementing LCA and especially in BIM.

Table 4. Number of vertical levels of decomposition and horizontal sub-divisions. A detailed description of the building element type is provided in the Appendix I. (Source: Prepared by authors)

	Nr of V-levels*	Country code										
		AT	BE	BR	CA	CH^1	CZ	DE	ES	FR	NL	NZ	UK
Number of H-Levels**	1	3 Shell, Core, External works	5 Substructure Structure Services Fittings Others	**6 Systems:** Structure Internal floors Façade Partitions Roof Plumbing	**4 Major Group Elements** A Substructure, B Shell, C Interiors, D Services	**3 Categories:** Structure Envelope Interior	Not specified	2 **Systems:** 300 Structure construction works, 400 Structure – services **300 Operating costs**	5^2 **Systems:** Structure; Envelope; Partitions; Finishing; Air conditioning and installations	4 **Systems/ Categories:** A Foundations; B Envelope; C Equipment D Other	5 **Category/System**: Foundations, Carcass, Finishing, Finishes; Installations E	1 EE_Elements and functions	4 Category/Systems 1 Substructure 2 Superstructure 3 Finishes Fittings, furnishings and equipment (FF&E) 4 Building services/MEP
	2	**14 Building parts:** 1. Foundation Substructure 2. Load bearing structural frame 3. Non load bearing elements 4. Facades 5. Roof 6. Parking facilities 7. Fittings and furnishings 8. In built lighting system 9. Energy system 10. Ventilation system 11. Sanitary systems 12. Other systems 13. Utilities 14. Landscaping	**9 Elements Definition:** 1. Ground substructure 2. Structure primary elements, carcass 3. Secondary elements of superstructure 4. Finishes to structure 5. Services mainly piped, ducted 6. Services mainly electrical 7. Fittings 8. Loose furniture equipment 9. External elements other elements.	**14 Building parts:** 1.Main structure; 2.Complementary structure; 3.Façade; 4.Internal partitions; 5.Roof; 6.Internal finishing; 7.Façade finishing; 8.External flooring; 9.Painting; 10. Waterproof system; 11. External windows and doors; 12. Internal windows and doors; 13. Building services; 14. Equipment	**17 Group of Elements:** 1. Foundation 2. Basement construction 3. Super structure 4. Exterior Enclosure 5. Roofing 6. Interior Construction 7. Stairs 8. Interior Finishes 9. Conveying 10. Plumbing 11. HVAC 12. Fire Protection 13. Electrical 14. Equipment 15. Furnishing 16. Special Construction 17. Service Building Demolition	**16 Building elements:** 1. Foundation 2. Exterior wall 3. Interior wall 4. Pillars 5. Floors 6. Stairs and Ramps 7. Balcony 8. Roof 9. Technical equipment 10. Exterior Window and doors 11. Partitions, doors 12. Fixed equipment 13. Ceiling 14. Special Technical equipment 15. Outdoor equipment 16. Furniture equipment	**14 Building parts** 1. Foundation 2. Waterproofing layers 3. Vertical and horizontal construction elements 3. Roof construction 4. Roof deck 5. Staircase 6. Internal partitions 7. Non-bearing cladding 8. Finishes 9. Final floor covering 10. Windows and doors	**21 Building group of elements/process:** **300 Structure – construction works** 310 Excavation 320 Foundations 330 External walls 340 Internal walls 350 Floors and ceilings 360 Roofs 370 Structural fitments 390 Other construction-related activities **400 Structure – services** 410 Sewerage, water and gas systems 420 Heat supply systems 440 Power installations 450 Telecommunications and other communications systems 460 Transport systems 470 Function-related equipment and fitments 480 Building automation 490 Other services-related work **300 Operating costs** 310 Supply 400 Repair costs 420 Repair of installations 430 Repair of external works 440 Repair of equipment	**18^3 Building group of elements/process:** 01. Demolitions 02. Terrain 03. Foundations 04. Sewerage 05. Structure 06. Masonry 07. Roof 08. Installations 09. Isolations 10. Finishing 11. Carpentry and safe and security elements 12. Glass 13. Paint 14. Equipment 15. Urban 17.Waste Management 19.Security and health	**14 Building parts:** B1 Exterior walls B2 Interior walls B3 Windows and doors B4 Ground floors B5 Intermediate floors B6 Roofs C1 Heating and cooling C2 Ventilation C3 Solar systems C4 Plumbing C5 Electricity D1 Columns D2 Beams D3 Parking	**32 Groups of Elements:** 1. Soil provisions 2. Floors on foundation 3. Foundational constructions 4. Beam foundations 5. External walls 6. Inner walls 7. Floors 8. Stairs and inclines 9. Roofs 10. Main supporting constructions 11. Exterior wall openings 12. Interior wall openings 13. Balustrades and guard rails 14. Roof openings 15. Exterior wall finishes 16. Interior wall finishes 17. Floor finishes 18. Ceiling finishes 19. Roof finishes 20. Heat generation 21. Drainage 22. Water 23. Gasses 24. Cold generation and 25. distribution 26. Heat distribution 27. Air treatment 28. Central electro-technical provisions 29. Transportation 30. Fixed kitchen provisions 31. Fixed sanitary provisions 32. Fixed storage provisions 33. Terrain	**15 EF_Elements** 1.Site elements 2.Structural elements 3.Wall and barrier elements 4.Roofs, floor and paving elements 5.Stairs and ramps 6.Tunnel, vessel and tower elements 7.Signage, fittings, furnishings and equipment 8.Flora and fauna elements 9.Waste disposal functions 10. Piped supply functions 11. Heating, cooling and refrigeration functions 12. Ventilation and air conditioning functions 13. Electrical power and lighting functions 14. Communications, security, safety and protection functions 15. Transport functions	**28 Building elements** 0.1 Toxic/Hazardous/Contaminated Material treatment 0.2 Major Demolition Works 0.3 & 0.5 Temporary/Enabling Works 0.4 Specialist groundworks 1.1 Substructure 2.1 Frame 2.2 Upper floors incl. balconies 2.3 Roof 2.4 Stairs and ramps 2.5 External Walls 2.6 Windows and External Doors 2.7 Internal Walls and Partitions 2.8 Internal Doors 3.1 Wall finishes 3.2 Floor finishes 3.3 Ceiling finishes 4.1 Fittings, Furnishings & Equipment incl. Building-related* and Non-building-related** 5.1–5.14 Services incl. Building-related* and Non-building-related** 6.1 Prefabricated Buildings and Building Units 7.1 Minor Demolition and Alteration Works 8.1 Site preparation works 8.2 Roads, Paths, Pavings and Surfacings 8.3 Soft landscaping, Planting and Irrigation Systems 8.4 Fencing, Railings and Walls 8.5 External fixtures 8.6 External drainage 8.7 External Services 8.8 Minor Building Works and Ancillary Buildings
	3	**41 Building elements type**	**61 Element/process type**	-	**57 Individual Elements**	**58 Building elements type (also called "Building components")**	-	**142 Element/process type**	**115 Elements/process type**	**10 Sub-elements/materials**	**111 Building elements type**	**66 Building elements type**	Not specified
	4	-	A brief description of the sub-elements, materials, products sub-division is given. Detailed descriptions is provided in the document (De Troyer, 2008).	-	A brief description of the sub-elements, materials, products sub-division is given. Detailed descriptions is provided in the document (Charette & Marshall, 1999).	Here is used the KBOB list (*KBOB. Okobilanzdaten Im Baubereich*, n.d.).	-	-	A definition and description of default sub-elements, materials, products, machinery and labour is given. Detailed descriptions is provided in the BBCA document (Andalusian Government, 2017).	-	-	-	-

* Number of Vertical Levels of decomposition. ** Number of Horizontal Levels of decomposition. 1 The listed items comprise a selection of the most relevant items for the purpose of systematic building decomposition. 1 Based on CTE (CTE, 2006) (Spanish Building Technical Code) primary classification. 3 Based on BBCA (Andalusian Government, 2017)Classification.

4.3.2 Systematic Building Decomposition in the context of digital design tools - BIM and LCA

In current practice, the systematic building decomposition in the context of digital design tools is supported by using *classification systems,* which allows (among others) to insert naming codes/tags and list elements in the BIM model. Two of the most used BIM software -Autodesk Revit (Revit, 2021) and AchiCad (GRAPHISOFT, 2017)- allows to integrate many classification systems in the BIM model in an easy and user-friendly way (included in the default configuration of the software or by a downloadable add-in or packaged). Autodesk Revit (Revit, 2021), for example, integrates *Autodesk Classification Manager for Revit* (Autodesk Revit, n.d.) an add-in that allows to integrate UniFormat (Charette & Marshall, 1999), MasterFormat, OmniClass (International Organization for Standardization (ISO) et al., n.d.), Uniclass, or a custom database classification system to the BIM model. Archicad (GRAPHISOFT, 2017), for example, integrates a 'BIM Content' that can be imported from its web page. Actually, the available national classification systems are the followings (updated to 19/08/2020) : Önorm 6241-2 (AT), Uniclass 2015 (UK), Uniclass 2 (UK), CAWS, SFG20, RICS NRM 1, RICS NRM 3, NBS Create, MasterFormat, OmniClass (International Organization for Standardization (ISO) et al., n.d.), ASTM UniFormat II (US) (Charette & Marshall, 1999), 2010 CSI UniFormat (US), NATSPEC, CCS, BIM7AA, Rumsfunktionskoder - CC001_001_001, Rumsfunktion - CD002_001_001, Funktionskoder Regionservice -CD001_001_004, BIMTypeCode, NS 3451 – Beygningsdelstabell, TALO 2000 Hankenimikkeistö, TALO 2000 Building Component Classification, SINAPI, NL/SfB (NL), EcoQuestor, STABU-Element, BB/SfB (BE), VMSW, GuBIMclass (ES).

Table 5 introduces the list of existing classification systems and shows if the standard is used by the Annex participant country for implementing LCA. Notice that several standards integrated in ArchiCAD (Classification manager) are mainly focused on the BIM methodology than on the definition of classification systems for construction works, such as the ÖNORM B 6241-2 (ÖNORM, 2015a) "Digital structure documentation - Part 2: Building Information Modelling (BIM) - Level 3-iBIM".

An automatic workflow between the classification system and the BIM model can reduce effort when integrating LCA in the BIM workflow. The current situation towards the integration of the classification system in the most used BIM commercial software shows that just the most popular classification systems (e.g., Master Format, Uniformat) are included in the automatic workflow of the software, that can be to the fact that the some of the BIM software have adapted their capabilities to the national requirements (e.g., Revit to United States of America).

Moreover, Table 5 also shows that the integration of the classification system into the BIM automatic workflow is still scarce in the context of the Annex participant countries. The most frequently used BIM software have not yet included at all the possibility to have an automatic workflow between the different national classification system used for LCA purpose and the BIM model.

Table 5. Integration of classification systems (tables) in BIM. Source based on: Classification system and its use in Autodesk (Autodesk Revit, n.d.) and BIM content for ArchiCAD (GRAPHISOFT, 2017).

Revit		
Classification system	**Country of origin**	**Annex participant in practice**
UniFormat (Charette & Marshall, 1999)	US	Canada
MasterFormat	US	-
OmniClass (International Organization for Standardization (ISO) et al., n.d.)	US	-
Uniclass	UK	New Zealand
a custom database classification system	-	-
ArchiCAD		
2010 CSI UniFormat	US	-
BB/SfB	BE	Belgium
BIM7AA	DK	-
BIMTypeCode	SE	-
CAWS	UK	-
CCS	DK	-
CCTB	BE	-
EcoQuestor	NL	-
Funktionskoder Regionservice - CD001_001_004	SE	-
GuBIMclass	ES	-
MasterFormat	US	-
NATSPEC	AU	-
NBS Create	UK	
NL/SfB	NL	NL
NS 3451 – Beygningsdelstabell	NO	-
OmniClass [18]	US	-
ÖNORM B 6241-2	AT	-
RICS NRM 1	UK	UK
RICS NRM 3	UK	-
Rumsfunktion - CD002_001_001	SE	-
Rumsfunktionskoder	SE	-
SFG20	UK	-
SINAPI	BZ	-
STABU-Element	NL	-
TALO 2000 Building Component Classification	FI	-
TALO 2000 Hankenimikkeistö	FI	-
Uniclass 2	UK	-
Uniclass 2015	UK	New Zealand
UniFormat (Charette & Marshall, 1999)	US	Canada
VMSW	BE	-

Previous studies provide evidence that one of the most important application of the classification systems into current BIM workflow is for cost estimation (International Construction Information Society, 2018b). Thus, could it be possible to transfer the lessons learnt for implementing it for LCA purposes? Currently, the use of the classification systems (designed focused on cost planning) for conducting cost estimation (International Construction Information Society, 2018b) and LCA (Cavalliere et al., 2019; Naneva et al., 2020; Röck et al., 2018b) in BIM is growing, and the Swiss context is an example of that. For cost estimation, two possible approaches are identified: the "component-oriented" and BIM compatible with the e-BKP (CRB, 2009) and the "execution-oriented" compatible with the BKP classification (International Construction Information Society, 2018b). The "elemental" or "component-oriented" approach is considered a suitable method to calculate the total costs of building works (International Construction Information Society, 2018a) and the sustainable assessment (Lützkendorf, 2019). This approach is also more compatible with the BIM workflow (analysed in detail in Section 6) than the "execution-oriented" approach.

The process requires among others, the quantification and the use of classification systems to identify and organise the building elements that compose the building. Performing a classification and identification coding of objects provides better possibilities for securing that everything has been properly included (International Construction Information Society, 2017).

In BIM, which is the generic classification of building elements that compose a model? The IFC Version 4.1.0.0 scheme (buildingSMART, 2020) (interoperable BIM format) propose an element classification that distinguish the physically existent objects given by the *IfcElement* entity (buildingSMART, 2020). The *IfcElement* entity cover the abstract supertypes of:
IfcBuildingElement, *IfcFurnishingElement, IfcElectricalElement, IfcDistributionElement, IfcTransportElement, IfcEquipmentElement, IfcFeatureElement, IfcElementAssembly, IfcVirtualElement.*

The *IfcBuildingElement* entity cover the major functional part of a building and comprise all elements that are primarily part of the construction of a building, its structural and space separating system, which are all physically existent and tangible things (buildingSMART, 2020). The *IfcBuildingElement* entity covers the abstract supertypes of:
IfcBuildingElementProxy, IfcCovering, IfcBeam, IfcColumn, IfcCurtainWall, IfcDoor, IfcMember, IfcRailing, IfcRamp, IfcRampFlight, IfcWall, IfcSlab, IfcStairFlight, IfcWindow, IfcStair, IfcRoof, IfcPile, IfcFooting, IfcBuildingElementComponent, IfcPlate.

The IFC element classification recognises the following physical building parts: Covering, Roof, Column, Curtain wall, Door, Railing, Ramp, Ramp flight, Wall, Slab, Stair, Window, Roof, Pile, Footing, Plate. The element classification also covers the furnishing, electrical elements, distribution element, transport element, equipment, element assembly, and virtual elements.

4.3.3 Systematic Building Decomposition to conduct LCA during building design stages in BIM

In BIM, multiple levels of object definition are needed during the building's design stages. At early design stage, generic objects are used to compose the model. At detailed design stage the amount of information about the objects increase, but the object (e.g. a door) will still be the object, changes are detected in the granularity and precision of the object information (International Construction Information Society, 2017). Based on previous research (Santos et al., 2019) related to the integration of BIM and LCA in the design stages, two milestones or stages to conduct the LCA are identified: **the early design and the detail stage. At the Early design stage**: general LOD/LOG up to 200, element definition (lower modelling precision, use of generic objects). **At the detail design stage:** general LOD/LOG upper than 300, product/material definition (higher element modelling precision and product/material definition). The **element definition** relates to the geometry definition of the building elements, which could correspond to an up to 200 LOD/LOG. At this level the layers of the building elements are not at all defined. The **product/material definition** referes to an upper level of detail of the information about the building elements, where the layers and specific materials are already defined (at least 300 LOD/LOG).

As well as during the modelling process in BIM, in building decomposition the granularity of the data structure can increase as well as the number of vertical levels of decomposition. This means that generally the higher number of vertical levels, the greater number of building elements, building sub-elements, products and materials are identified. However, modelling tools not always allows to manage objects/materials/components/products at the same level of decomposition as the structures for building decomposition (International Construction Information Society, 2017).

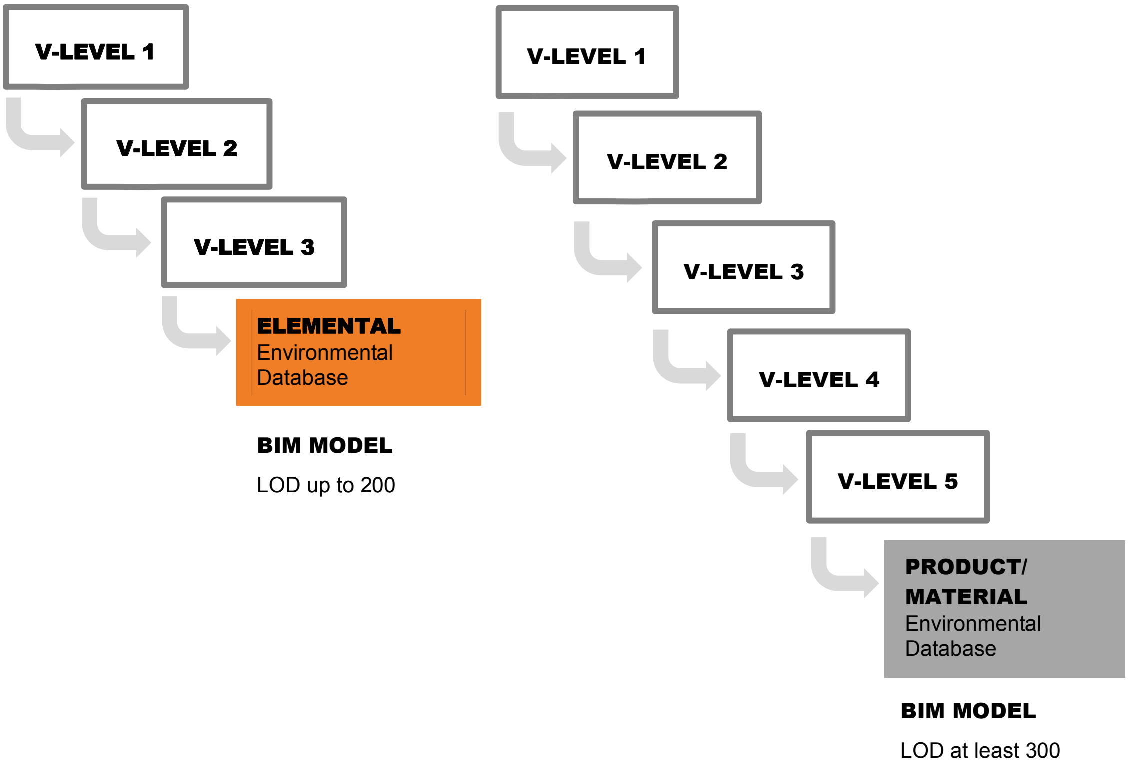
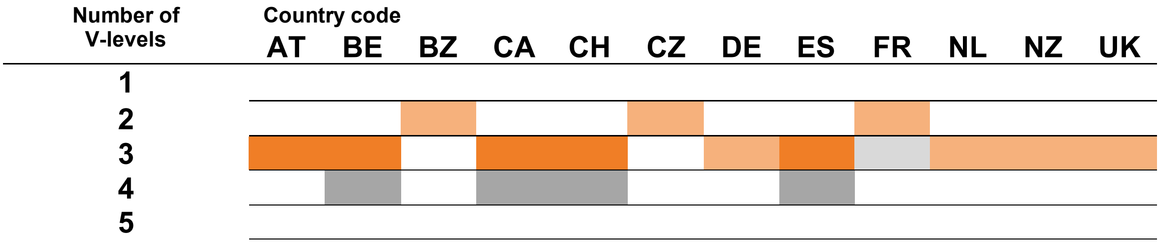


Figure 8. Example of the V-Level correlation with the environmental databases structure.

Figure 8 gives an example of the possible correlation between the vertical levels of decomposition, the environmental (LCA) database structure, the LOD/LOG/LOI of the BIM model, and design stage of the building. There, two possible design stages are considered: early and detail. These stages are ideally defined by two possible decomposition "milestones": i) **the elemental classification** (for early design) and ii) the **product/material classification** (for detail design). Thus, are the early and detailed LCA related to a specific elemental or product/material level of decomposition? Regarding the studied structures, the elemental classification can probably be performed at the vertical-levels 2/3 approx., which means that the environmental impact calculation can be ideally performed by using a BIM model with an up to 200 LOD (LOG/LOI), and an environmental database which integrates an elemental decomposition structure (e.g. Bauteilkatalog (Holliger Consult, n.d.)). The product/material classification (for detail design) can be performed following the elemental classification but increasing the granularity of data. Considering the studied structures, the product/material classification (for detail design) can probably be performed at the V-levels 3/5 approx., which means that the environmental impact calculation can be ideally performed by using a at least 300 LOD (LOG/LOI) BIM model and an environmental database which integrates a material/product structure (e.g. EPD database, or KBOB (*KBOB. Okobilanzdaten Im Baubereich*, n.d.)). Following, Table 7 introduce an overview of these aspects in the context of the Annex participants.

Table 7. Differences on vertical and horizonal level definition and the correlation with the design stages. (Source: Prepared by the authors based on national standards and guidelines for building decomposition to conduct LCA)



Number of V-levels	**Country code** **AT**	**BE**	**BZ**	**CA**	**CH**	**CZ**	**DE**	**ES**	**FR**	**NL**	**NZ**	**UK**
1												
2			🟠			🟠			🟠			
3	🟧	🟧		🟧	🟧		🟠	🟧	░	🟠	🟠	🟠
4		▓		▓	▓			▓				
5												

References: Number of Vertical Levels of decomposition

Orange (dark and light): early design stage / Grey (dark and light): detailed design stage

The obtained results confirm that the criteria to perform the elemental decomposition of the building is heterogeneous. Considering that the elemental classification (needed at the early design stages), is the decomposition of the building parts into items such as pillars, beams, roof, floor, external walls, windows, doors, balconies, etc. some data structure combine different levels of disaggregation. For example, Austrian structure combines group of elements such as “Foundations_Substructure” and “Load bearing structural frame” at level 2, where is contained the element “External walls” (level 3) while the German structure includes at level 2 a group of elements called “External walls” as well as “Foundations”. Also, the decomposition regarding the number of elements considered can be different, for example the German structure includes 9 categories for decomposing the “external walls” group (331 Load-bearing external walls, 332 Non-load-bearing external walls, 333 External columns, 334 External doors and windows, 335 Cladding units, 336 Internal linings (of external walls), 337 Prefabricated façade units, 338 Solar protection, 339 External walls, other items), while the Dutch structure includes a group of elements called “External walls” at level 2 and at level 3 includes a type-of classification of that element into “Cavity walls”, “System walls”, “Curtain wall”, “Façade”. Due to that fact the rules for identifying the elemental decomposition and the definition of the vertical level are diverse, the Table 7 use two different colors for identifying the elemental classification level, the orange is used to indicate the cases that clearly fit into the above-mentioned criteria and the light orange is used for indicating the cases that partially perform it. Reading the sub-elemental and material decomposition (needed at the detailed design stages), similar difficulties are detected.

In general, Table 7 provide evidence of the differences in the granularity of the building decomposition structures (elemental or product/material decomposition) used by the Annex country participants to conduct early or detail LCA. Those differences can affect the data structure for the building decomposition not only to organize the LCI, but also the data set of databases and other needed data sources for implementing the LCA. Moreover, regarding the evolution of the building definition through the design stages, several standards that combines the decomposition into *system* and into *elements* approaches do not always integrate a hierarchical approach in the building elemental decomposition of all the building elements. It means that for example, the “Internal walls finishing” are not included in the internal wall’s category, they are grouped in other category called “Finishing” (e.g., Austrian standard).

4.4 Synthes of the section

Difference along the national standards and guidelines used for the systematic building decomposition are detected. Thus, along the analysis and discussion of results can be extracted that:

- -The differences affect the levels of vertical decomposition and mainly the horizontal sub-divisions.
- The principles of specialization of the structures are generally based on the class (defined by the ISO 12006-2 (ISO, 2012a) standard) “Construction Result”, and provide in several cases a combination of decomposition into elements and system of the building.
- The integration of the classification systems in the current workflow in BIM (default configuration of the most used BIM software) is still scarce and depend on the level of maturity (or popularity) of the BIM implementation.
- The elemental and subsequent vertical decomposition of the building parts do not fulfill the same criteria and rules. These differences can affect among others the organization of the environmental databases when considering the LCA application at design stages (early and detail).
- Given that one of the detected difficulties in comparing the systems was the heterogeneities and differences in the standards / guidelines to building decomposition, the following chapter is focus on comparing them based on a case study. Therefore, we aim to illustrate the scope and implications of using a systematic building decomposition when conducting LCA.

5. Case study Be2226 building: building decomposition and their implications to conduct a LCA

5.1 Brief description of the case study reference building

The reference building “be2226” (see Figure 9) office building is located in Lustenau (Austria). Previously used as a reference building to compare national LCA methods in the IEA EBC Annex 72 ST 1 Activity 1.2 and reported in (Frischknecht et al., 2019). The present comparison started by using the same template information developed for (Frischknecht et al., 2019) to apply different national classification systems and standards/guidelines for the building decomposition and organize the building information. The template comprehends the building element types presented in Table 8, including: foundation, external walls, floor structure, roof structure, stairs, flooring, roofing, windows, doors and building services (see also Appendix II).

Figure 9. External view of the be2226 reference building. (Source: IEA EBC Annex 72. ST 1 Activity 1.2).

Table 8. Overall building structure, elements with respective sub-elements and materials (Source: IEA EBC Annex 72. ST 1 Activity 1.2).

Building element Type	Building Element
Foundation	FN01_Structural foundation, driven piles new, d42.0
	FN02_Structural foundation, slab-on-grade slab, reinf. Concrete, 25.0
	FN03_Structural foundation, special
	FC01_Perimeter insulation (slab-on-grade)
External walls	EW01_Exterior wall, outer brick + plaster, 40.5
	EW02_Exterior wall, brick attica, 38.0
Floor structure	FS01_Floor structure, upper floors, concrete slab+plaster, 24.5
Roof structure	RS01_Roof structure, concrete slab, 24.0
Stairs	ST01_Stair primary, concrete, w100.0
	ST02_Stair secondary, wood, w100.0
Internal walls	IW01_Interior wall, brick + plaster 27.0
	IW02_Interior wall, brick + plaster 17.0
	IW03_Interior wall, brick+plaster, 12.0
Flooring	FL01_Floor finish, ground floor, 29.5
	FL02_Floor finish, upper floors, 14.5
Roofing	RF01_Roofing, sealing+insulation+foil+gravel, 36.0
Windows	WE01_Windows exterior, ground floor, incl. side panel
	WE02_Windows exterior, upper floors, incl. side panel
Doors	DE01_Door exterior, ground floor, incl. side panel
	DI01_Door interior, wooden door + frame
	DI02_Door interior, glass door (modelled as wall), 5.5
	DI03_Door interior, wooden door + frame
Building services	SA01_Sanitary equipment
	EL01_Elevator

5.2 Methods

The office building “be2226” [24] was used to illustrate the differences and similarities in the organization of building parts, and to analyse the implications of using those national standards/guidelines to organize the building information relevant for LCA, including the organization of the Life Cycle Inventory (LCI), LCA databases and results communication (Soust-Verdaguer et al., 2020). We also analysed the implications of integrating these standards/guidelines into BIM for LCA purposes. The objective of using this reference building lies in the fact that the LCI was automatically extracted from the BIM model. Thus, the LCA calculation procedure was based on the automatic bill of material quantities from the BIM model (Frischknecht et al., 2019), that enables to discuss the implications of using a systematic building decomposition to conduct building LCA in BIM.

The case study used a common template to identify the basis of the elements and materials that composes the building. Then by using the different standards and guidelines for the systematic building decomposition it is numbered the quantity of mayor element groups considered, the quantity of groups of elements, the quantity of element types, the specific element, sub-elements and materials. Depending on the granularity, levels and subdivision that the standard or guidelines propose are defined the number of items contained in the Table 9.

Here, a comparative analysis of the national standards and guidelines for building decomposition and their implications to conduct LCA, considering the be2226 building case study, was conducted regarding:

- The life cycle inventory and the communication of results (data structure and grouping principles)
- The reference service life definition (at which level and which group/element/product etc.)

5.3 Results and Discussion

The presented results are founded on the **tables and data structures** obtained from conducting the building decomposition by using the national standard/guidelines to the reference building “be2226.”

5.3.1 Tables and data structures

The decomposition of the building parts into vertical levels and horizontal sub-division, was discussed in accordance with the ISO principles for classification and composition. There, the vertical decomposition allows the subdivision or classification of a system into sub-systems using ‘part-of’ relations, while the horizontal decomposition allows the order of classes in sub-division determined by ‘type-of’ relations (Soust-Verdaguer et al., 2020) (see Figure 10). The different national standards and guidelines for systematic building decomposition were compared considering the vertical levels and horizontal sub-division decomposition.

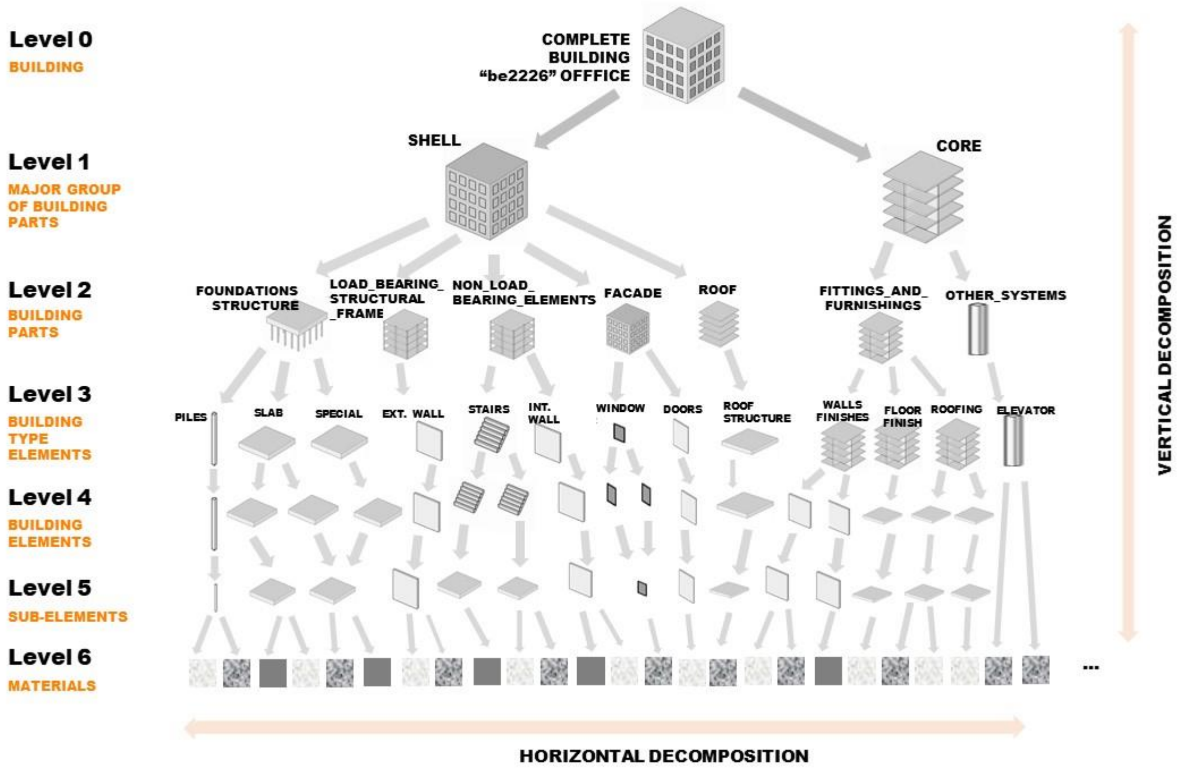


Figure 10. Scheme of the systematic building decomposition of the be2226 reference building following the Austrian ÖNORM B 1801-1 (ÖNORM, 2015b). (Source: based on (Soust-Verdaguer et al., 2020) and prepared by authors based on the Austrian standard Austrian ÖNORM B 1801-1 (ÖNORM, 2015b)).

The tables and data structures summarize the number of levels of vertical decomposition and sub-divisions of horizontal decomposition, that are used to organize ‘part-of’ (vertical) and ‘type-of’ (horizontal) relations of the reference building “be2226” (Soust-Verdaguer et al., 2020). The Appendix II includes the detailed results and the data sources to develop Table 9.

Table 9. Number of vertical levels of decomposition and horizontal sub-divisions. (Source: Prepared by the authors based on national regulation in construction and LCA application to buildings)

Number of H- subdivisions**

Nr of V-levels*	Country code											
	AT	BE	BR	CA	CH	CZ	DE	ES	FR	NL	NZ	UK
1	2 Shell, Core	3 Structure, Substructure and Services	6 Systems/elements: Structure Internal floors Façade Partitions Roof Plumbing	4 Major Group Elements A Substructure, B Shell, C Interiors, D Services	4 Categories: C- Structure E- Envelope G- Interior. F- Roof D- Technical equipment	Not specified	2 Systems: 300 Structure construction works, 400 Structure – services	5^1 Systems: Structure; Envelope; Partitions; Finishing; Air conditioning and installations	3 Systems/ Categories: A Foundations; B Envelope; C Others	6 Category/System Foundations, Carcass, Finishing, Finishes; Installations E Fixed provisions	1 EE_Elements and functions	5 Category/Systems 1 Substructure 2 Superstructure 3 Finishes 4 Fittings, furnishings and equipment (FF&E) 5 Building services/MEP
2	7 Building parts: Foundation Substructure; Load bearing structural frame; Non load bearing elements, Facades; Roof, Fittings and furnishings, Other_systems	6 Group of Elements: 1.Ground substructure 2.Structure primary elements, carcass 3.Secondary elements of superstructure 4.Finishes to structure 5. Services mainly electrical 6.Loose furniture equipment	14 Building parts: Main structure; Complementary structure; Façade; Internal partitions; Roof; Internal finishing; Façade finishing; External flooring; Painting; Waterproof system; External windows and doors; Internal windows and doors; Building services; Equipment	8 Group of Elements A10 Foundations; B10 Superstructure B20 Exterior Closure; B30 Roofing C10 Interior Construction; C20 Staircases C30 Interior Finishes Conveying E20 Furnishings	10 Building elements: 1. Foundation 2. Stairs 3. Exterior wall above ground 4. Window 5. Floor 6. Roof 7. Interior wall 8. Ceiling 9. Technical equipment 10.Sanitary equipment	14 Building parts Foundation Waterproofing layers Vertical and horizontal construction elements Roof construction Roof deck Staircase Internal partitions Non-bearing cladding Finishes Final floor covering Windows and doors	8 Building parts: 320 Foundations, 330 External walls, 340 Internal walls; 350 Floor and ceilings. 360 Roofs; 370 Structural fitments; 460 Transport systems	9^2 Group of Elements: 03. Foundations 05. Structure 06. Masonry 07. Roof 08. Installations 09. Isolations 10. Finishing 11. Carpentry and safe and security elements 12. Glass	9 Building parts: A Foundations; B1 Exterior walls B2 Interior walls B3 Windows and doors B4 Ground floors B5 Intermediate floors B6 Roofs C Sanitary Equipment Transports	16 Groups of Elements: Floors on foundation; Foundational construction; External walls; Inner walls; Floors; Stairs and inclines; Roofs Main supporting construction; Exterior wall openings; Interior wall openings; Exterior wall finishes; Interior wall finishes; Floor finishes; Ceiling finishes; Roof finishes; Transportation	6 EF_ Structural elements Wall and barrier elements Roofs, floor and paving elements Stairs and ramps Signage, fittings, furnishings and equipment Transport functions	13 Groups of Elements: 1.1 Substructure 2.2 Upper floors incl. balconies 2.3 Roof 2.4 Stairs and ramps 2.5 External Walls 2.6 Windows and External Doors 2.7 Internal Walls and Partitions 2.8 Internal Doors 3.1 Wall finishes 3.2 Floor finishes 3.3 Ceiling finishes 4.1 Fittings, Furnishings & Equipment 5.1–5.14 Services incl. Building-related
3	16 Building elements type	18 Building elements type	-	18 Individual Elements	16 Building components	Not specified	16 Elements type	12 Building elements type	47 Materials	25 Building elements type	10 Building elements type	24 Building elements
4	26 Building elements	33 Building elements	-	52 Sub-elements	72 Materials	Not specified	27 Building elements	20 Building Element	-	31 Building elements	21 Building elements	42 Sub-elements
5	45 Building sub-elements	54 Sub-elements	-	69 Materials	-	Not specified	58 Sub-elements	53^2 Material	-	50 Sub-elements	48 Sub-elements	59 Materials
6	67 Materials	73 Materials	-		-	-	73 Materials	-	-	70 Materials	73 Materials	-

* Number of Vertical Levels of decomposition. ** Number of Horizontal subdivisions of decomposition. [1] Based on CTE (CTE, 2006) (Spanish Building Technical Code) primary classification. [2] Based on BBCA (Andalusian Government, 2017) Classification.

5.3.2 Table structures: number of levels of decomposition

The template inventory (included in Appendix II) was organised by a hierarchical structure that provides an elemental classification (including piles, slabs, etc..), a sub-elemental classification (including concrete for foundation, etc.), and a material classification (including concrete in situ, reinforcing steel, etc), which leads to three vertical levels of decomposition. The information contained in the template does not recognise specific manufacturer for the materials; thus, this information is not included in the structures for building decomposition of the reference building which is also a limitation of the present study.

The structure is organised according to the material quantity take-off that was automatically extracted from the BIM model. Thus, the structure allows to track the materials and sub-materials that integrates each building element.

Table 10. Part of the template inventory (complete version in Appendix II). (Source: IEA EBC Annex 72. ST1 Activity 1.2)

Building Element	**Sub-element**	**Material**
FN01_Structural foundation, driven piles new, d42.0	Concrete Foundation Pilar	Concrete In Situ
		Reinforcing Steel

Regarding the obtained results, most standards or guidelines recommend integrating at least six vertical levels of decomposition (from the complete building level (level 0) to the material level (level 6). Generally, a first level was identified that provides a rough classification of the building, by identifying the main systems of major group of elements regarding their function (e.g., structure, envelope), the second level comprised a classification of the group of elements (e.g. foundation), a third level included an elemental type classification (e.g. external wall), a fourth level composed an elemental specific classification (for example by identifying the different type of external walls), a fifth level integrated a sub-elemental classification (for example by identifying the layers that composed the different type of external walls), and a sixth level that integrated a material classification process (for example by identifying the specific materials and products that composed the different layers of each type of external walls). For the case study (“be2226” reference building), the maximum number of materials extracted from the template inventory was 73, which corresponds to the decomposition of 24 building specific elements (included in the BIM model) into 54 sub-elements, and finally into 73 materials (Soust-Verdaguer et al., 2020). The account of elements/sub-elements and materials was performed by tracking the elemental and sub-elemental that the material belong to. For example, the material “Concrete In Situ” is considered as the building material that belongs to the sub-element “Concrete Foundation Pilar”, and the building element “FN01_Structural foundation, driven piles new, d42.0”, and was considered different as the material “Concrete In Situ” that belongs to the sub-element “Concrete Foundation Slab”, and the building element “FN02_Structural foundation, slab-on-grade slab, reinf. Concrete, 25.0”.

Obtained results provide evidence of the differences in terms the organization of the first vertical level of the elements or systems classification (Table 9). Probably, the major differences were detected at the first level, which affected the rest of the building decomposition. For example, the Austrian standard can be used to consider two major groups (Core and Shell), while the Swiss and Spanish codes respectively take into account four categories (Structure, Technical equipment, Envelope, Interior) or five systems (Structure; Envelope; Partitions; Finishing; Air conditioning and installations) (Soust-Verdaguer et al., 2020).

Results shows that in most of the analysed cases, the levels of desegregation and grouping principles from vertical levels 1–3 depended on the structure that was defined by the standard/guideline for building decomposition (Soust-Verdaguer et al., 2020). The decomposition at the subsequent levels (levels 4–6), mainly depended on the building characteristics and the granularity of the BIM model, i.e., the variety of element types/sub-elements and materials. Therefore, the results demonstrate that the organization of the higher levels of decomposition (from element to material) were not carefully described in the on the

standards and guidelines, their organization were mainly a consequence of the elemental building decomposition.
Moreover, the main differences between the number of elements, sub-elements and materials considered are related to the decomposition of *system* and *element* approaches. The combination of both allows can produce deviations/disparity for example when considering finishing materials and products that could be performed by grouping type of materials (such as lime plaster interior for walls) or by grouping type of element (such as external wall, internal wall).

5.3.3 Table structures: grouping principles and naming codes

Differences in naming codes and conventions, following different criteria on the taxonomy and organization of the different levels of decomposition were also detected (Soust-Verdaguer et al., 2020). As abovementioned in section 5.3.1, could be partly due to translation or local construction culture and meanings.

5.3.4 Implications regarding aspects of LCA

The results show differences in the organization of the building parts, the granularity or precision in the building decomposition, the sub-divisions and the levels of decomposition of the standards /guidelines across the use of the different systems/standards for building decomposition when conducting LCA (Soust-Verdaguer et al., 2020). There, various aspects are involved, such as the structure of the LCI, LCA databases, communication of results and the consideration of the service life.

5.3.4.1 Implications in the life cycle inventory (data structure) and communication of results

A standardized structure for organizing and grouping the building parts, potentially affects the ability to verify the LCI completeness. It means that, the more detailed and hierarchically organized the LCI is, the easier it is to identify the building parts/elements/sub-elements/materials (Soust-Verdaguer et al., 2020). One of the consequences of using one or other standard for the systematic building decomposition, is that differences in the number of tagged materials or elements included in the LCI can be detected. For example, Table 9 shows that the number of tagged materials for Austria was 67 and for France was 47. It means that the way that elements, sub-elements and material are organized can affect the number of tagged building materials, and the possibility of tracking elements and building systems.
In the communication of results, the relevance of performing a systematic building decomposition affects the ability to detect hotspots and the optimization of the environmental performance by modifying building parts/elements/sub-elements/materials. An adequate balance between completeness and utility should be considered. Thus, the more levels of vertical and horizontal decomposition are used, the more accurate building decomposition process can be carried out, but this approach also increases the complexity of the data structure, which is a significant drawback (Soust-Verdaguer et al., 2020).

5.3.4.2 Implications in the service life consideration

The service life definition of the building systems, group of elements, elements, components, product and material is a relevant aspect when conducting building LCA. There, the structure for the building decomposition plays an important role, because it affects among others the comparability of results.
Table 11 summarize the obtained results for the service life consideration included in the IEA EBC Annex 72 ST 1 Activity 1.2. The activity comprised a basis template building decomposition structure where each country declared the years of service life assumed to conduct the LCA of the reference building “be2226”. Based on the obtained results, the most considered systems/elements/materials were substructure, external and internal walls. For those systems/elements the building service life (in years) was heterogeneously considered, except for the **Substructure system**. There, most countries considered 50 or 60 years and a similar granularity of the data structure (including “Foundations”, “Basement walls”, and “Ground floor construction”). Also, the same number of years were assumed for all the building elements that compose the **Substructure system.** In contrast, the **Building services system** was one of the most

heterogeneous, because of the neglection the system in the system boundaries of the LCA or because of the differences in the years of service life (from 15 to 50). Regarding the **Finishes,** differences has been detected, among which the definition of the service life depending on the building materials (e.g., Belgium and the Netherlands).

In sum, the obtained results provide evidence that the consideration of the building service life has similar or compatible elemental decomposition structures, that can be compared. Similar trends in the consideration and assumption have been detected in most countries. There, the **Substructure and structure systems** (external walls, frames, internal walls (supporting), roof, stairs and ramps) mostly assumed the same number service life years (around 50 or 60 years). While other systems such as the finishes provide evidence of the differences in the service life assumptions and its decomposition, which can depend among others, on the regional regulations related or the materials and construction characteristics.

Table 11. Summary of the obtained results for the service life consideration based on the IEA EBC Annex 72 ST 1 Activity 1.2. (Source: IEA EBC Annex 72 ST1 Activity 1.2.)

Building element	AT	BE	BR	CA	CZ	CH	DE	ES	FR	NL	NZ	UK
Substructure												
Foundations	60	60	50	60	60	60	50	50	50	1000	>60	60
Basement walls	-	60	50	60	60	60	50	50	50	1000	>60	-
Ground floor construction	60	60	50	60	60	60	50	50	50	1000	>60	-
Superstructure												
External walls												
External walls (below ground)	-	60	50	60	60	60	50	50	50	1000	>60	60
External walls (above ground)	100	60	50	60	60	60	50	50	50	15-75	>60	60
Frames (pillars and beams)	-	60	-	60	-	60	N/A	N/A	50	1000	>60	60
External doors	30	30	20	60	30	30	35	25	30	1000	60	40
Windows	30	30	20	21	30	30	30	25	30	1000	60	40
Internal walls												
internal wall construction (supporting)	100	60	50	60	60	60	50	50	50	-	60	60
partition wall and doors (non-supporting)	30	30	20	60	30	30-60	50	25	30	-	60	30
Floors (structural)	50	60	8	60	60	60	50	50	50	-	60	60
Ceilings	80	60	50	60	60	60	40	50	50	1000	30	60
Roof structural construction	60	60	50	60	60	60	50	50	50	75	60	30
Stairs and ramps (structural)	70	60	50	60	60	60	50	50	50	50	60	-
Building Services												
Water system	-	20	20	N/A	30	-		N/I	50	75	N/D	-
Sewage system	-	20	20	N/A	30	-	no	25	50	50	N/D	-
Electrical system	-	20	20	N/A	30	30	no	N/I	50	50	N/D	-
Heating system (heat producer)	-	20	-	N/A	20	20	N/A	N/I	20	15-30	N/D	-
Heating system (heat distribution)	-	20	-	N/A	30	30	N/A	N/I	50	30-50	N/D	-
Cooling system	-	20	20	N/A	30	-	N/A	N/I	20	-	N/D	-
Ventilation system	-	20	-	N/A	30	30	no	N/I	20	25-35	N/D	-
Conveying system	-	20	13	N/A	-	-	25	25		-	N/D	40
Data system	-	20	20	N/A	-	-	no	N/I		-	N/D	-
Fire protection system	-	20	20	N/A	-	-	no	N/I		-	N/D	-
Finishes												
External finishes walls (below ground)	60	60	50	60	60	60	N/A	50	50	-	>60	-
External finishes walls (above ground)												
external coating	30	40	20	60	40	40	N/A	50	10	-	8	30
external thermal insulation (compact facade)	-	DM	20	60	30	30	N/A	50	50	75	N/D	30
facade cladding (ventilated)	-	20-40 DM	20	60	40	40		50	50	75	N/D	30
facade system	-	DM	40	60	40	40	N/A	50	50	75	50 - 60	30
External finishes roof (below ground)	-		50		60	60	N/A	50	50	-	N/D	30
External finishes roof (above ground)												
roof cladding - flat roof	30	DM	13	30	30	30	40	50	50	30	15 - 25	30
roof cladding - inclined roof	-	DM	13	N/A	40	40	N/A	50	50	40	30 - 60	30
Internal finishes (walls, floors)	30	DM	13	25-60	30	30	N/A	25	10	15-40 DM	60	25
Furniture	-	N/I	-	-	-	-	N/A	N/I		-	N/D	-

Fixed Furniture	-	N/I	-	-	-	-	N/A	N/I		-	N/D	-
External												
Balcony	-	N/I	50	N/A	40	40	N/A	N/I	50	75 DM	N/D	-
Vegetation	-	N/I	-	-	-	-	N/A	N/I		-	N/A	-
Pavements	-	N/I	-	-	-	-	no	N/I	50	-	N/A	-

N/A: not applicable, N/D: No data, N/I: not included; DM: depending on type of material

5.3.5 Implications for design phases in design tools (BIM)

One of the most relevant implications of integrating LCA into BIM is that it can reduce efforts to conduct the bill of material quantities (Soust-Verdaguer et al., 2016), through the automatic material take-off. Thus, a systematic building decomposition specific rules can be useful to organize the material take-off of the building elements/objects. However, in BIM methodology multiple levels of object definition are needed during the design development process and also the precision of the modelling also changes during the design process (Soust-Verdaguer et al., 2020).

The results of this study confirm that the organization of the building elements/objects differed, and especially their hierarchy also differed (Soust-Verdaguer et al., 2020). For example, the French table used for building decomposition defines that the elements of the "Exterior walls" contains the finishing materials (e.g., "B Envelope"→ "B1 Exterior walls"→"B12 Finishes") in the "Envelope" system. Nevertheless, the Austrian standard considered the internal wall finishes as part of a separate group called "Wall and ceiling finishes" (e.g., "Core (fittings, furnishings and services)"→ "Fittings_and_furnishings" → "Wall and ceiling finishes"). This means that, the information about the object (e.g. "finish materials") was hierarchically grouped in the French table based on a principle associated with the object itself (e.g."Interior walls"), while the Austrian standard treated the object as a new sub-system (e.g., "Core (fittings, furnishings and services)") that contained all the building finishing (such as "Sanitary fittings, Ceilings, Wall and ceiling finishes, Floor coverings and finishes") (Soust-Verdaguer et al., 2020). Moreover, for organizing other systems and elements/objects such as the structure or the external walls, similar differences were also detected. Thus, no matter which standards/guidelines are considered to be the most appropriate, our results indicate that the decomposition or desegregation level of the building elements/objects needs to mirror the way that the objects are organized in the model, especially when considering the different design phase in BIM and their hierarchical organization (Soust-Verdaguer et al., 2020). This approach can reduce efforts on identifying hotspots and developing strategies to reduce impacts at design stages. Moreover, most of countries that mainly based the decomposition on the *elemental approach*, include the maximum number of building materials (73). If this approach is combined with the *system* decomposition approach can provide more guarantees (improving the traceability and transparency) when organizing the LCI and the communication of results in LCA. It can help for example to identify hotspots by building systems, building elements, building materials and a combination of all. For example, when considering the finishing system, it should be also possible to decomposed it into the building elements that compose the system (e.g., external walls finishing type 1, internal walls finishing type 1, floor finishing type 1).

5.4 Synthes of the section

Twelve national standards were compared by applying to a reference building and illustrating the implications of the findings regarding aspects of the LCA.

- The results confirmed the above-mentioned tendencies related to the differences on the number and organization of the levels of decomposition, which affected the completeness and the organization of the LCI (such as the number of elements, materials, etc.) and the organization of the LCA results.

- The detected differences also affected the consideration of the element service life (life spam) and the elemental decomposition.

Based on the obtained results, the following section presents the final discussion of the topic, the detected challenges and provide recommendations.

1. Challenges and recommendations

The present work demonstrates that one of the major benefits of using a systematic approach to the building decomposition is that it provides transparency and guaranty to obtain a traceable and comprehensive organization of the building elements, sub-elements and materials. It means that depending on the granularity of the needed information about the building, for different purposes in the LCA (hots spots identification, communication of results, etc.), the organization of the information (e.g., the number of elements and how they are grouped) can be easily recognized. The conducted overview of the different national standards used for the systematic building decomposition provide evidence of the heterogeneity in the organization and grouping principles of the building information structures for implementing the LCA, supporting the relevance of using and communicating which standards or guideline was used. Moreover, we detected the existence of challenges related to the interoperability, translation and harmonization of available standards and guidelines for systematic building decomposition to conduct LCA. Consequently, we conclude that (at least at the moment) it cannot be possible, in the short term, to define one harmonized information structure to the systematic building decomposition for implementing the LCA, due to the great heterogeneity and the strong connection of these structures with national or regional datasets and databases (e.g., environmental impacts databases) for implementing the LCA (e.g., KBOB). However, in the long term, the possibility of defining a common reference or harmonized standard can be addressed. Two great tendencies are detected when analyzing the different standards and guidelines, the first one provides a decomposition based on the recognition of the main systems (system approach) and the second is more focused on the classification of the building elements (elemental approach) based on their function. Both approaches are needed and provide a valid structure for the building decomposition. Most of the standards and guidelines are based on a combination of both, except the Uniclass 2015 standard (CPIc, 2015) that explicit it and provide one table for each approach. Regarding the implementation of LCA in BIM, and the integration of systematic building decomposition into BIM methodology, on the one hand, the elemental approach can be more compatible with the BIM workflow that the *system* approach, because it allows to track and identify the hierarchical decomposition of the building including elements, sub-elements and, materials and products. On the other hand, the *system* approach allows to obtain a global overview of the systems, but limited capability to track and identify specific elements, sub-elements and materials of the building. In sum, both approaches are complementary regarding the scale and complexity of the building, design stage that is implemented the LCA and scope of the study.

The study also provides evidence of the limits of the building decomposition hierarchy structure which come up to material level, thus, when introducing the circularity principles in the construction sector the integration of information about material flows (e.g. raw materials, manufacturing process, etc.) became necessary. The approach can be relevant regarding the concepts of “material passport” (*BAMB. Materials Passports*, 2019) and “building and material inventories” (Leibniz Institute of Ecological Urban and Regional Development & Karlsruhe Institute of Technology, 2020), and especially to support decisions related to the replacement of components and the deconstruction of existing buildings (Lützkendorf, 2019) (potential of reuse, recycling).

The present work confirms that considering different national standards used for the systematic building decomposition, the highest vertical level of desegregation (from sub-element to manufacturer level) are less described and include limited rules for their organization. That fact provide evidence that further developments should be performed, in order to improve comparability and transparency when conducting LCA, especially at detailed design stages. Also, further harmonization could be performed related to the building definition at different design stages and the building decomposition. There, a possible path to solve it could be to define a common elemental decomposition structure (adapted to the different national standards and guidelines), in order to identify those elements that should be defined at early design stages and those elements and systems that should be defined at detailed design stages.
Thus, when considering the analyzed standards and guidelines for systematic decomposition, and building elements classification used in BIM (IFC), the building decomposition at the element level can comprise the following items:

Element level decomposition	**Sub-element and Material level decomposition**
Substructure and superstructure	
Foundations	Main sub-element and materials
Basement	Main sub-element and materials
External walls	Main sub-element and materials (including external wall finishes)
Pillars (columns)	Main sub-element and materials
Beams	Main sub-element and materials
Doors (interior and exterior)	Main sub-element and materials
Windows (interior and exterior)	Main sub-element and materials
Internal wall	Main sub-element and materials (including internal wall finishes)
Floors (slabs)	Main sub-element and materials (including finishes)
Ceilings	Main sub-element and materials (including finishes)
Roof	Main sub-element and materials (including finishes)
Stairs	Main sub-element and materials
Ramps	Main sub-element and materials
Exterior and equipment	
Furniture, equipment, and outdoor equipment (e.g. Vegetation, Pavements)	Main sub-element and materials
Building services	
Water, Sewage, and gas system	Main sub-element and materials
Electrical/Power/Lighting system	Main sub-element and materials
HVAC system	Main sub-element and materials
Communication/Telecommunications/Data and Fire protection system	Main sub-element and materials

The element level (at early design stage) can include a general classification of the building elements regarding their main function in the building. At detailed stages the number of building elements can be higher than at the early stage because other secondary elements (e.g. sealing and joining elements) are integrated in the model and LCA inventory. Hence, at the sub-element and material level the decomposition can include (at least) the main sub-elements and materials that are composing the elements (a consequence of the element classification).

The case study application to the reference building confirmed the detected tendencies when comparing the national standards and guidelines to perform a systematic building decomposition. It also illustrates the scope and implications of the differences when conducting LCA.
To conclude, opportunities are detected over the integration of classification systems to perform the systematic decomposition in BIM for cost estimation proposes. There, the maturity and level of

development of the datasets and databases is higher than in the LCA. Also, in some cases such as the Spanish standard (e.g., BCCA) the use of predefined dataset for describing the materials, products, machinery and labor around an element can provide more transparency to the LCA application (especially for example when detailed modelling A5, B4 and C1 modules).

Therefore, several conclusions and recommendations are drafted:

- To use, whenever possible, a classification system **based on hierarchical grouping principles**, and allows to identify the main systems and elements that compose the building which improves transparency on LCA application and support during the design stages.
- To promote the **compatibility** of structures for systematic building decomposition with environmental, economic, etc. datasets and databases, that enables to improve the interoperability of data during design stages of buildings.
- To **promote** the use of structures for systematic building decomposition that allows a whole life cycle classification, based on the ISO 12006-2(ISO, 2012a) principle of object classes ("Construction Resource", "Construction Process", "Construction Result", and "Property/Characteristic").
- Special care should be paid when comparing different countries LCA, where the use of the same standard and guidelines for building decomposition should be implemented to provide a fair case study comparison.

Some recommendations related to the BIM workflow:

- To promote the **development** of packages or add-ins or encourage the integration in the default configuration of the BIM software, of the most frequently used classification systems for LCA application.
- To integrate the lessons learnt from the cost estimation/LCC workflow in BIM, based on the **element-oriented approach**, which can help to increase the use of classification systems to conduct LCA in BIM.

2. References

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3. Appendix I. Examples of Systematic Building decomposition based on national standards/guidelines

Table 1. Example of Systematic Building Decomposition- Austria (Source: based on the ÖNORM B1801 (ÖNORM, 2015b))

Building parts	Related building elements
Shell	
Foundation_Substructure	Piles
	Basements
	Retaining walls
Load_bearing_structural_frame	Frame (beams, columns and slabs)
	Upper floors
	External walls
	Balconies
Non_load_bearing_elements	Ground floor slab
	Internal walls, partitions and doors
	Stairs and ramps
Façades	External wall systems, cladding and shading devices
	Façade openings (including windows and external doors)
	External paints, coatings and renders
Roof	Structure
	Weatherproofing
Parking_facilities	Above ground and underground (within the curtilage of the building and servicing the building occupiers)
Core (fittings, furnishings and services)	
Fittings_and_furnishings	Sanitary fittings
	Cupboards, wardrobes and worktops (where provided in residential property)
	Ceilings
	Wall and ceiling finishes
	Floor coverings and finishes
In_built_lighting_system	Light fittings
	Control systems and sensors
Energy_system	Heating plant and distribution
	Cooling plant and distribution
	Electricity generation and distribution
Ventilation_system	Air handling units
	Ductwork and distribution
Sanitary_systems	Cold water distribution
	Hot water distribution

Other_systems	Water treatment systems
	Drainage system
	Lifts and escalators
	Firefighting installations
	Communication and security installations
	Telecoms and data installations
External works	
Utilities	Connections and diversions
	Substations and equipment
Landscaping	Paving and other hard surfacing
	Fencing, railings and walls
	Drainage systems

Table 2. Example of Systematic of Building Decomposition. Summary of the classification Structure of the BCCA- Spain (including level 2 and level 3) – (Source: Banco de Costes de la Construcción de Andalucía- Spain (Andalusian Government, 2017))

"Chapter"	"Sub-chapter"
01. Demolitions	01A. Masonry
	01C. Foundations
	01E. Buildings
	01I. Installations
	01K. Carpentry and safe and security elements
	01Q. Roof
	01R. Coating
	01S. Sewerage
	01T. Previous works
	01W. Others
	01X. Structures
02. Terrain	02A. Open air
	02P. Well
	02R. Backfilling and compacting
	02T. Transports
	02W. Others
	02Z. Ditches
03. Foundations	03A. Armors
	03C. Special foundations
	03E. Formwork
	03H. Concrete
	03R. Recovery
	03W. Others
04. Sewerage	04C. Hanging networks
	04E. Buried networks
	04R. Recovery
	04V. Vertical networks
	04W. Others
05. Structure	05A. Steel
	05F. Slabs
	05H. Concrete
	05M. Timber
	05R. Recovery
	05W. Others
06. Masonry	06A. Brick arches and vaults
	06B. Blocks
	06C. Cuarry
	06D. Partitions
	06E. Special enclosures
	06L. Brick
	06P. Prefabricated
	06R. Recovery
	06W. Others
07. Roof	07H. Horizontal
	07I. Inclined
	07R. Recovery
	07W. Others

08. Installations	08C. Climatization
	08E. Electricity
	08F. Plombering
	08K. Communication
	08L. Gas and liquid
	08M. Electromechanics
	08N. Solar energy
	08P. Protections
	08R. Recovery
	08S. Healthiness
	08W. Others
09. Isolations	09A. Acoustic
	09I. Weatherproofing
	09R. Recovery
	09T. Thermic
	09W. Others
10. Finishing	10A. Cladding
	10C. Continuous
	10L. Light
	10P. stair treads
	10R. Recovery
	10S. Floor
	10T. Roof
	10W. Others
11. Carpentry and safe and security elements	11A. Steel
	11L. lightweight alloys
	11M. Wood
	11P. Plastic
	11R. Recovery
	11S. Security and protection
	11W. Others
12. Glass	12A. Insulating glass
	12L. Laminated glass
	12N. Simple glass
	12R. Recovery
	12S. Synthetics
	12W. Others
13. Paint	13E. Exteriors
	13I. Interiors
	13R. Recovery
	13S. Specials
	13W. Others
14. Equipment	14M. Furniture
	14R. Recovery
	14W. Others
15. Urban	15A. Sewage
	15C. Circulation indicators
	15E. Electricity
	15G. Gas and liquid
	15J. Garden
	15M. Earth movements
	15P. Flooring
	15R. Recovery
	15S. Water supply
	15T. Telephone and data distribution
	15U. Urban equipment
	15W. Others
17. Waste Management	17A. Metals
	17F. Bitumen
	17H. Concrete, Ceramic, tile and gypsum
	17I. Isolation materials
	17M. Wood, plastic, paper and glass
	17R. Mixed waste
	17T. Earth
	17W. Others

19. Security and health	19L. Service rooms
	19S. Security
	19W. Others

Table 3. Example of Systematic Building Decomposition- Germany (Source: Building LCA DGNB based on DIN 276 (DIN, 2008))

300 Structure – construction works	310 Excavation	311 Excavation work
		312 Support work
		313 Dewatering
		319 Excavation, other items
	320 Foundations	321 Soil improvement
		322 Shallow foundations
		323 Deep foundations
		324 Subfloors and base slabs
		325 Floorings
		326 Waterproofing of structure
		327 Drainage
		329 Foundations, other items
	330 External walls	331 Load-bearing external walls
		332 Non-load-bearing external walls
		333 External columns
		334 External doors and windows
		335 Cladding units
		336 Internal linings (of external walls)
		337 Prefabricated façade units
		338 Solar protection
		339 External walls, other items
	340 Internal walls	341 Load-bearing internal walls
		342 Non-load-bearing internal walls
		343 Internal columns
		344 Internal doors and window
		345 Internal linings (of internal walls)
		346 Prefabricated wall units
		349 Internal walls, other items
	350 Floors and ceilings	351 Floor structures
		352 Floorings
		353 Ceiling linings
		359 Floors and ceilings, other items
	360 Roofs	361 Roof structures
		362 Roof lights, roof openings
		363 Roofing
		364 Roof coverings
		369 Roofs, other items
	370 Structural fitments	371 General purpose fitments
		372 Special-purpose fitments
		379 Structural fitments, other items
	390 Other construction-related activities	391 Site equipment
		392 Scaffolding
		393 Safety measures

		394 Demolition work
		395 Repair work
		396 Final disposal of materials
		397 Additional work
		398 Temporary construction work
		399 Other construction-related activities, other items
400 Structure – services	410 Sewerage, water and gas systems	411 Sewerage systems
		412 Water supply systems
		413 Gas supply systems
		419 Sewerage, water and gas systems, other items
	420 Heat supply systems	421 Heat generators
		422 Heat distribution networks
		423 Space heating
		429 Heat supply systems, other items
		430 Air treatment systems
		431 Ventilation systems
		432 Partial air conditioning systems
		433 Air conditioning systems
		434 Refrigerating plants
		439 Air treatment systems, other items
	440 Power installations	441 High and medium voltage plants
		442 Independent power supply installations
		443 Low-voltage switchgears
		444 Low voltage installation equipment
		445 Lighting systems
		446 Lightning protection and earthing systems
		449 Power installations, other items
	450 Telecommunications and other communications systems	451 Telecommunications systems
		452 Search and signalling equipment
		453 Time metering systems
		454 Electroacoustic equipment
		455 Television and aerial systems
		456 Security systems
		457 Transmission networks
		459 Telecommunications and other communications systems, other items
	460 Transport systems	461 Lifts
		462 Escalators, moving pavements
		463 Inspection and maintenance conveyors
		464 Conveying plants
		465 Cranes
		469 Transport systems, other items

	470 Function-related equipment and fitments	471 Kitchen fitments
		472 Laundry and dry cleaning equipment
		473 Media supply systems
		474 Medical and laboratory equipment
		475 Fire-fighting installations
		476 Swimming baths equipment
		477 Process heat plants, refrigeration plants, process air plants
		478 Disposal facilities
		479 Function-related equipment and fitments, other item
	480 Building automation	481 Automated systems
		482 Control cabinets
		483 Management and operator facilities
		484 Room control systems
		485 Transmission networks
		489 Building automation, other items
	490 Other services-related work	491 Site equipment
		492 Scaffolding
		493 Safety measures
		494 Demolition work
		495 Repair work
		496 Final disposal of materials
		497 Additional work
		498 Temporary construction work
		499 Other services-related work, other items
NKG base on DIN 18960		
300 Operating costs		
	310 Supply	311 Water
		312 Oil
		313 Gas
		314 Solid fuels
		315 Urban district heating
		316 Electricity
		317 Technical media
		319 Supply, other items
	400 Repair costs	410 Structural repairs
		411 Foundations
		412 External walls
		413 Internal walls
		414 Floors and ceilings
		415 Roofs
		416 Structural fitments
		419 Structural repairs, other items
	420 Repair of installations	421 Sewerage, water and gas systems
		422 Heat supply systems
		423 Air treatment systems

		424 Power installations
		425 Telecommunications and other communications systems
		426 Transport systems
		427 Function-related equipment and fitments
		428 Building automation
		429 Repair of installations, other items
	430 Repair of external works	431 Ground surfaces
		432 Hard surfaces
		433 External construction works
		434 External services
		435 External fitments
		439 Repair of external works, other items
	440 Repair of equipment	441 Equipment
		442 Works of art
		449 Repair of equipment, other items

Table 4. Example of Systematic Building Decomposition- Switzerland. (Source: Selection of items prepared by the authors based on e-BKP-H SN 506 511 (CRB, 2009))

Level 1	Level 2	Level 3
Construction Category	Architectural element	Component according to BKP-H
C- Structure	Foundation	C1 Base slab, foundation
	Exterior wall	C2.1 A Exterior wall under ground
		C2.1 B Exterior wall above ground
	Interior wall	C2.2 Interior wall
	Pillars	C3 Pillars
	Floors	C 4.1 Floors
	Stairs and Ramps	C 4.2 Stairs and ramps
	Balcony	C4.3 Balcony
	Roof	C4.4 Roof
	Others	C5 Additional services to the structural work
D- Installations	Technical equipment	D1 Electric equipment
		D2 Building automation
		D3 Security
		D4 Fire protection
		D5 Heat generation
		D5.3 / D5.4 Heat distribution and delivery
		D6 Refrigeration
		D7 Ventilation
		D8 Water distribution installations, gas and compressed air
		D9 Transport
E- Envelope	Wall under ground	E1 Exterior wall finishing under ground
	Facade	E2 Exterior wall finishing above ground
	Exterior Window and doors	E3.1 Window
		E3.2 Doors
F- Roof	Roof	F1 Roof covering
		F2 Additional elements in roof
G- Interior	Partitions, doors	G1 Partition wall
		G 1.2 Movable partitions
		G 1.3 Interior windows
		G 1.4 Interior doors
		G 1.5 Blackout blinds
	Floor	G2 Floor covering

	Walls	G3 Interior wall finishing
		G4 Interior ceiling/roof finishing
	Fixed equipment	G5 Fixed equipment
		G6 Additional services to interior fittings
	Exterior wall under ground	G2 Floor covering
	Ceiling	G4 Interior ceiling/roof finishing
H- Installations specials	Special Technical equipment	H1 Production facilities and laboratories
		H2 Industrial kitchens
		H3 Laundries, cleaning facilities
		H4 Hospital facilities
		H5 Training facilities and culture
		H6 Sports and leisure facilities
		H7 Other specific installations
I Buildings Surroundings	Outdoor equipment	I1 Outdoor Facilities
		I3 Green spaces
		I4 Hard surfaces
		I5 Protective devices, outside
		I6 Installations, outdoors
		I7 Furniture and machinery, outdoors
J- Furnishings, decoration	Furniture equipment	J1 Furniture
		J2 Small elements
		J3 Textile
		J4 Work of art

Table 5. Example of Systematic Building Decomposition- France (Source:Equer model (Centre Efficacité énergétique des Systèmes de Mines ParisTech, n.d.))

Level 1	Level 2	Level 3
A Foundations		
B Envelope	B1 Exterior walls	B11 Materials
		B12 Finishes
	B2 Interior walls	B21 Materials
		B22 Finishes
	B3 Windows and doors	
	B4 Ground floors	B41 Materials
		B42 Finishes
	B5 Intermediate floors	B51 Materials
		B52 Finishes
	B6 Roofs	B61 Materials
		B62 Finishes
C Equipment	C1 Heating and cooling	
	C2 Ventilation	
	C3 Solar systems	
	C4 Plumbing	
	C5 Electricity	
D Other	D1 Columns	
	D2 Beams	
	D3 Parking	

Table 6. Example of Systematic Building Decomposition- Czech Republic (Source: Provided by the authors)

Level 1
Foundation
Waterproofing layers
Compacted fill, backfill material (imported from the place outside the building)
Vertical and horizontal construction elements including overhanging structures
Roof construction
Roof deck
Staircase
Railing
Internal partitions
Non-bearing cladding
Finishes
Final floor covering
Windows and doors
Thermal and acoustic insulation

Table 7. Example of Systematic Building Decomposition- the Netherlands (Source: Provided by the authors based on (Stichting Bouwkwaliteit, 2014)).

Level 1	Level 2	Level 3
Foundations	Soil provisions	Sand supplements
		Dam walls
	Floors on foundation	Soil sealants
		Floor, constructive
	Foundational constructions	Foundational beams
		Foundational feet
		Basement walls
		Tall brickwork
		Basement wall insulation
	Beam foundations	Foundational beams
Carcass	External walls	Cavity walls
		System walls
		Curtain wall
		Façade
	Inner walls	System walls, non-supporting
		System walls, non-supporting, moveable
		Massive walls, non-supporting
		Coverings, system walls, non-supporting
		Fixing profiles, system walls, non-supporting
	Floors	Self-supporting floors
		Balcony and gallery floors
	Stairs and inclines	Internal stairs
		Central stairs
	Roofs	Flat roofs
		Inclined roofs
	Main supporting constructions	Massive walls, supporting
		Beams
		Consoles
		Supporting beams
		Columns
		Constructions
		System walls, supporting
Finishing	Exterior wall openings	mounting frames
		Exterior frames
		Exterior windows
		Exterior doors
		Transportation doors
		Exterior glass
		Dense façade filling

		Window-stills
		Ventilation grids
		Water barriers (flood defenses)
		Window sill
		Blinds and shades
	Interior wall openings	Interior frames
		Interior doors
		Interior glass
		Interior doorsteps (thresholds)
	Balustrades and guard rails	Balustrades
		Guard rails
	Roof openings	Attic windows
		Light domes
		Light streets
Finishes	Exterior wall finishes	Cavity walls
		Coverings
		Finishing layers
		Insulation layers
	Interior wall finishes	Coverings
		Finishing layers
	Floor finishes	Screed floors
		Finishing layers
		Insulation layers
	Ceiling finishes	Lowered ceilings
		Finishing layers
		Coverings and grids, lowered ceilings
		Fixing profiles, lowered ceilings
	Roof finishes	Coverings, outside
		Water barriers (flood defenses)
		Flat roof covering
		Inclined roof covering
		Finishing layers
		Insulation layers, flat roof
		Insulation layers, inclined roof
Installations W	Heat generation	Heat generation installation civil engineering work construction
		Warm faucet water installations
		Heat generation installations utility construction
		Solar heating installations
		Solar boiler systems
	Drainage	Exterior sewer systems, parcel
		Exterior sewer systems, neighbourhood
		Interior sewer systems
		Gutters
		Water drainage
	Water	Water pipes
	Gasses	Gas pipes
	Cold generation and distribution	Cold generation installation
		Cold dissipation systems
	Heat distribution	Heat distribution systems
		Heat dissipation systems
	Air treatment	Air treatment systems
		Air distribution systems
Installations E	Central electro-technical provisions	Electricity pipes
		Electricity generation systems
	Transportation	Lift cabins
		Lift installations
Fixed provisions	Fixed kitchen provisions	Kitchen cabinets
		Countertops
	Fixed sanitary provisions	Toilets
		Washing provisions (sinks)
		Shower provisions
		Bathing provisions
	Fixed storage provisions	Storage provisions

Terrain	Terrain	Boundary partitions
		Privacy partitions
		Pavements

Table 8. Example of Systematic Building Decomposition- New Zealand (Source Uniclass 2015 (CPIc, 2015))

Level 1	Level 2
Site elements	Construction sites
	Work areas
Structural elements	Substructure
	Superstructure
	Bridge abutments and piers
Wall and barrier elements	Walls
	Doors and windows
	Barriers
Roofs, floor and paving elements	Roofs
	Floors
	Pavements
	Bridge decks
Stairs and ramps	Stairs
	Ramps
Tunnel, vessel and tower elements	Vessels and trenches
	Towers, chimneys and masts
	Tunnels and shafts
Signage, fittings, furnishings and equipment	Signage
	Fittings
	Furnishings
	Equipment
Flora and fauna elements	Planted elements
	Grassed elements
	Fauna elements
	Fish and eel pass elements
Waste disposal functions	Gas waste collection
	Wet waste collection
	Drainage collection
	Dry waste collection
	Gas waste treatment and disposal
	Wet waste treatment and disposal
	Drainage treatment and disposal
	Wastewater treatment and disposal
	Dry waste treatment and disposal
Piped supply functions	Gas extraction and treatment
	Liquid fuel extraction and treatment
	Water extraction and treatment
	Gas supply
	Fire extinguishing supply
	Steam supply
	Liquid fuel supply
	Process liquid supply
	Water supply
	Piped solids supply
Heating, cooling and refrigeration functions	Rail and paving heating
	Space heating and cooling
	Refrigeration
	Drying
Ventilation and air conditioning functions	Ventilation
	Air conditioning
Electrical power and lighting functions	Electrical power generation
	Electricity distribution and transmission
	Lighting
Communications, security, safety and protection functions	Communication
	Signalling
	Security
	Safety and protection
	Environmental safety
	Control and management

	Protection
	Communication
Transport functions	Cable transport
	Conveyors
	Cranes and hoists
	Lifts
	Rail tracks

Table 9. Example of Systematic Building Decomposition- Belgium (Source: BB/SfB)

Level 1	Level 2	Level 3
Substructure	Ground substructure	Ground
		Floor beds
		Retaining walls, foundations
		Pile foundations
		Other substructure elements
		Parts, Accessories etc. special to substructure elements
Structure	Structure primary elements, carcass	Walls, external walls
		Internal walls, partitions
		Floors, galleries
		Stairs, ramps
		Roofs
		Building frames, other primary elements
		Parts, accessories, etc. special to primary elements, carcass
	Secondary elements of superstructure	Secondary elements to walls, external walls.
		Secondary elements to internal walls, partitions
		Secondary elements to floors
		Suspended ceilings
		Secondary elements to roofs
	Finishes to structure	Wall finishes, external
		Wall finishes, internal
		Floors finishes
		Ceiling finishes
		Roof finishes
		Other finishes to structure
		Parts, accessoires etc. Special to finishes to structure elements
Services	Services mainly piped, ducted	Waste disposal, drainage
		Liquid supply
		Gases supply
		Space cooling
		Space heating
		Air conditioning, ventilation
		Other piped, ducted services
		Parts, accessoires etc. Special to piped ducted services elements
	Services mainly electrical	Electrical supply
		Power
		Lighting
		Communications
		Transport
		Security, control, other services
		Parts, accessoires etc. Special to electrical services elements
Fittings	Fittings	Circulation fittings
		Rest work fittings
		Culinary fittings
		Sanitary, hygiene fittings
		Cleaning maintenances fittings
		Storage, screening fittings
		Special activity fittings

		Other fittings
		Parts, accessories etc. special to fittings elements
	Loose furniture equipment	Circulation loose furniture equipment
		Rest, work loos furniture, equipment
		Culinary loose furniture, equipment
		Sanitary hygiene loose furniture, equipment
		Cleaning, maintenance, loose furniture equipment
		Storage, screening, loose furniture, equipment
		Special activity loose furniture, equipment
		Other loose furniture, equipment
		Parts, accessories etc. common to loose furniture, equipment
Others	External elements other elements.	External works
		Other elements
		Parts, accessories etc. common to two or more elements divisions

Table 10. Example of Systematic Building Decomposition- UK (Source: Prepared by the authors based on the report Whole life carbon assessment for the built environment (RICS, 2018) and the BCIS SFCA (RICS & BCIS, 2012))

	Building part/Element group	Building element
	Demolition	0.1 Toxic/Hazardous/Contaminated Material treatment
		0.2 Major Demolition Works
0	Facilitating works	0.3 & 0.5 Temporary/Enabling Works
		0.4 Specialist groundworks
1	Substructure	1.1 Substructure
2	Superstructure	2.1 Frame
		2.2 Upper floors incl. balconies
		2.3 Roof
		2.4 Stairs and ramps
2	Superstructure	2.5 External Walls
		2.6 Windows and External Doors
2	Superstructure	2.7 Internal Walls and Partitions
		2.8 Internal Doors
3	Finishes	3.1 Wall finishes
		3.2 Floor finishes
		3.3 Ceiling finishes
4	Fittings, furnishings and equipment (FF&E)	4.1 Fittings, Furnishings & Equipment incl. Building-related* and Non-building-related**
5	Building services/MEP	5.1–5.14 Services incl. Building-related* and Non-building-related**
6	Prefabricated Buildings and Building Units	6.1 Prefabricated Buildings and Building Units
7	Work to Existing Building	7.1 Minor Demolition and Alteration Works
8	External works	8.1 Site preparation works
		8.2 Roads, Paths, Pavings and Surfacings
		8.3 Soft landscaping, Planting and Irrigation Systems
		8.4 Fencing, Railings and Walls
		8.5 External fixtures
		8.6 External drainage
		8.7 External Services
		8.8 Minor Building Works and Ancillary Buildings

* Building-related items: Building-integrated technical systems and furniture, fittings and fixtures built into the fabric. Building-related MEP and FF&E typically include the items classified under Shell and core and Category A fit-out. ** Non-building-related items: Loose furniture, fittings and other technical equipment like desks, chairs, computers, refrigerators, etc. Such items are usually part of Category B fit-out.

Table 11. Example of Systematic Building Decomposition– Canada (UNIFORMAT II) (Source: Prepared by the authors based on UNIFORMAT II (Charette & Marshall, 1999))

Level 1	Level 2	Level 3

Major Group of Element	Group of Elements	Individual elements
Substructure	Foundation	Standard Foundations
		Special Foundations
		Slab on Grade
	Basement construction	Basement Excavation
		Basement Walls
Shell	Super structure	Floor Construction
		Roof Construction
	Exterior Enclosure	Exterior Walls
		Exterior windows
		Exterior Doors
	Roofing	Roofing coverings
		Roof Openings
Interior	Interior Construction	Partitions
		Interior Doors
		Fittings
	Stairs	Stairs Construction
		Stair Finishes
	Interior Finishes	Wall finishes
		Floor Finishes
		Ceiling Finishes
Services	Conveying	Elevators & Lifts
		Escalators &Moving Walks
		Other Covering Systems
	Plumbing	Plumbing Fixtures
		Domestic Water Distribution
		Sanitary Waste
		Rain Water Drainage
		Other Plumbing Systems
Equipment & Furnishing	HVAC	Energy Supply
		Heat Generating Systems
		Cooling Generating Systems
		Distribution Systems
		Terminal & Package Units
		Controls &Instrumentation
		Systems Testing & Balancing
		Other HVAC Systems &Equipment
	Fire Protection	Sprinklers
		Standpipes
		Fire Protection Specialities
		Other Fire Protection Systems
	Electrical	Electrical Service & Distribution
		Light and Branch Wiring
		Communication &Security
		Other Equipment
	Equipment	Commercial Equipment
		Institutional Equipment
		Vehicular Equipment
		Other Equipment
	Furnishing	Fixed Furnishing
		Movable Furnishings
Special Construction & Demolition	Special Construction	Special Structure
		Integrated Construction
		Special Construction Systems
		Special facilities
		Special Control and Instrumentation
	Service Building Demolition	Building Elements Demolition
		Hazardous Components Abatement

Table 12. Example of Building Decomposition– Brazil (Source: Prepared by authors based on ABNT NBR 15575 (NBR 15575-1: Edificações Habitacionais — Desempenho Parte 1: Requisitos Gerais, 2013))

Level 1	Level 2
Major Group of Element	Group of Elements
Structure	Main structure;

	External flooring;
Roof	Roof;
	Waterproof system;
Façade	Façade;
	External windows and doors;
	Façade finishing;
	Painting;
Partitions	Internal partitions;
	Internal finishing;
	Internal windows and doors;
Internal floors	Complementary structure;
Plumbing	Building services;
	Equipment

4. Appendix II. Results of the Systematic Building decomposition of the “be2226” reference building using different national standards/guidelines

Table 1. Basis initial template

Element level data (L1)	Sub-element (L2)	Material level data (L3)	
Level 1: Building element	Level 2: Sub-element (workblock/layer)	Level 3: Material	Nr
FN01_Structural foundation, driven piles new, d42.0			
	Concrete Foundation Pilar		
	Concrete Foundation Pilar	Concrete In Situ	1
	Concrete Foundation Pilar	Reinforcing Steel	2
FN02_Structural foundation, slab-on-grade slab, reinf. Concrete, 25.0			
	Concrete Foundation Slab	Concrete In Situ	3
	Concrete Foundation Slab	Reinforcing Steel	4
FN03_Structural foundation, special		---	
	Concrete Foundation Slab		
	Concrete Foundation Slab	Concrete In Situ	5
	Concrete Foundation Slab	Reinforcing Steel	6
FC01_Perimeter insulation (slab-on-grade)			
	Perimeter Insulation	XPS	7
EW01_Exterior wall, brick + plaster, 83.0			
	Lime Plaster Exterior	Lime Plaster	8
	Brick wall Insulating	Brick	9
	Brick wall Insulating	Cement Mortar	10
	Mortar Layer	Cement Mortar	11
	Brick wall Structural	Brick	12
	Brick wall Structural	Cement Mortar	13
	Lime Plaster Interior		
	Lime Plaster Interior	Lime Plaster	14
EW02_Exterior wall, brick attica, 38.0			
	Brick wall Insulating	Brick	15
	Brick wall Insulating	Cement Mortar	16
	Lime Plaster Interior	Lime Plaster	17
FS01_Floor structure, upper floors, concrete slab+plaster, 24.5			
	Concrete Floor	Concrete In Situ	18
	Concrete Floor	Reinforcing Steel	19
	Plaster Ceiling	Lime Plaster	20
RS01_Roof structure, concrete slab, 24.0			
	Concrete Roof	Concrete In Situ	21
	Concrete Roof	Reinforcing Steel	22

	Plaster Ceiling	Lime Plaster	23
ST01_Stair primary, concrete, w100.0			
	Stair Steps	Concrete Prefab	24
ST02_Stair secondary, wood, w100.0			
	Stair Steps	Sawn Timber	25
IW01_Interior wall, brick + plaster, 27.0			
	Brick wall Interior	Brick	26
	Brick wall Interior	Cement Mortar	27
	Lime Plaster Interior	Lime Plaster	28
IW02_Interior wall, brick + plaster, 17.0			
	Brick wall Interior	Brick	29
	Brick wall Interior	Cement Mortar	30
	Lime Plaster Interior	Lime Plaster	31
IW03_Interior wall, brick+plaster, 12.0			
	Brick wall Interior	Brick	32
	Brick wall Interior	Cement Mortar	33
	Lime Plaster Interior	Lime Plaster	34
FL01_Floor finish, ground floor, 29.5			
	Screed	Anhydrite Floor	35
	Sealing Floor	PVC foil	36
	Acoustic Insulation Floor	Rockwool	37
	Sawn Timber	Sawn Timber	38
	Sawn Timber	Sawn Timber	39
	Double Flooring System	Double flooring system	40
FL02_Floor finish, upper floors, 14.5			
	Screed	Anhydrite Floor	41
	Sealing Floor	PVC foil	42
	Acoustic Insulation Floor	Rockwool	43
	Wood	Plywood	44
	Wood	Sawn Timber	45
RF01_Roofing, sealing+insulation+foil+gravel, 36.0			
	Roof Sealing	EPDM	46
	Insulation Roof XPS	XPS	47
	Roof Sealing	PVC foil	48
	Gravel Roof	Gravel	49
WE01_Windows exterior, ground floor, incl. side panel, 405.0x185.0			
	Window Glazing	Glazing Triple	50
	Window Frame	Frame Wood	51
	Window Ventilation Panel	Plywood	52
	Window Ventilation Panel	Vacuum Insulation Panel	53
WE02_Windows exterior, upper floors, incl. side panel, 295.0x185.0			
	Window Glazing	Glazing Triple	54
	Window Frame	Frame Wood	55
	Window Ventilation Panel	Plywood	56
	Window Ventilation Panel	Vacuum Insulation Panel	57
DE01_Door exterior, ground floor, incl. side panel, 405.0x185.0			
	Door Exterior Frame	Frame Wood	58
	Door Exterior Panel	Plywood	59
	Door Exterior Panel	Vacuum Insulation Panel	60

DI01_Door interior, wooden door + frame, 310.0x90.0			
	Door Interior Frame	Door Frame	61
	Door Interior Panel	Plywood	62
DI02_Door interior, glass door frameless 5.5 (modelled as wall), 310.0x180.0cm			
	Door Interior Panel	Glazing Double	63
DI03_Door interior, wooden door + frame, 290.0x90.0			
	Door Interior Frame	Door Frame	64
	Door Interior Panel	Plywood	65
SA01_Sanitary equipment			
	Toilets	SanitaryCeramics	66
	Basins	SanitaryCeramics	67
EL01_Elevator			
	Elevator	Aluminium	68
	Elevator	Cast Iron	69
	Elevator	Copper	70
	Elevator	Steel	71
	Elevator	Polyethylene	72
	Elevator	Electronics	73
24 Elements	37 Sub-elemnets	73 Materials	

Table 2. Example of Systematic Building Decomposition- Austria (Source: Prepared by the authors based on the ÖNORM B1801 (ÖNORM, 2015b))

Building parts	Related building elements				
Shell (substructure and superstructure)					
Building part	Building element type	Building element (specific)	Sub-element	Material	Nr
Foundation_Substructure	Piles	1. Pilar	1.1 Concrete Foundation Pilar	1.1.1 Concrete In Situ	1
				1.1.2 Reinforcing Steel	2
	Basements	2. Foundation Slab	2.1 Concrete Foundation Slab	2.2.1 Concrete In Situ	3
				2.1.2 Reinforcing Steel	4
			2.2 Concrete Foundation Slab_special	2.2.1 Concrete In Situ	5
				2.2.2 Reinforcing Steel	6
		3. Perimeter Insulation	3.1 Perimeter Insulation	3. XPS	7
Load_bearing_structural_frame	Upper floors	4. Floor structure, upper floors	4.1 Concrete Floor	4.1.1 Concrete In Situ	8
				4.1.2 Reinforcing Steel	9
	External walls	5. Exterior wall	1. Exterior wall, brick + plaster, 83.0	1.1 Lime Plaster Brick	10
				1.2 Cement Mortar	11
				1.3 Cement Mortar	12
				1.4 Brick	13
				1.5 Cement Mortar	14
				1.6 Lime Plaster	15
			2. Exterior wall, brick attica, 38.0	2.1 Brick 2.2 Cement Mortar 2.3 Lime Plaster	16 17 18
Non_load_bearing_elements	Internal walls, partitions and doors	6. Interior wall, brick + plaster	6.1 Brick wall Interior	6.1.1 Brick	19
				6.1.2 Cement Mortar	20
		7. Interior wall, brick + plaster	7.1 Brick wall Interior	7.1.1 Brick	21
				7.1.2 Cement Mortar	22
		8. Interior wall, brick+plaster	8.1 Brick wall Interior	8.1.1 Brick	23
				8.1.2 Cement Mortar	24
		9. Door exterior, ground floor,	9.1 Door Exterior Frame	9.1.1 Frame Wood	25
			9.2 Door Exterior Panel	9.2.1 Plywood	26
				9.2.2 Vacuum Insulation Panel	27
		10. Door interior, wooden door + frame,	10.1 Door Exterior Frame	10.1.1 Door Frame	28
			10.2. Door Exterior Panel	10.2.1 Plywood	29
		11. Door interior, glass door	11.1. Door Exterior Panel	11.1.1 Glazing Double	30
		12. Door interior, wooden door + frame	12.1 Door Exterior Frame	12.1.1 Door Frame	31
			12.2. Door Exterior Panel	12.2.1 Plywood	32
	Stairs and ramps	14. Stair primary, concrete	14.1 Stair Steps	14.1.1 Concrete Prefab	33
		15. Stair secondary, wood	15.1 Stair Steps	15.1.1 Sawn Timber	34
Facades	Façade openings (including windows and external doors)	16. Windows exterior ground floor,	16.1. Window Glazing	16.1.1. Glazing Triple	35
			16.2 Window Frame	16.2.1 Frame Wood Plywood	36
			16.3 Window Ventilation Panel	16.3.1 Vacuum Insulation Panel	37

		17. Windows exterior, upper floors,	17.1. Window Glazing 17.2 Window Frame 17.3 Window Ventilation Panel	17.1.1. Glazing Triple 17.2.1 Frame Wood Plywood 17.3.1 Vacuum Insulation Panel	38 39 40
Roof	Structure	18. Roof structure, concrete slab,	18.1 Concrete Roof	18.1.1 Concrete In Situ	41
				18.1.2 Reinforcing Steel	42
	Weatherproofing	19. Roofing	19.1 Roof Sealing	19.1.1 EPDM	43
			19.2 Insulation Roof XPS	19.2.1 XPS	44
			19.3 Roof Sealing	19.3.1 PVC foil	45
			19.4 Gravel Roof	19.4.1 Gravel	46
Core (fittings, furnishings and services)					
Fittings_and_ furnishings	Sanitary fittings	20. Toilets	20.1 Toilets	20.1.1 Sanitary Ceramics	47
		21. Basins	21.1 Basins	21.1.1 Sanitary Ceramics	48
	Wall and ceiling finishes	22. Wall finishes	22.1 Lime Plaster Interior	22.1.1. Lime Plaster	49
		23. Ceiling finishes	23.1. Plaster Ceiling	23.1.1 Lime Plaster	50
	Floor coverings and finishes	24. Floor finish, ground floor	24.1 Screed	24.1.1 Anhydrite Floor	51
			24.2 Sealing Floor	24.2.1 PVC foil	52
			24.3 Acoustic Insulation Floor	24.3.1 Rockwool	53
			24.4 Sawn Timber	24.4.1 Sawn Timber	54
			24.5 Sawn Timber	24.5.1 Sawn Timber	55
			24.6 Double Flooring System	24.6.1 Double Flooring System	56
		25. Floor finish, upper floors,	25.1 Screed	25.1.1 Anhydrite Floor	57
			25.2 Sealing Floor	25.2.1 PVC foil	58
			25.3 Acoustic Insulation Floor	25.2.3 Rockwool	59
			25.4 Wood	25.2.4 Plywood	60
			25.5 Wood	25.2.5 Sawn Timber	61
55Other_systems	Lifts and escalators	26. Elevator	26.1. Elevator	26.1.1 Aluminium	62
				26.1.2. Cast Iron	63
				26.1.3. Copper	64
				26.1.4 Steel	65
				26.1.5 Polyethylene	66
				26.1.6 Electronics	67

Table 3. Example of Systematic Building Decomposition. Summary of Classification Structure of BCCA- Spain – (Source: Prepared by the authors based on Banco de Costes de la Construcción de Andalucía- Spain)

"Chapter"	"Sub-chapter"	Element	Material	Nr
03. Foundations				
	03C. Special foundations	03CPS. Concrete Foundation Pilar	03CPS.	
			Concrete In Situ	1
			Reinforcing Steel	2
	03H. Concrete	03HAL. Concrete Foundation Slab	03HAL.	
			Concrete In Situ	3
			Reinforcing Steel	4
05. Structure	05F. Slabs	05F. Slabs Floor structure	05F.	
			Concrete In Situ	5
			Reinforcing Steel	6
	05H. Concrete	05H. Roof structure	05H.	
			Concrete In Situ	7
			Reinforcing Steel	8
06. Masonry	06D. Partitions	06DSS. Brick wall Interior	06DSS.	
			Brick	9
			Cement Mortar	10
	06L. Brick	06LEM. Brick wall Structural	06LEM	

			Lime Plaster	11
			Brick	12
			Cement Mortar	13
			Cement Mortar	14
			Brick	15
			Cement Mortar	16
07. Roof	07H. Horizontal	07HNW Roofing	07HNW00009	
			EPDM	17
			XPS	18
			PVC foil	19
			Gravel	20
08. Installations	08F. Plumbing	08FSI. Toilet 08FSL. Bassin	08FSI. Toilet	21
			08FSL. Bassin	22
	08MA. Elevators	08MAA. Elevators	08MAA. Elevators	
			Electronics	23
09. Isolations	09T. Thermal	Slab-on-grade Perimeter Insulation	XPS	24
10. Finishing	10C. Continuous	10CEE Exterior wall – 10CEE Interior wall -	10CEE Lime Plaster Interior	25
	10S. Floor	10SCW Floor, ground floor and upper floor	10SCW Floor, ground floor	
			Anhydrite Floor	26
			PVC foil	27
			Rockwool	28
			Sawn Timber	29
			Sawn Timber	30
			Double flooring system	31
			10SCW Floor finish, upper floors,	
			Anhydrite Floor	32
			PVC foil	33
			Rockwool	34
			Plywood	35
			Sawn Timber	36
	10T. Roof	10CGG. Wood Roof	10CGG. Plaster Ceiling	37
11. Carpentry and safe and security elements	11M. Wood	11MPP. Wood door, ground floor and upper floors	11MPP Door Frame ground floor	38
			11MPP Door Frame wooden door + frame	39
			11MPP. Door Frame wooden door + frame	40
			11MWW. Plywood	41
			11MWW. Plywood	42
			11MWW. Vacuum Insulation Panel	43
		11MVP. Wood window, ground floor and upper floors	11MVP. Frame Wood ground floor	44
			11MWW Plywood	45
			11MWW Vacuum Insulation Panel	46
			11MVP Frame Wood upper floor	47
			11MWW. Plywood	48
			11MWW Vacuum Insulation Panel	49
	11SE. Stairs.	11SEV. Stairs.	11SEV Concrete Stairs.	50
			11SEV Sawn Timber Stairs	51
12. Glass	12W. Others	12LSR. Windows exterior, ground floor and upper floor.	12LSR. Glazing Triple	52
		12ACT. Door interior	12LSR. Glazing Double	53

Table 4. Example of Systematic Building Decomposition- Germany (Source: Prepared by the authors based on Building LCA DGNB based on DIN 276 (DIN, 2008))

300 Structure – construction works						
	320 Foundations	323 Deep foundations		Concrete Foundation	Concrete In Situ	1

			Structural foundation, driven piles	Pilar	Reinforcing Steel	2
		324 Subfloors and base slabs	Structural foundation, slab-on-grade slab	Concrete Foundation Slab	Concrete In Situ	3
					Reinforcing Steel	4
			Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	5
					Reinforcing Steel	6
		326 Waterproofing of structure	Perimeter Insulation	Perimeter Insulation	XPS	7
	330 External walls	331 Load-bearing external walls	Exterior wall, brick + plaster	Lime Plaster Exterior	Lime Plaster	8
				Brick wall Insulating	Brick	9
					Cement Mortar	10
				Mortar Layer	Cement Mortar	11
				Brick wall Structural	Brick	12
					Cement Mortar	13
				Lime Plaster Interior	Lime Plaster	14
			Exterior wall, brick attica,	Brick wall Insulating	Brick	15
					Cement Mortar	16
				Lime Plaster Interior	Lime Plaster	17
		334 External doors and windows	Windows exterior, ground floor,	Window Glazing	Glazing Triple	18
				Window Frame	Frame Wood	19
				Window Ventilation Panel	Plywood	20
					Vacuum Insulation Panel	21
			Windows exterior, upper floors	Window Glazing	Glazing Triple	22
				Window Frame	Frame Wood	23
				Window Ventilation Panel	Plywood	24
					Vacuum Insulation Panel	25
			Door exterior, ground floor	Door Exterior Frame	Frame Wood	26
				Door Exterior Panel	Plywood	27
					Vacuum Insulation Panel	28
	340 Internal walls	341 Load-bearing internal walls	Interior wall, brick + plaster	Brick wall Interior	Brick	29
					Cement Mortar	30
				Lime Plaster Interior	Lime Plaster	31
			Interior wall, brick + plaster	Brick wall Interior	Brick	32
					Cement Mortar	33
				Lime Plaster Interior	Lime Plaster	34
			Interior wall, brick + plaster	Brick wall Interior	Brick	35
					Cement Mortar	36
				Lime Plaster Interior	Lime Plaste	37
		344 Internal doors and window	Door interior, wooden	Door Interior Frame	Door Frame	38
				Door Interior Panel	Plywood	39

			door + frame			
			Door interior, glass door frameless	Door Interior Panel	Glazing Double	40
			Door interior, wooden door + frame	Door Interior Frame	Door Frame	41
				Door Interior Panel	Plywood	42
	350 Floors and ceilings	351 Floor structures	Floor structure, upper floors, concrete	Concrete Floor	Concrete In Situ	43
					Reinforcing Steel	44
		352 Floorings	Floor finish, ground floor	Screed	Anhydrite Floor	45
				Sealing Floor	PVC foil	46
				Acoustic Insulation Floor	Rockwool	47
				Sawn Timber	Sawn Timber	48
				Sawn Timber	Sawn Timber	49
				Double Flooring System	Double flooring system	50
			Floor finish, upper floors	Screed	Anhydrite Floor	51
				Sealing Floor	PVC foil	52
				Acoustic Insulation Floor	Rockwool	53
				Wood	Plywood	54
				Wood	Sawn Timber	55
		353 Ceiling linings	Floor	Plaster Ceiling	Lime Plaster	56
	360 Roofs	361 Roof structures	Roof structure, concrete slab	Concrete Roof	Concrete In Situ	57
					Reinforcing Steel	58
		363 Roofing	Roofing	Roof Sealing	EPDM	59
				Insulation Roof XPS	XPS	60
				Roof Sealing	PVC foil	61
				Gravel Roof	Gravel	62
		369 Roofs, other items	Roof interior finish	Plaster Ceiling	Lime Plaster	63
	370 Structural fitments	379 Structural fitments, other items	Stair primary, concrete	Stair Steps	Concrete Prefab	64
			Stair secondary, wood	Stair Steps	Sawn Timber	65
400 Structure – services	410 Sewerage, water and gas systems	412 Water supply systems	Sanitary equipment	Toilets	Sanitary Ceramics	66
				Basins	Sanitary Ceramics	67

	460 Transport systems	461 Lifts	Elevator	Elevator	Aluminium	68
					Cast Iron	69
					Copper	70
					Steel	71
					Polyethylene	72
					Electronics	73

Table 5. Example of Systematic Building Decomposition- Switzerland (Source: Selection of the main elements and process prepared by the authors based on e-BKP-H SN 506 511 (CRB, 2009)).

Level 1	Level 2	Level 3			Material	Nr
Construction Category	Architectural element	Component according to BKP-H	Element	Sub-element		
C- Structure	Foundation	C1 Base slab, foundation	Piles	Concrete Foundation Slab	Concrete In Situ	1
					Reinforcing Steel	2
C- Structure			Slab	Concrete Foundation Slab	Concrete In Situ	3
					Reinforcing Steel	4
C- Structure			Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	5
					Reinforcing Steel	
C- Structure			Perimeter insulation	Perimeter Insulation	XPS	6
C- Structure	Stairs	C 4.2 Stairs	Stair primary, concrete,	Stair Steps	Concrete Prefab	7
C- Structure			Stair secondary, wood	Stair Steps	Sawn Timber	8
C- Structure	Exterior wall above ground	C2.1B Exterior wall above ground	Exterior wall, brick + plaster	Brick wall Insulating	Brick	9
					Cement Mortar	10
				Mortar Layer	Cement Mortar	11
				Brick wall Structural	Brick	12
					Cement Mortar	13
C- Structure			Exterior wall, brick attica,	Brick wall Insulating	Brick	14
					Cement Mortar	14
E- Envelope		E2 Exterior wall finishing above ground	Exterior wall	Lime Plaster Exterior	Lime Plaster	15
			Exterior wall	Lime Plaster Exterior	Lime Plaster	16
C- Structure	Interior wall	C2.2 Interior wall	Interior wall	Brick wall Interior	Brick	17
					Cement Mortar	18
C- Structure			Interior wall	Brick wall Interior	Brick	19
					Cement Mortar	20
			Interior wall	Brick wall Interior	Brick	22
					Cement Mortar	23
G- Interior		G3 Interior wall finishing	Interior wall	Lime Plaster Interior	Lime Plaster	24
			Interior wall	Lime Plaster Interior	Lime Plaster	25
			Interior wall	Lime Plaster Interior	Lime Plaster	26
E- Envelope	Window and doors	E3.1 Window	Windows exterior, ground floor,	Window Glazing	Glazing Triple	27
				Window Frame	Frame Wood	28
				Window Ventilation Panel	Plywood	29
					Vacuum Insulation Panel	30
E- Envelope			Windows exterior, upper floors	Window Glazing	Glazing Triple	31
				Window Frame	Frame Wood	32
				Window Ventilation Panel	Plywood	33
					Vacuum Insulation Panel	34
E- Envelope		E3.2 Doors	Door exterior	Door Exterior Frame	Frame Wood	35
				Door Exterior Panel	Plywood	36

					Vacuum Insulation Panel	37
G- Interior	Doors	G 1.4 Door interior	Door interior	Door Interior Panel	Glazing Double	38
			Door interior	Door Exterior Frame	Frame Wood	39
				Door Exterior Panel	Plywood	40
					Vacuum Insulation Panel	41
			Door interior	Door Exterior Frame	Frame Wood	42
				Door Exterior Panel	Plywood	43
					Vacuum Insulation Panel	44
C- Structure	Floor	C4.1 Floor		Concrete Floor	Concrete In Situ	45
					Reinforcing Steel	46
C- Structure	Roof	C4.4 Roof	Roof	Concrete Roof	Concrete In Situ	47
					Reinforcing Steel	48
G- Interior	Ceiling	G4 Interior ceiling/roof finishing	Roof	Plaster Ceiling	Lime Plaster	49
F- Roof		F1 Roof covering	Roofing	Roof Sealing	EPDM	50
				Insulation Roof XPS	XPS	51
				Roof Sealing	PVC foil	52
				Gravel Roof	Gravel	53
G- Interior		G2 Floor covering	Floor finish, ground floor	Screed	Anhydrite Floor	54
				Sealing Floor	PVC foil	55
				Acoustic Insulation Floor	Rockwool	56
				Sawn Timber	Sawn Timber	57
				Sawn Timber	Sawn Timber	58
				Double Flooring System	Double flooring system	59
			Floor finish, upper floors	Screed	Anhydrite Floor	60
				Sealing Floor	PVC foil	61
				Acoustic Insulation Floor	Rockwool	62
				Wood	Plywood	63
				Wood	Sawn Timber	64
D-Technical equipment	Technical equipment	D 9.1 Transport installations	Elevator	Elevator	Aluminium	65
					Cast Iron	66
					Copper	67
					Steel	68
					Polyethylene	69
					Electronics	70
G- Interior	Sanitary equipment	G 5.6 Accessories	Sanitary equipment	Toilets	Sanitary Ceramics	71
				Basins	Sanitary Ceramics	72

Table 6. Example of Systematic Building Decomposition- France (Source: Prepared by the authors based on Equer model (Centre Efficacité énergétique des Systèmes de Mines ParisTech, n.d.)

Level 1	Level 2	Level 3	Nr
Building part /system	Element	Material	
A Foundations		Concrete In Situ	1
		Reinforcing Steel	2
		XPS	3
B Envelope	B1 Exterior walls	B11 Materials	
		Lime Plaster	4
		Brick	5
		Cement Mortar	6
		B12 Finishes	
		Lime Plaster	7
	B2 Interior walls	B21 Materials	
		Brick	8
		Cement Mortar	9
		B22 Finishes	

		Lime Plaster	10
	B3 Windows and doors	Glazing Triple	11
		Frame Wood	12
		Plywood	13
		Vacuum Insulation Panel	14
		Door Frame	15
		Glazing Double	16
		Plywood	17
	B4 Ground floors	B41 Materials	
		Concrete In Situ	18
		Reinforcing Steel	19
		Lime Plaster	20
		B42 Finishes	
		Anhydrite Floor	21
		PVC foil	22
		Rockwool	23
		Sawn Timber	24
		Double flooring system	25
		Plywood	26
	B5 Intermediate floors	B51 Materials	
		Concrete In Situ	27
		Reinforcing Steel	28
		Lime Plaster	29
		B52 Finishes	
		Anhydrite Floor	30
		PVC foil	31
		Rockwool	32
		Plywood	33
	B6 Roofs	B61 Materials	
		Concrete In Situ	34
		Reinforcing Steel	35
		EPDM	36
		XPS	37
		PVC foil	38
		B62 Finishes	
		Lime Plaster	39
Others	Sanitary equipment	Sanitary Ceramics	40
		Sanitary Ceramics	41
	Elevator	Aluminium	42
		Cast Iron	43
		Copper	44
		Steel	45
		Polyethylene	46
		Electronics	47

Table 7. Example of Systematic Building Decomposition- Belgium (Source: Prepared by the authors based on BB/SfB (De Troyer, 2008))

Level 1	Level 2	Level 3	Element type	Sub-element type	Material	Nr
Substructure	Ground substructure	Floor beds	Structural foundation, slab-on-grade slab	Concrete Foundation Pilar	Concrete In Situ	1
					Reinforcing Steel	2
		Pile foundations	Structural foundation, driven piles new, d42.0	Concrete Foundation Slab	Concrete In Situ	3
					Reinforcing Steel	4
		Other substructure elements	Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	5
					Reinforcing Steel	6
		Parts, Accessories etc. special to substructure elements	Perimeter Insulation	Perimeter Insulation	XPS	7
				Brick wall Insulating	Brick	8

Structure	Structure primary elements, carcass	Walls, external walls	Exterior wall, brick + plaster		Cement Mortar	9
				Mortar Layer	Cement Mortar	10
				Brick wall Structural	Brick	11
					Cement Mortar	12
			Exterior wall, brick + plaster	Brick wall Insulating	Brick	13
					Cement Mortar	14
		Internal walls, partitions	Interior wall,	Brick wall Interior	Brick	15
					Cement Mortar	16
			Interior wall,	Brick wall Interior	Brick	17
					Cement Mortar	18
			Interior wall,	Brick wall Interior	Brick	19
					Cement Mortar	20
		Floors, galleries	Floor structure,	Concrete Floor	Concrete In Situ	21
					Reinforcing Steel	22
		Stairs, ramps	Stair primary, concrete	Stair Steps	Concrete Prefab	23
			Stair secondary, wood,	Stair Steps	Sawn Timber	24
		Roofs	Roof structure,	Concrete Roof	Concrete In Situ	25
					Reinforcing Steel	26
	Secondary elements of superstructure	Secondary elements to walls, external walls.	Windows exterior, ground floor	Window Glazing	Glazing Triple	27
				Window Frame	Frame Wood	28
				Window Ventilation Panel	Plywood	29
					Vacuum Insulation Panel	30
			Windows exterior, upper floors	Window Glazing	Glazing Triple	31
				Window Frame	Frame Wood	32
				Window Ventilation Panel	Plywood	33
					Vacuum Insulation Panel	34
			Door exterior, ground floor,	Door Exterior Frame	Frame Wood	35
				Door Exterior Panel	Plywood	36
					Vacuum Insulation Panel	37
		Secondary elements to internal walls, partitions	Door interior	Door Interior Frame	Door Frame	38
				Door Interior Panel	Plywood	39
			Door interior	Door Interior Panel	Glazing Double	40
			Door interior	Door Interior Frame	Door Frame	41
				Door Interior Panel	Plywood	42
	Finishes to structure	Wall finishes, external	Exterior wall	Lime Plaster Exterior	Lime Plaster	43
			Exterior wall	Lime Plaster Exterior	Lime Plaster	44
		Wall finishes, internal	Exterior wall	Lime Plaster Interior	Lime Plaster	45
			Exterior wall	Lime Plaster Interior	Lime Plaster	46
			Interior wall	Lime Plaster Interior	Lime Plaster	47
			Interior wall	Lime Plaster Interior	Lime Plaster	48
			Interior wall	Lime Plaster Interior	Lime Plaster	49
		Roof finishes	Roof finishes	Roof Sealing	EPDM	50
				Insulation Roof XPS	XPS	51
				Roof Sealing	PVC foil	52
				Gravel Roof	Gravel	53
		Ceiling finishes	Roof	Plaster Ceiling	Lime Plaster	54
		Floors finishes	Floor finish, ground floor	Screed	Anhydrite Floor	55
				Sealing Floor	PVC foil	56
				Acoustic Insulation Floor	Rockwool	57
				Sawn Timber	Sawn Timber	58
				Sawn Timber	Sawn Timber	59
				Double Flooring System	Double flooring system	60
			Floor finish, upper floors	Screed	Anhydrite Floor	61
				Sealing Floor	PVC foil	62
				Acoustic Insulation Floor	Rockwool	63

				Wood	Plywood	64
				Wood	Sawn Timber	65
Services	Services mainly electrical	Transport	Elevator	Elevator	Aluminium	66
					Cast Iron	67
					Copper	68
					Steel	69
					Polyethylene	70
					Electronics	71
	Loose furniture equipment	Sanitary hygiene loose furniture, equipment	Toilets	Toilets	Sanitary Ceramics	72
			Basins	Basins	Sanitary Ceramics	73

Table 8. Example of Systematic Building Decomposition- UK (Source: Prepared by the authors based on the report Whole life carbon assessment for the built environment (RICS, 2018) and the BCIS SFCA (RICS & BCIS, 2012))

	Building part/Element group	Building element		Sub element	Material	Nr
1	Substructure	1.1 Substructure	Structural foundation, slab-on-grade slab	Concrete Foundation Slab	Concrete In Situ	1
					Reinforcing Steel	2
			Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	3
					Reinforcing Steel	4
			Structural foundation, driven piles	Concrete Foundation Pilar	Concrete In Situ	5
					Reinforcing Steel	6
			Perimeter Insulation	Perimeter Insulation	XPS	7
2	Superstructure	2.2 Upper floors incl. balconies	Floor structure, upper floors	Concrete Floor	Concrete In Situ	8
					Reinforcing Steel	9
		2.3 Roof	Roof structure, concrete slab	Concrete Roof	Concrete In Situ	10
					Reinforcing Steel	11
		2.4 Stairs and ramps	Stair primary, concrete,	Stair Steps	Concrete Prefab	12
			Stair secondary, wood,	Stair Steps	Sawn Timber	13
2	Superstructure	2.5 External Walls	Exterior wall, brick + plaster	Brick wall Insulating	Brick Cement Mortar	14 15
				Mortar Layer	Cement Mortar	16
				Brick wall Structural	Brick Cement Mortar	17 18
			Exterior wall, brick attica,	Brick wall Insulating	Brick Cement Mortar	19 20
		2.6 Windows and External Doors	Windows exterior, ground floor	Window Glazing Window Frame Window Ventilation Panel	Glazing Triple Frame Wood Plywood Vacuum Insulation Panel	21 22 23 24
			Windows exterior, upper floors	Window Glazing Window Frame Window Ventilation Panel	Glazing Triple Frame Wood Plywood Vacuum Insulation Panel	25 26 27 28
2	Superstructure	2.7 Internal Walls and Partitions	Interior wall, brick + plaster	Brick wall Interior	Brick Cement Mortar	29 30

			Interior wall, brick + plaster	Brick wall Interior	Brick	31
					Cement Mortar	32
		2.8 Internal Doors	Door interior, wooden door + frame,	Door Interior Frame	Door Frame	33
				Door Interior Panel	Plywood	34
			Door interior, glass door frameless	Door Interior Panel	Glazing Double	35
			Door interior, wooden door + frame	Door Interior Frame	Door Frame	36
				Door Interior Panel	Plywood	37
3	Finishes	3.1 Wall finishes	Interior	Lime Plaster Interior	Lime Plaster	38
			Exterior	Lime Plaster Exterior	Lime Plaster	39
		3.2 Floor finishes	Floor finish, ground floor	Screed	Anhydrite Floor	40
				Sealing Floor	PVC foil	41
				Acoustic Insulation Floor	Rockwool	42
				Sawn Timber	Sawn Timber	43
				Sawn Timber	Sawn Timber	44
				Double Flooring System	Double flooring system	45
			Floor finish, upper floors	Screed	Anhydrite Floor	46
				Sealing Floor	PVC foil	47
				Acoustic Insulation Floor	Rockwool	48
				Wood	Plywood	49
				Wood	Sawn Timber	50
		3.3 Ceiling finishes	Floor and roof	Plaster Ceiling	Lime Plaster	51
4	Fittings, furnishings and equipment (FF&E)	4.1 Fittings, Furnishings & Equipment incl. Building-related* and Non-building-related**	Sanitary equipment	Toilets	Sanitary Ceramics	52
				Basins	Sanitary Ceramics	53
5	Building services/MEP	5.1–5.14 Services incl. Building-related* and Non-building-related**	Elevator	Elevator	Aluminium	54
					Cast Iron	55
					Copper	56
					Steel	57
					Polyethylene	58
					Electronics	59
* Building-related items: Building-integrated technical systems and furniture, fittings and fixtures built into the fabric. Building-related MEP and FF&E typically include the items classified under Shell and core and Category A fit-out. ** Non-building-related items: Loose furniture, fittings and other technical equipment like desks, chairs, computers, refrigerators, etc. Such items are usually part of Category B fit-out.						
Not included						
RF01_Roofing, sealing+insulation+foil+gravel, 36.0				Roof Sealing	EPDM	
				Roof Sealing	XPS	
				Insulation Roof XPS	PVC foil	
				Gravel Roof	Gravel	

Table 9. Example of Systematic Building Decomposition- the Netherlands (Source: Prepared by the authors based on (Stichting Bouwkwaliteit, 2014))

Level 1	Level 2	Level 3	Level 4	Sub element	Material	Nr
	Floors on foundation	Soil sealants				
		Floor, constructive	Structural foundation, slab-	Concrete Foundation Slab	Concrete In Situ	1
					Reinforcing Steel	2

			on-grade slab			
			Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	3
					Reinforcing Steel	4
	Foundational constructions	Foundational feet	Structural foundation, driven piles	Concrete Foundation Pilar	Concrete In Situ	5
					Reinforcing Steel	6
		Basement wall insulation	Perimeter Insulation	Perimeter Insulation	XPS	7
Carcass	External walls	Façade	Exterior wall, brick + plaster	Lime Plaster Exterior	Lime Plaster	8
				Brick wall Insulating	Brick	9
					Cement Mortar	10
				Mortar Layer	Cement Mortar	11
				Brick wall Structural	Brick	12
					Cement Mortar	13
			Exterior wall, brick	Brick wall Insulating	Brick	14
				Lime Plaster Interior	Cement Mortar	15
	Inner walls	System walls, non-supporting	Interior wall, brick + plaster	Brick wall Interior	Brick	16
					Cement Mortar	17
			Interior wall, brick + plaster	Brick wall Interior	Brick	18
					Cement Mortar	19
			Interior wall, brick + plaster	Brick wall Interior	Brick	20
					Cement Mortar	21
	Floors	Self-supporting floors	Floor structure, upper floors	Concrete Floor	Concrete In Situ	22
					Reinforcing Steel	23
	Stairs and inclines	Internal stairs	Stair secondary, wood,	Stair Steps	Sawn Timber	24
		Central stairs	Stair primary, concrete	Stair Steps	Concrete Prefab	25
	Roofs	Flat roofs	Roof structure, concrete slab	Concrete Roof	Concrete In Situ	26
					Reinforcing Steel	27
Finishing	Exterior wall openings	Exterior windows	Windows exterior, ground floor	Window Glazing	Glazing Triple	28
				Window Frame	Frame Wood	29
				Window Ventilation Panel	Plywood	30
					Vacuum Insulation Panel	31
			Windows exterior, upper floors,	Window Glazing	Glazing Triple	32
				Window Frame	Frame Wood	33
				Window Ventilation Panel	Plywood	34
					Vacuum Insulation Panel	35
		Exterior doors	Door exterior, ground floor	Door Exterior Frame	Frame Wood	36
				Door Exterior Panel	Plywood	37
					Vacuum Insulation Panel	38
	Interior wall openings	Interior doors	Door interior, wooden door	Door Interior Frame	Door Frame	39
				Door Interior Panel	Plywood	40
			Door interior, wooden door + frame	Door Interior Frame	Door Frame	41
				Door Interior Panel	Plywood	42
		Interior glass	Door interior, glass door	Door Interior Panel	Glazing Double	43
Finishes	Exterior wall finishes	Finishing layers	Exterior wall		Lime Plaster	44
	Interior wall finishes	Finishing layers	Interior wall		Lime Plaster	45
	Floor finishes	Finishing layers	Floor finish, ground floor	Screed	Anhydrite Floor	46
				Sealing Floor	PVC foil	47
				Sawn Timber	Sawn Timber	48
				Sawn Timber	Sawn Timber	49
				Double Flooring System	Double flooring system	50
			Floor finish, upper floors	Screed	Anhydrite Floor	51
				Sealing Floor	PVC foil	52
				Wood	Plywood	53
				Wood	Sawn Timber	54

		Insulation layers	Floor finish	Acoustic Insulation Floor	Rockwool	55
	Ceiling finishes	Finishing layers	Roof	Plaster Ceiling	Lime Plaster	56
	Roof finishes	Water barriers (flood defenses)	Roofing	Roof Sealing	EPDM	57
					PVC foil	59
		Finishing layers	Roofing	Gravel Roof	Gravel	60
		Insulation layers, flat roof	Roofing	Insulation Roof XPS	XPS	61
Installations E	Transportation	Lift cabins	Elevator	Elevator	Aluminium	62
					Cast Iron	63
					Copper	64
					Steel	65
					Polyethylene	66
		Lift installations			Electronics	67
Fixed provisions	Fixed sanitary provisions	Toilets	Toilet	Toilet	Sanitary Ceramics	68
		Washing provisions (sinks)	Basin	Basin	Sanitary Ceramics	69

Table 10. Example of Systematic Building Decomposition- Czech Republic (Source: Prepared by authors)

Level 1	Nr
Foundation	1
Waterproofing layers	2
Compacted fill, backfill material (imported from the place outside the building)	3
Vertical and horizontal construction elements including overhanging structures	4
Roof construction	5
Roof deck	6
Staircase	7
Internal partitions	8
Non-bearing cladding	9
Finishes	10
Final floor covering	11
Windows and doors	12
Thermal and acoustic insulation	13

Table 11. Example of Systematic Building Decomposition- Uniclass 2015- New Zealand (Source: Prepared by authors based on Uniclass 2015)

Code	Group	Sub gr.	Title	Element	Sub element	Material	Nr
EF_20	20		Structural elements				
EF_20_05	20	05	Substructure	Structural foundation, driven piles new	Concrete Foundation Pilar	Concrete In Situ	1
						Reinforcing Steel	2
				Structural foundation, slab-on-grade slab,	Concrete Foundation Slab	Concrete In Situ	3
						Reinforcing Steel	4
				Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	5
						Reinforcing Steel	6
EF_20_10	20	10	Superstructure	Floor structure, upper floors, concrete	Concrete Floor	Concrete In Situ	7
						Reinforcing Steel	8
				Roof structure, concrete slab,	Concrete Roof	Concrete In Situ	9
						Reinforcing Steel	10
				Perimeter insulation slab-on-grade	Perimeter insulation	XPS	11

EF_25	25		Wall and barrier elements				
EF_25_10	25	10	Walls	Exterior wall, brick + plaster, 83.0	Lime Plaster Exterior	Lime Plaster	12
					Brick wall Insulating	Brick	13
						Cement Mortar	14
					Mortar Layer	Cement Mortar	15
					Brick wall Structural	Brick	16
						Cement Mortar	17
					Lime Plaster Interior	Lime Plaster	18
				Exterior wall, brick attica, 38.0	Brick wall Insulating	Brick	19
						Cement Mortar	20
					Lime Plaster Interior	Lime Plaster	21
				Interior wall, brick + plaster	Brick wall Interior	Brick	22
						Cement Mortar	23
					Lime Plaster Interior	Lime Plaster	24
				Interior wall, brick + plaster	Brick wall Interior	Brick	25
						Cement Mortar	26
					Lime Plaster Interior	Lime Plaster	27
				Interior wall, brick+ plaster	Brick wall Interior	Brick	28
						Cement Mortar	29
					Lime Plaster Interior	Lime Plaster	30
EF_25_30	25	30	Doors and windows	Door	Door exterior, ground floor	Frame Wood	31
						Plywood	32
						Vacuum Insulation Panel	33
					Door interior, wooden door + frame	Door Frame	34
						Plywood	35
					Door interior, glass door frameless	Glazing Double	36
					Door interior, wooden door + frame	Door Frame	37
						Plywood	38
				Window	Windows exterior, ground floor,	Glazing Triple	39
						Frame Wood	40
						Plywood	41
						Vacuum Insulation Panel	42
					Windows exterior, upper floors,	Glazing Triple	43
						Frame Wood	44
						Plywood	45
						Vacuum Insulation Panel	46
EF_30	30		Roofs, floor and paving elements				
EF_30_10	30	10	Roofs	Roof structure, concrete slab	Plaster Ceiling	Lime Plaster	47
				Roofing, sealing+insulation+foil+gravel	Roof Sealing	EPDM	48
					Insulation Roof XPS	XPS	49
					Roof Sealing	PVC foil	50

					Gravel Roof	Gravel	51
EF_30_20	30	20	Floors	Floor structure, upper floors, concrete	Plaster Ceiling	Lime Plaster	52
EF_30_60	30	60	Pavements	Floor finish, ground floor	Sealing Floor	Anhydrite Floor	53
						PVC foil	54
					Acoustic Insulation Floor	Rockwool	55
					Sawn Timber	Sawn Timber	56
					Sawn Timber	Sawn Timber	57
					Double Flooring System	Double flooring system	58
				Floor finish, upper floors	Screed	Anhydrite Floor	59
					Sealing Floor	PVC foil	60
					Acoustic Insulation Floor	Rockwool	61
					Wood	Plywood	62
					Wood	Sawn Timber	63
EF_35	35		Stairs and ramps				
EF_35_10	35	10	Stairs	Stair Steps	Stair Steps Concrete	Concrete Prefab	64
					Stair Steps Timber	Sawn Timber	65
EF_40	40		Signage, fittings, furnishings and equipment	Toilets	Toilets	Sanitary Ceramics	66
					Basins	Sanitary Ceramics	67
EF_80	80		Transport functions				
EF_80_50	80	50	Lifts	Elevator	Elevator	Aluminium	68
						Cast Iron	69
						Copper	70
						Steel	71
						Polyethylene	72
						Electronics	73

Table 12. Example of Systematic Building Decomposition– Canada (UNIFORMAT II) (Source: Prepared by the authors based on UNIFORMAT II (Charette & Marshall, 1999))

Level 1	Level 2	Level 3	Element	Sub-element	Material	Nr
Major Group of Element	Group of Elements	Individual elements				
Substructure	Foundation	Standard Foundations	Structural foundation, driven piles	Concrete Foundation Pilar	Concrete In Situ	1
					Reinforcing Steel	2
		Special Foundations	Structural foundation, special	Concrete Foundation Slab	Concrete In Situ	3
					Reinforcing Steel	4
		Slab on Grade	Structural foundation, slab-on-grade slab	Concrete Foundation Slab	Concrete In Situ	5
					Reinforcing Steel	6
			Perimeter insulation (slab-on-grade)	Perimeter insulation	XPS	7
Shell	Super structure	Floor Construction	Floor structure, upper floors,	Concrete Floor	Concrete In Situ	8
					Reinforcing Steel	9

		Roof Construction	Roof structure, concrete slab	Concrete Roof	Concrete In Situ	10
					Reinforcing Steel	11
	Exterior Enclosure	Exterior Walls	Exterior wall, brick + plaster	Lime Plaster Exterior	Lime Plaster	12
				Brick wall Insulating	Brick	13
					Cement Mortar	14
				Mortar Layer	Cement Mortar	15
				Brick wall Structural	Brick	16
					Cement Mortar	17
			Exterior wall, brick + plaster	Brick wall Insulating	Brick	18
					Cement Mortar	19
		Exterior windows	Windows exterior, ground floor	Window Glazing	Glazing Triple	20
				Window Frame	Frame Wood	21
				Window Ventilation Panel	Plywood	22
					Vacuum Insulation Panel	23
			Windows exterior, upper floors	Window Glazing	Glazing Triple	24
				Window Frame	Frame Wood	25
				Window Ventilation Panel	Plywood	26
					Vacuum Insulation Panel	27
		Exterior Doors	Door exterior, ground floor,	Door Exterior Frame	Frame Wood	28
				Door Exterior Panel	Plywood	29
					Vacuum Insulation Panel	30
	Roofing	Roofing coverings	Roofing	Roof Sealing	EPDM	31
				Insulation Roof XPS	XPS	32
				Roof Sealing	PVC foil	33
				Gravel Roof	Gravel	34
Interior	Interior Construction	Partitions	Interior wall, brick + plaster	Brick wall Interior	Brick	35
					Cement Mortar	36
			Interior wall, brick + plaster	Brick wall Interior	Brick	37
					Cement Mortar	38
			Interior wall, brick + plaster	Brick wall Interior	Brick	40
				Lime Plaster Interior	Cement Mortar	41
		Interior Doors	Door interior, wooden door + frame,	Door Interior Frame	Door Frame	42
				Door Interior Panel	Plywood	43
			Door interior, wooden door + frame,	Door Interior Panel	Glazing Double	44
			Door interior, wooden door + frame	Door Interior Frame	Door Frame	45
				Door Interior Panel	Plywood	46
	Stairs	Stairs Construction	Stair Steps	Stair Steps	Concrete Prefab	47
		Stair Finishes	Stair Steps	Stair Steps	Sawn Timber	48
	Interior Finishes	Wall finishes	Walls	Lime Plaster Interior	Lime Plaster	49
		Floor Finishes	Floor finish, ground floor	Screed	Anhydrite Floor	50
				Sealing Floor	PVC foil	51
				Acoustic Insulation Floor	Rockwool	52
				Sawn Timber	Sawn Timber	53
				Sawn Timber	Sawn Timber	54
				Double Flooring System	Double flooring system	55
			Floor finish, upper floors	Screed	Anhydrite Floor	56
				Sealing Floor	PVC foil	57
				Acoustic Insulation Floor	Rockwool	58
				Wood	Plywood	59
				Wood	Sawn Timber	60

		Ceiling Finishes	Roof and floor	Plaster Ceiling	Lime Plaster	61
Services	Conveying	Elevators & Lifts	Elevator	Elevator	Aluminium	62
					Cast Iron	63
					Copper	64
					Steel	65
					Polyethylene	66
					Electronics	67
	Furnishing	Fixed Furnishing	Toilets	Toilets	Sanitary Ceramics	68
			Basins	Basins	Sanitary Ceramics	69

Table 13. Example of Systematic Building Decomposition– Brazil (Source: Prepared by authors based on ABNT NBR 15575 (NBR 15575-1: Edificações Habitacionais — Desempenho Parte 1: Requisitos Gerais, 2013))

Level 1	Level 2
Major Group of Element	Group of Elements
Structure	Main structure;
	External flooring;
Roof	Roof;
	Waterproof system;
Façade	Façade;
	External windows and doors;
	Façade finishing;
	Painting;
Partitions	Internal partitions;
	Internal finishing;
	Internal windows and doors;
Internal floors	Complementary structure;
Plumbing	Building services;
	Equipment

LCA strategy for uncertainty in design phases

A Contribution to IEA EBC Annex 72

April 2023

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International Energy Agency

LCA strategy for uncertainty in design phases

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Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_2eq	CO_2 equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines

ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process

Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Introduction

The uncertainties of the LCA can have different sources which can be divided into two great categories (Figure 1)
– Exogenous uncertainty, namely uncertainty that the designer cannot influence;
– Uncertainties during the design steps, namely uncertainties that the designer can influence.
This document focuses on the uncertainties that can be influenced by the designer.

On the one hand, it is obvious that the designer has major influence on the final environmental impacts of a building. On the other hand, a building project is a long process with multiple actors, and many small influential decisions will be taken during the duration of the project. Therefore, the designer has the difficult task of carrying the long term and overall vision of the project while being able to take the right decisions all along the project. It means that, although a large amount of uncertainty exists in the early phase of the project, some key choices taken in the beginning will in fine highly influence the environmental impacts of the building. How can the right decision be taken? When is it possible to take one decisive choice? This is the complex task of the designer.

Therefore, it is important to know which kind of uncertainties exist in an LCA study, which are the possible pathways to reduce them, and which workflows to reduce the uncertainties have proven to be the most efficient.

Objectives

The aim is to define a strategy for design decision-makers which would allow them to handle and analyse LCA-related uncertainty in different design steps.

1. Context and purpose

This document relates to activity 2.3 of ST2. It aims to define an LCA strategy for design decision makers to handle and analyse uncertainty in different design phases. It provides an overview of different uncertainty sources in building LCA, dividing them into two great categories (Figure 1) (i) exogenous uncertainty, namely uncertainty that the designer cannot influence, and (ii) uncertainties during the design phases, namely uncertainties that the designer can influence. The document provides guidance on how to handle uncertainties from the second category.

Strictly, uncertainty arises due to lack of knowledge about the true value of a quantity or its precise definition. It should be distinguished from variability, which is attributable to the natural heterogeneity of values. Uncertainty can be reduced by more accurate and precise measurements. Variability cannot be reduced by further measurement, although better sampling can improve knowledge about variability. In this chapter, 'uncertainty' encompasses uncertainty and variability.

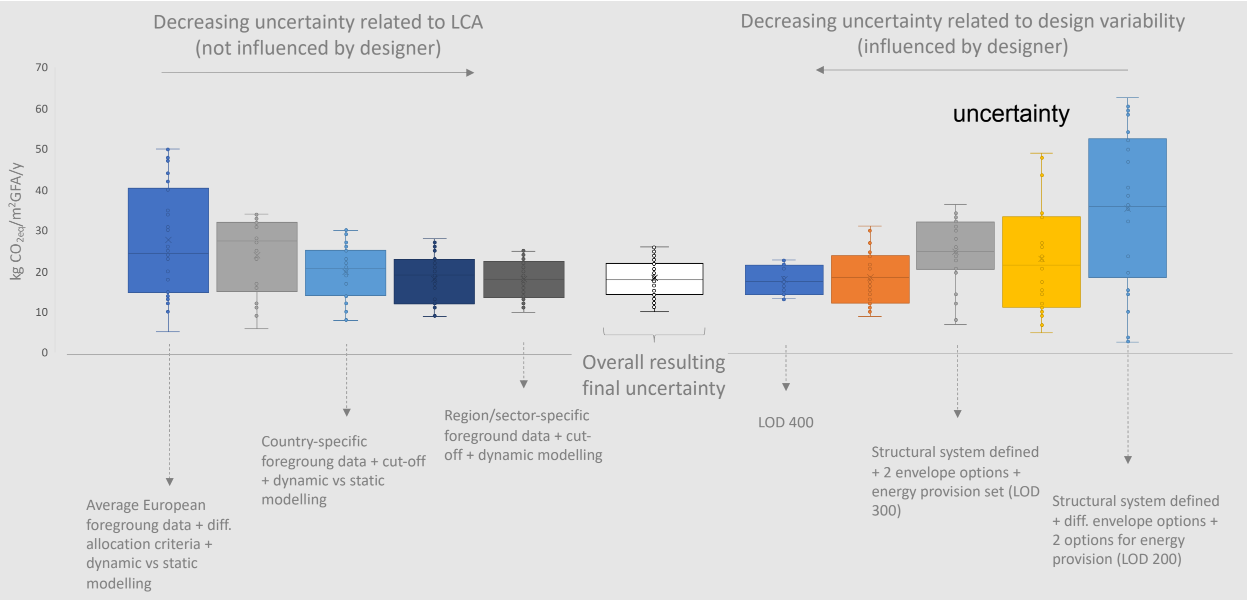


Figure 1: Uncertainty sources in building LCA, divided according to the designer's influence.

The guidelines herein proposed allow design decision makers wishing to assess the environmental impact of their projects to follow two different paths to handle uncertainty:

- In a typical design flow, the report offers literature-based instructions to address the range of potential impact when various construction systems are yet to be specified, using the design's Levels of Development (LOD) as thresholds.
- In an optimized design flow, the report builds on existing research (Jusselme, 2020) and patent application (Jusselme, 2018) that propose a method for generating design solutions aiming to satisfy a low carbon performance target.

2. Uncertainty sources in building LCA

4.1 Uncertainty in building LCA due to exogenous sources (LCA method)

Uncertainty related with exogenous sources relates to the classic LCA uncertainty described in ST1 method. These uncertainties come from the uncertainties in service life of building elements (Hoxha et al., 2017), uncertainties in the exact quantities of materials finally used on site (discrepancy between as planned and used on site) (Souza et al., 1998), uncertainties related with exact environmental impact of building material production (Chen et al., 2010), uncertainties on LCIA calculation methods (Lasvaux et al., 2015), uncertainty in user behaviour during building operation (Sunikka-Blank and Galvin, 2012), on climate change or future energy mixes (Galimshina et al. 2020). A classification of these uncertainties is presented in table 1.

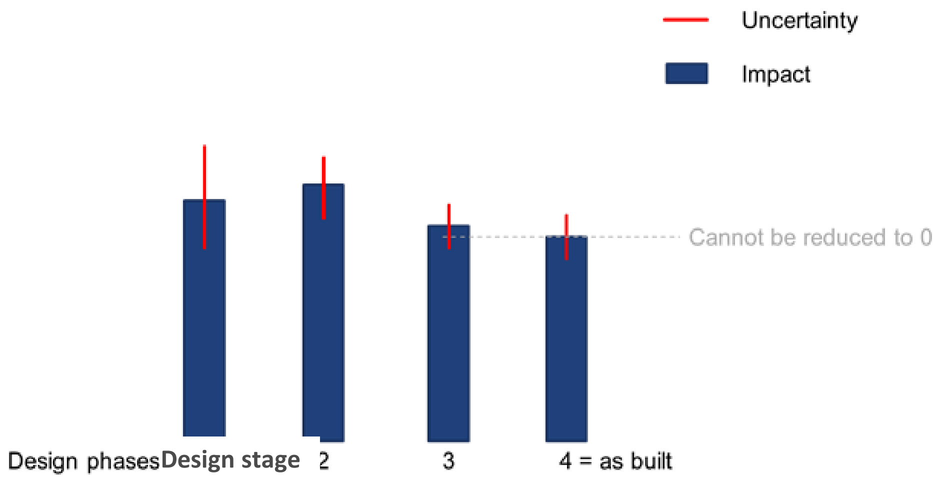


Figure 2: Qualitative representation of the development of the uncertainty during the design process form the early stage 1 to the final as-built stage 4.

Table 1: Uncertainties encountered in building LCAs. Uncertainty sources specific to buildings are highlighted in blue. Although not all these uncertainties can be controlled by designer. Translated from Pannier (2017).

Uncertainty type	Sources	LCA phase
Parameter uncertainty	Assumptions about the building (i.e., building envelope, service life), its systems and site (networks, shadows) Quality of environmental data (inaccurate emission measurements, lack of inventory data, lack of data representativeness)	LCI
	Uncertainties on substances' life time and their relative contribution to impact Lack of impact data	LCIA
Model uncertainty	Annual or hourly energy calculations Static or dynamic modelling, linear or non-linear modelling	LCI
	Static or dynamic modelling, linear or non-linear modelling	LCIA
Choice uncertainty	Functional unit and system boundaries choices LCA approach choice (attributional or consequential)	Goal definition
	Choice of allocation methods, technology level, marginal or generic data	LCI

	Negligence of certain impact categories Choice of characterization methods	LCIA
Spatial variability	Occupant transportation and waste generation Regional variation in emission inventories	LCI
	Occupant transportation and waste generation Regional variation in environmental sensitivity	LCIA
Temporal variability	Weather variables Energy systems Building Occupancy Temporal variation of emission inventories	LCI
	Choice of time horizon Change in environmental characteristics over time	LCIA
Variability between individual cases	Building Occupancy Differences in performance of equivalent products	LCI
	Differences in environmental and human characteristics	LCIA
Epistemic uncertainty	Definition of long-term scenarios Ignorance of system behaviour	LCI
Error	Various types of errors (e.g., during data input by the user)	All phases
Meta-uncertainty	Estimation of uncertainty	LCI and LCIA

4.2 Uncertainty in building LCA due to variability during the design phases

During the phases, the designer will have to choose between multiple options. In the early design stage, an exterior wall could be made out of masonry, timber, concrete or rammed earth, for example. Figure 3 conceptually visualises the mean value of these options and the minimum and maximum value as a range. In design stage 2, this range is reduced and the mean value (bar) rises. This means A) the variability is reduced, because more material specifications have been fixed, e.g., it has been defined that the wall should be made out of concrete and B) the mean value rises, because the embodied GWP of an average concrete wall is higher than the average of masonry, timber, concrete and rammed earth. Only looking at the GWP, this choice led to higher environmental impact, because the average values has been increased (it might have been good regarding other performance criteria, such as structural performance, for example). The uncertainty is still relatively high, because the thickness of the wall, the amount of reinforcement and the concrete type have not yet been defined. Continuing this hypothetical example, the uncertainty is further reduced in design stage 3, because now the thickness of the wall and the concrete type might have been defined. The exact amount of reinforcement might still be unknown and a small amount of variability remains. If the wall is thinner than the average and a low carbon concrete is used, the average value is reduced. As such, it was an “environmentally good” choice. Finally, in the as-built phase, the uncertainty is reduced to zero, because all design parameters have been defined.

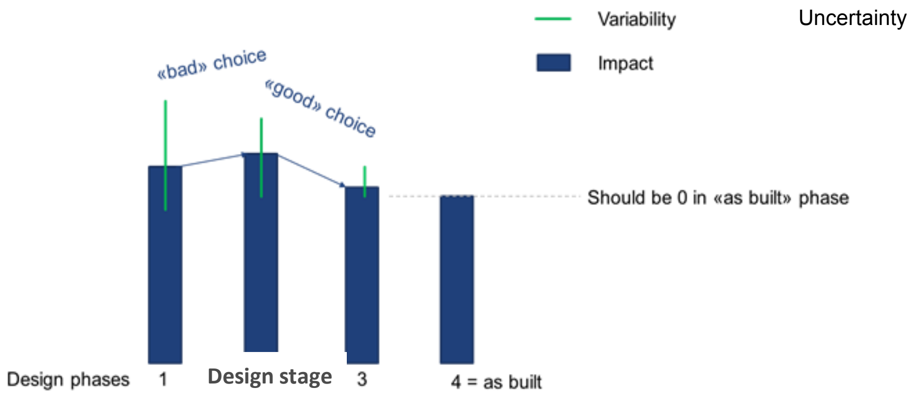


Figure 3: Qualitative representation of the development of environmental impacts and the variability during the design process form the early stage 1 to the final as-built stage 4.

Tecchio and co-authors (Tecchio et al., 2019) calls this approach “structured under-specification”. They defined five material levels and four assembly levels from general to detailed. Cavalliere and co-authors (Cavalliere et al., 2019) use a similar approach to link the level of information of BIM models with different Swiss LCA databases with increasing level of detail. Both studies take the average values of predefined catalogues with typical components. Hollberg and co-authors (Hollberg et al., 2019) define benchmarks for different building elements such as walls, ceilings, windows, etc. using real market shares of Switzerland to provide more realistic benchmarks that can be used as assumptions in this “structured under-specification”.

4.3 Uncertainty in building LCA due to incompleteness during the design phase

In early design stages, not all design parameters are known. To streamline the LCA process, many studies propose to focus on the most influential parameters first (see EeBGuide for example (Wittstock et al., 2011)). As such, in design stage 1, the structural parts and the envelope of a building might be assessed in more detail, while there is no information on the amount and the type of interior walls.

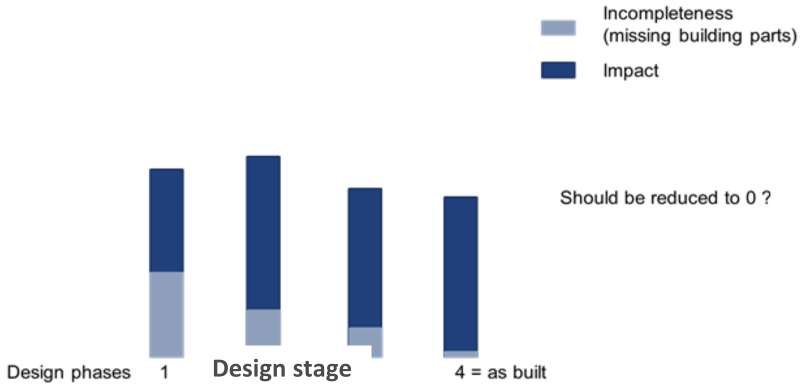


Figure 4: Qualitative representation of the development of environmental impacts and incomplete data (missing building parts) during the design process form the early stage 1 to the final as-built stage 4. In the LCA done as built there are still parts that are usually not considered as its expected they have a minor contribution to final LCA results.

To account for these missing components, assumptions can be made. Minergie-Eco (*Minergie, Berechnung Der Grauen Energie Bei MINERGIE-A®, MINERGIE-ECO®, MINERGIE-P-ECO® UND MINERGIE-A-ECO® BAUTEN*, 2016), provides typical values for the number of interior walls based on the net floor area for example. Theoretically, this incompleteness could be reduced to zero in the as-built phase, because all parameters are known. However, in practice the effort to account for every detail might not be worthwhile. Therefore, assumptions are also taken in the detailed design stage (4, in Figure 4). KBOB (*KBOB,* *Ökobilanzdaten Im Baubereich 2009/1:2016.*, 2016) provides values for technical equipment in the building based on the account of heated gross floor area of the building, for example. The DGNB certification system (*German Sustainable Building Council, DGNB System [WWW Document].*, 2018) allows for a simplified calculation method, neglecting staircases and handrails for example. To account for these missing data, a global factor of 20% is added to the final result.

With the increasing use of BIM, the level of detail of available information might become higher and the effort for a detailed assessment can be reduced. As such, the gap of incomplete data and be reduced step by step. Nevertheless, a 100% complete assessment does not seem realistic in practice in the near future.

5. Addressing uncertainty during the design process

5.1 LCA applied to the typical design process

Project phases can vary on the national level; a detailed overview of them is available in another report of IEA EBC Annex 72 as a product of activities 1.1 and 2.2 in the document Potentials and requirements for implementing LCA across different design stages, project phases and life cycle stages – Part 1 – 1 Common definition of design steps & project phases.

5.1.1 Uncertain design parameters

The designer can act on many different parameters that will influence the final environmental impact of the building. During the design process, choices can be done. In the following table we show when specific decision influencing the final environmental impact are usually done. However, it is also clear that in an ideally good sustainable design most of these decision can actually be taken from the very early design phases as it will be much less costly from an economic and environmental point of view to consider all options in the beginning than trying to adapt at the end depending on availability of material supplier or final geometry adjustment.

Table2: Main design parameters and their position along design process. PP: Pre-project; P: Project; BPA: Building permit application; T: tendering; C: Construction

Type of uncertainty	Source of uncertainty	Design phase
Parameter	Types and quantities of construction materials/ products	BPA
	Types of vehicles used for transportation	T
	Transport distance	T
	Types and quantities of energy carriers used for construction	C
	Layout/ Geometry	PP

	Type of energy carriers used during operation	P
	Performance of building envelope (e.g. U-value)	P
	Performance of service systems (e.g. efficiency)	BPA
	Climate data variability	PP

5.1.2 Link LCA only at early design

The initial project phase (also named strategic definition phase) does not contain any BIM model. Yet, some tools are still available, such as CAALA (*CAALA*, 2022) or custom-made Grasshopper scripts (e.g. Bombyx free tool developed at ETH) (Saso et al., 2019). In this workflow, the user can estimate the environmental impact of the design based on a very limited amount of information. Several drop-down menus (e.g., building size, building usage, energy preference, structural material) are combined with element inputs (function). Also, an estimated material can be defined. Areas connected to an individual element can be set manually or connected to the 3D “shoe box” model based on Sketch up or Rhino. Those models contain only surfaces, not thickness of the constructions or details regarding of windows, doors and other elements. Mentioned tools can be very helpful in the initial project phase. Usually, no uncertainty calculation are considered, although some recent development such as Bombyx v2 or in-house tools from architectural offices working with carbon budget description for client start to include a range of options (Hollberg, Kaushal, et al., 2020). In this case, in the early design, a wall for instance, is defined as an average wall with a probability of achieving best and worst environmental performance within a range of wall possibilities.

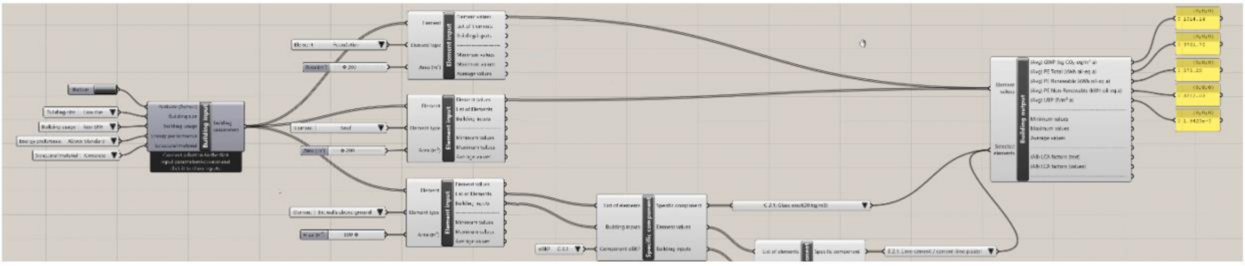


Figure 5: Example of the Rhino and Grasshopper based tool Bombyx. Source: internal archive.

5.1.3 Link LCA from early design phases up to final design

LCA can be processed in any design phase. However, the earlier the analysis is done, the higher level of uncertainty is included in the calculation. With the lack of details about the designed building, a type of simplification is needed. According to the current research, two different ways of simplification are possible: (1) adding uncertainty correction factors or (2) restructuring and aggregating the available databases. Both approaches can conclude to relatively precise results and can be valuable for design optimization.

Combining BIM and LCA was a clear direction of research in last decade. A comprehensive overview of this trend was published by Santos and co-authors (Santos et al., 2019) and show a significant increase of interest in this topic in the recent years.

Another study, produced by Mora and co-authors (Mora et al., 2020) shows tools used for a BIM-LCA approach. This study was based on 50 previously published research papers. As it is presented on Figure , an authoring BIM tool, Autodesk Revit is mainly used, and as a LCA tool the most common is a manual assessment in Excel.

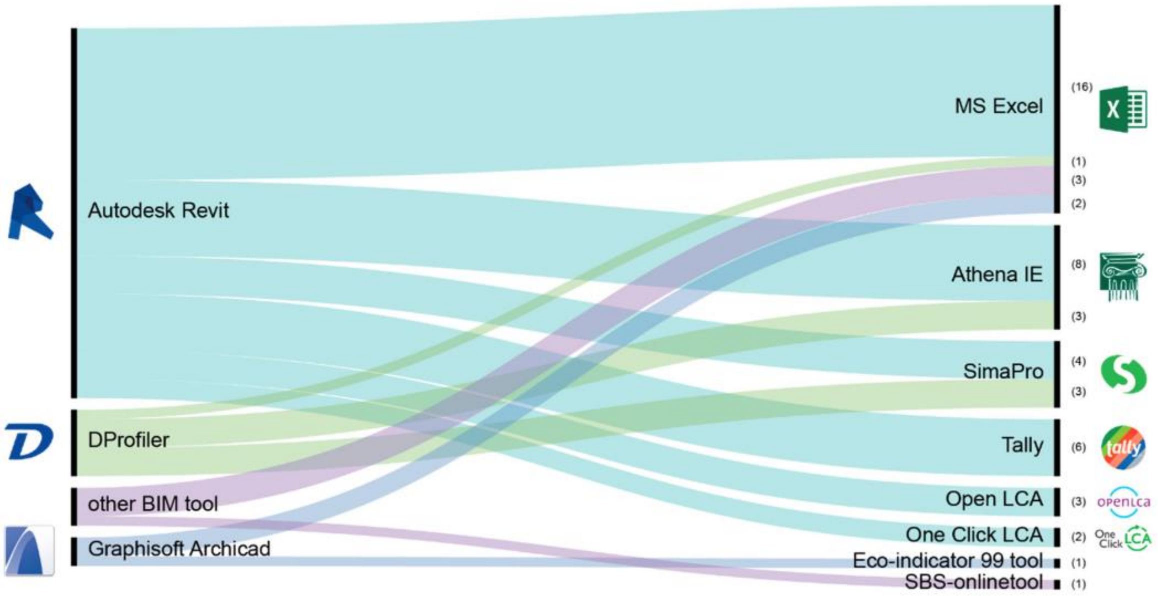


Figure 6: Software adoption in the selected cases studies; the coloured flow lines indicate the relationships between tools in data exporting from the BIM model to LCA analysis; on the left side, the chart gives evidence of the widespread adoption of Autodesk Revit (more than 80%) for BIM models; on the right side, the LCA tools are listed, counting in brackets the number of cases linked to each BIM software. Source: (Mora et al., 2020).

5.1.4 Adding uncertainty correction factors

One of the proposed methods is provided by Schneider-Marin and colleagues (Schneider-Marin et al., 2020). Her team defined the building in an early phase as a parametric design (concept phase) in which three groups of inputs are defined: (a) Geometrical data, which are taken out of the early BIM model (slab, floors, roof and external walls). Second group of inputs is (b) window construction and interior and they are defined by the user. The third group of inputs is defined as (c) technical specifications (u-values, construction thicknesses, reinforcement amount).

On top of the inputs, vagueness is added. It is defined as the amount of uncertainty on the mentioned groups of inputs in the early project phase. They define it as Building Development 2 (BDL 2). The values of vagueness are defined as 10% for (a) geometry and 25% for (b) window construction, interior and (c) technical specifications. Based on that, the authors processed the sensitivity analysis which demonstrated the uncertainty contribution to every mentioned group.

As a case study, a simple building was used. The proposed workflow combines the Industry Founded Classes (IFC) model with a generic database Oekobaudat. Authors repeated the mentioned process two more times (BDL 3 and 4) in more developed project phases and changed the uncertainty correction factors as it is shown in the following figure.

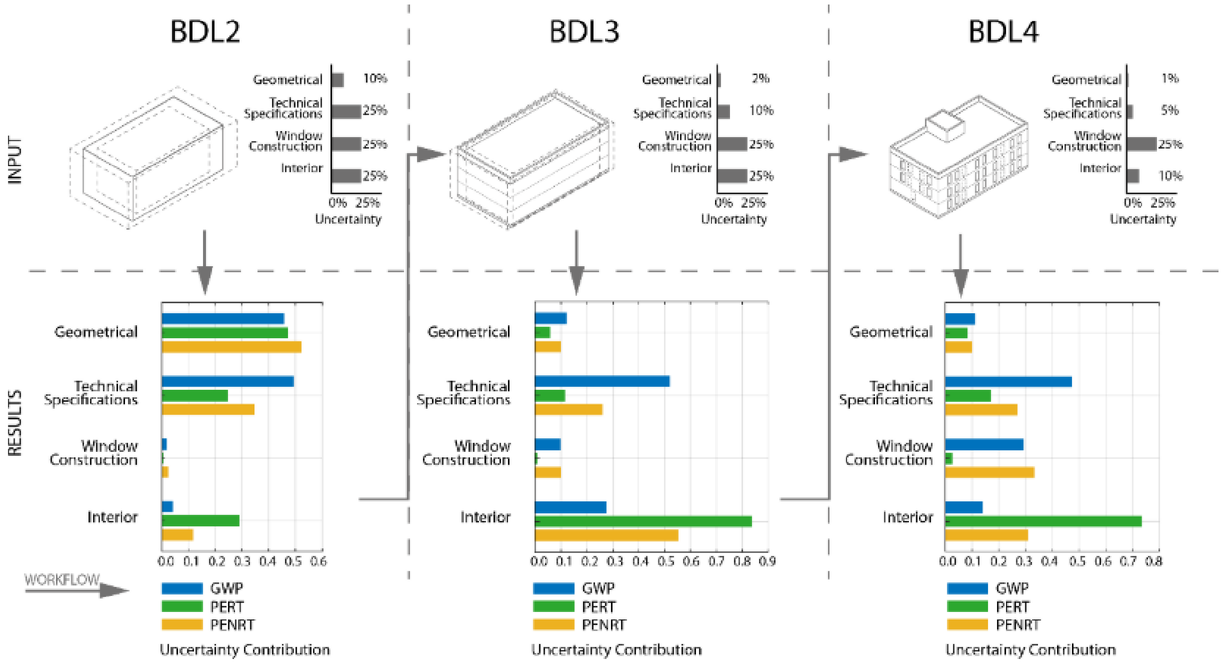


Figure 7: Overview of the used correction factors in a different phase. Source: (Schneider-Marin et al., 2020).

The second step of the proposed work was the contribution analysis which clearly showed the amount of embodied indicators (Primary Energy Renewable – PERT, Non-renewable - PENRT, and Global Warming Potential - GWP) in the specific parts of buildings. Results show around 50% of GWP for the building's bearing structure. After replacement of the reinforced concrete with wood, GWP decreased to 33%.

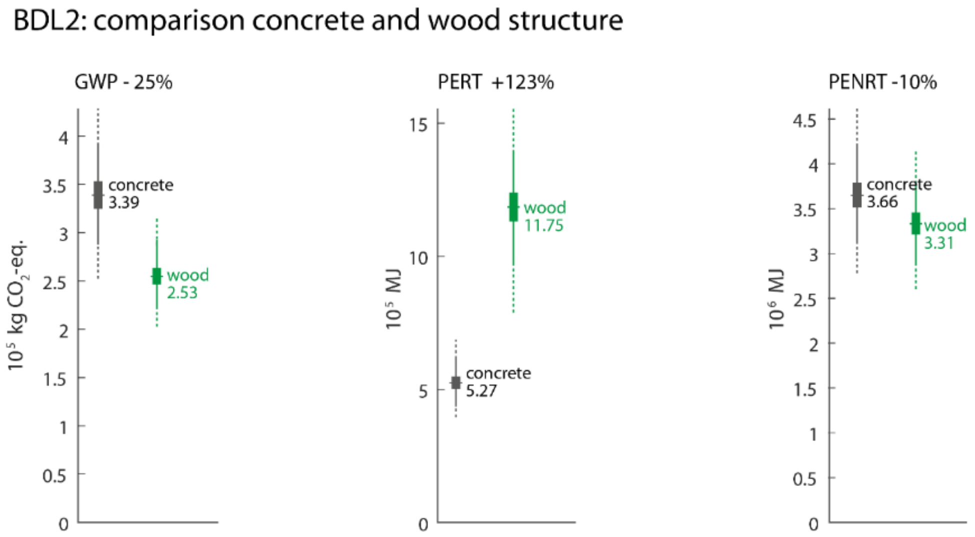


Figure 8: Contribution Analysis and comparison of concrete and timber structure. Source: (Schneider-Marin et al., 2020).

The study also shows that adding vagueness into consideration can be used for the embodied indicators in the early design phase successfully.

5.1.5 Restructuring & aggregating database

The second proposed approach is different. Instead of adding a correction factor, the database adjustment is used to be able to aggregate data from the early to detailed design phase. This method is similar to the Life Cycle Cost (LCC) analysis, because the decomposition method is applied according to the similar (usually national-based) rules. But instead of using costs, environmental data is used. Therefore, data can be used in the aggregated form, such as PE or GWP per m^2.

5.1.6 From building elements to building materials

The first example of the possible workflow was introduced by Naneva, A. et al. (Naneva et al., 2020). There is a struggle with data export from BIM, because a reliable type of data structure is needed. This workflow takes advantage of already existing LCC data structure, the Baukosten Hochbau (eBKP). This particular structure is valid for the Swiss context, but the principles of the workflow are transferable into any other country. The point is to pair the BIM elements within its different Level of Development (LOD) with the environmental data. In this study, the Bauteilkatalog for the early and KBOB for detailed phases were selected. The schema of the presented BIM development is shown in Figure .

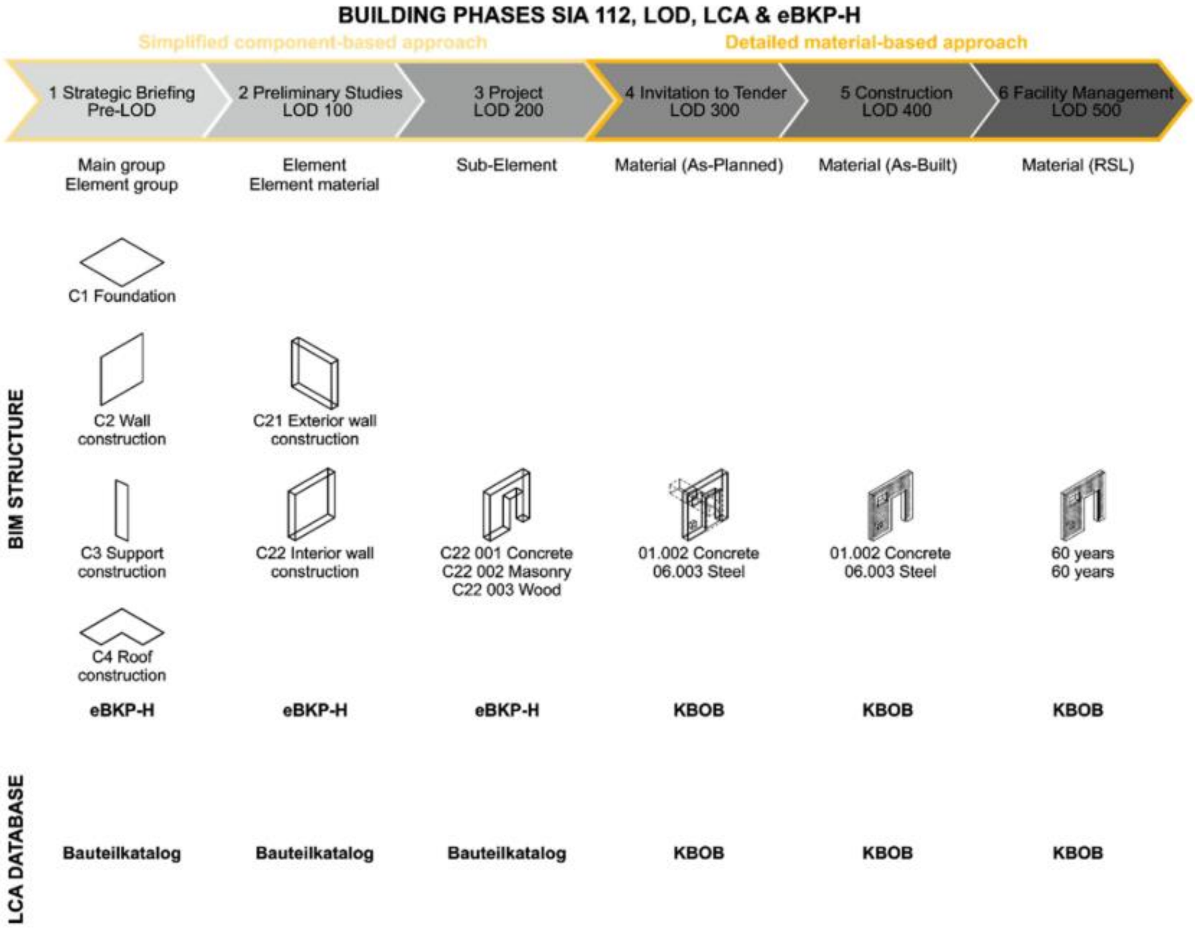


Figure 9: Overview of different BIM data structure and LCA database in a different project phase. Source: (Naneva et al., 2020).

Since this study is valid for various project phases, a dynamic approach was developed which covers BIM model (Revit), parametric scripting tool (Dynamo), LCA databases (Bauteilkatalog and KBOB). Results processed in the Dynamo script are returned back to the BIM model and addressed with newly created parameters. Thus, the result can be visualized in Revit by the element's environmental impact. This can be used as a valid tool for decision making and building optimisation. Moreover, the LCA report can be exported into a spreadsheet. The workflow is shown in Figure 5.

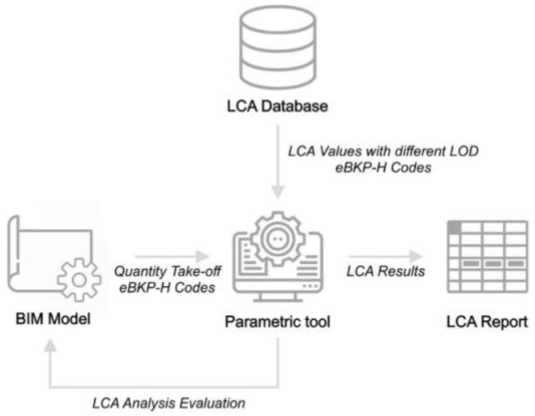


Figure 5: Proposed dynamic approach workflow. Source: (Naneva et al., 2020).

Another work from Cavalliere and colleagues (Cavalliere et al., 2019) used the structure of the building element description in order to calculate different average impact depending on the level of details for each specific component.

To propose the LCA at different design stages of design, the concept of Level of Development is used. The LOD defines the minimum content requirements for each element of the BIM at five progressively detailed level of completeness, from LOD 100 to LOD 500. Figure 6 gives a better understanding of design process and LODs of various construction activities.

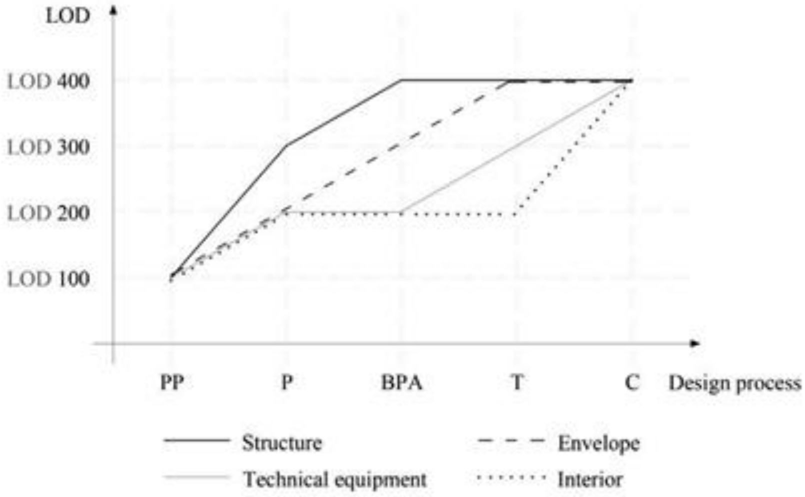
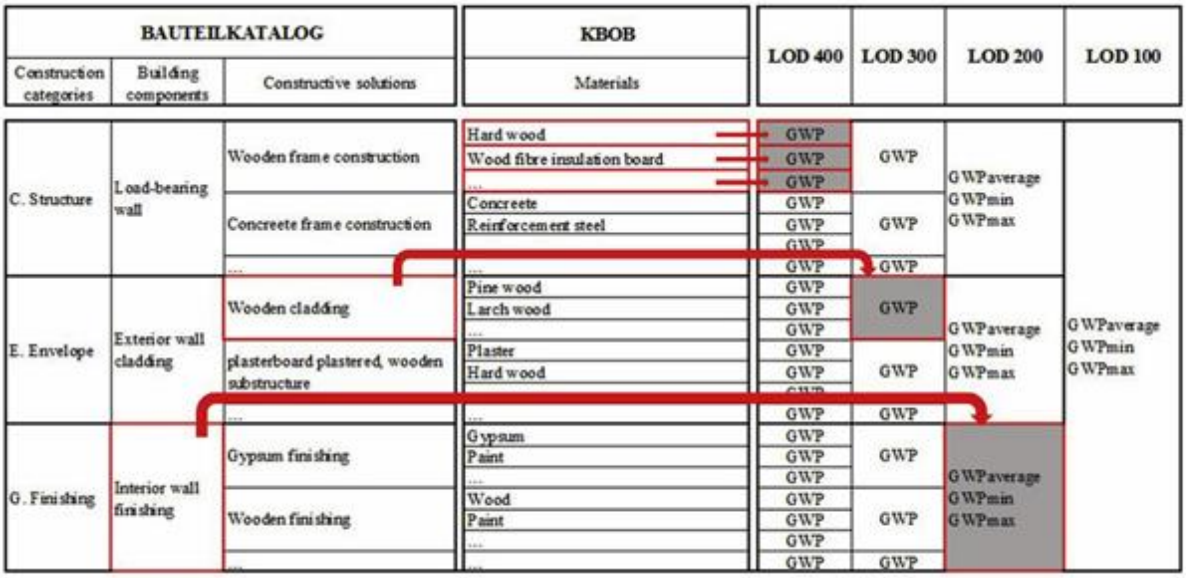


Figure 6: Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction. Source: (Cavalliere et al., 2019).

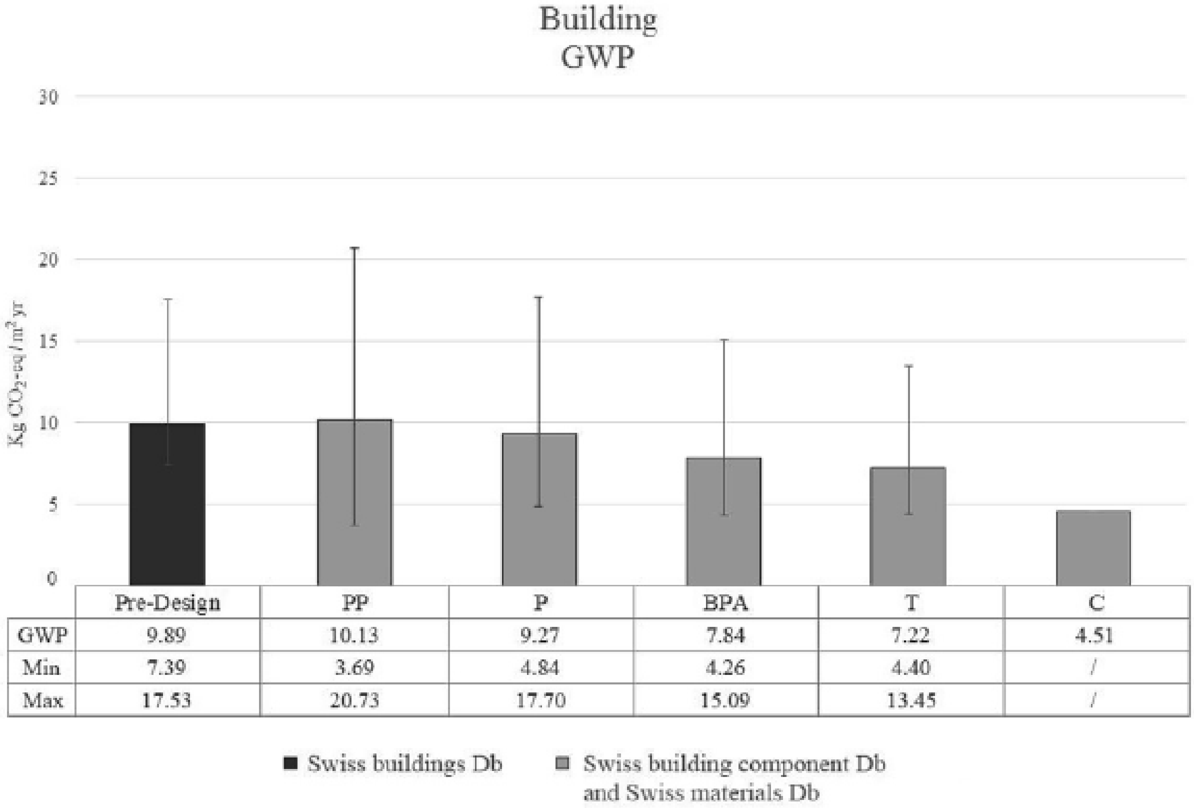
As shown on Figure 7, the element is composed of different components, and the impact of such components depend on the LOD, either very generic at a moment of the design process when a low level of details is known for this specific component. For instance, finishings are chosen very late while structural components are known earlier.



BAUTEILKATALOG			KBOB	LOD 400	LOD 300	LOD 200	LOD 100
Construction categories	Building components	Constructive solutions	Materials				
C. Structure	Load-bearing wall	Wooden frame construction	Hard wood	GWP	GWP	GWPaverage GWPmin GWPmax	GWPaverage GWPmin GWPmax
			Wood fibre insulation board	GWP			
			...	GWP			
		Concreete frame construction	Concreete	GWP	GWP		
			Reinforcement steel	GWP			
				GWP			
		...	...	GWP	GWP		
E. Envelope	Exterior wall cladding	Wooden cladding	Pine wood	GWP	GWP	GWPaverage GWPmin GWPmax	
			Larch wood	GWP			
			...	GWP			
		plasterboard plastered, wooden substructure	Plaster	GWP	GWP		
			Hard wood	GWP			
				GWP			
		...	...	GWP	GWP		
G. Finishing	Interior wall finishing	Gypsum finishing	Gypsum	GWP	GWP	GWPaverage GWPmin GWPmax	
			Paint	GWP			
			...	GWP			
		Wooden finishing	Wood	GWP	GWP		
			Paint	GWP			
			...	GWP			
		...	...	GWP	GWP		

Figure 7: Example of the proposed method for the LCA of an exterior wall above ground at the Building Permit Application phase. Source: (Cavalliere et al., 2019).

The proposed LCA method is validated using a case study of a multi-family house based on a real case study named WoodCube. The result of the study regarding the evolution of Global Warming Potential of the building during the design process is summarised in Figure 8.



	Pre-Design	PP	P	BPA	T	C
GWP	9.89	10.13	9.27	7.84	7.22	4.51
Min	7.39	3.69	4.84	4.26	4.40	/
Max	17.53	20.73	17.70	15.09	13.45	/

Figure 8: Evolution of calculated GWP of the building during the design process. Source: (Cavalliere et al., 2019).

The study shows that the results for the entire building in a certain design phase is in line with the forecasted variability range in the previous stages. The study also emphasises that the minimum values should only be considered as an indication of a potential and not a benchmark. Yet, the final result of the real case study is notably close to the minimum value in the PP phase, implying that I can be achieved in reality.

5.1.7 From generic materials to specific producers

An important aspect of any BIM-LCA task is connecting data from the BIM with the environmental database. This step is potentially problematic due to different national standards and environmental data available on the market. The universal and valid steps following the project's design phases are:

- Aggregated database (e.g. impact per m^2),
- Component database se (e.g. Bauteilkatalog),
- Material databa (e.g. KBOB),
- EPD database (e.g. https://ibu-epd.com/).

The first challenge is the ability to combine different data sources. As Cavalliere and co-authors (Cavalliere et al., 2019) argue, it is possible to combine different sources if the primary source is also the same (e.g. Ecoinvent). When primary data sources vary, it can also be combined but under specific conditions and a LCA expert should make the decision. Otherwise, the risk of potential uncertainty can significantly increase. Environmental assessment can only be precise if it is constantly updated along the project development. The EPD can be used for increasing accuracy (and decreasing uncertainty) of the calculation. As Anderson and Moncaster (Anderson & Moncaster, 2020) present on a case of concrete, it can be assumed that variations are similar to other materials (probably not that high). The impact can vary significantly according the exact type of concrete. As it is shown on Figure 9, high variations are present in the different EPDs.

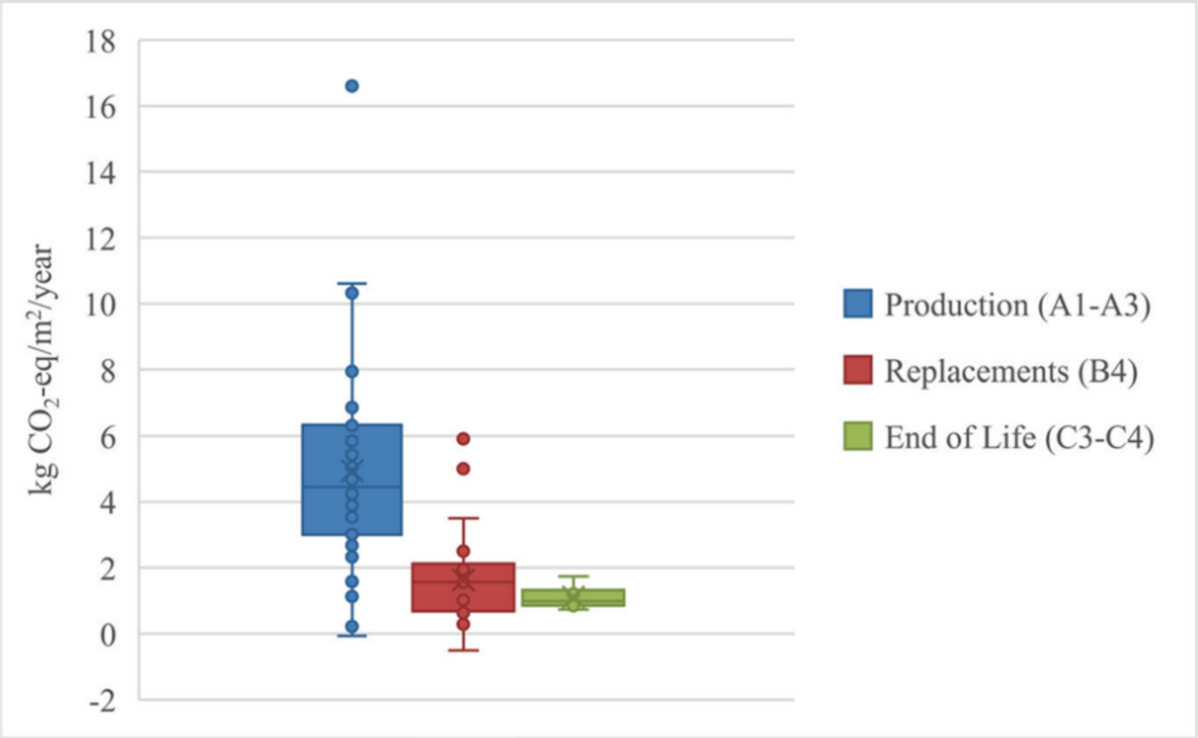


Figure 9: Variations in embodied greenhouse gases from different life-cycle stages representing product stage A1–A3 (56 cases), replacements B4 (42 cases) and end-of-life C3 and C4 (nine cases). Source: (Anderson & Moncaster, 2020).

One of the reasons explaining the high variation of the EPDs is that they provide product and country specific data. A clear picture of this argument is presented on Figure 10.

Therefore, it is important to use the data from EPDs when possible. Due to BIM, BoQ of high quality are available. Is it expectable that the result will be higher than with generic material (concrete in this case), but uncertainty will be lower. A potential problem can be the lack of EPDs available on the markets.

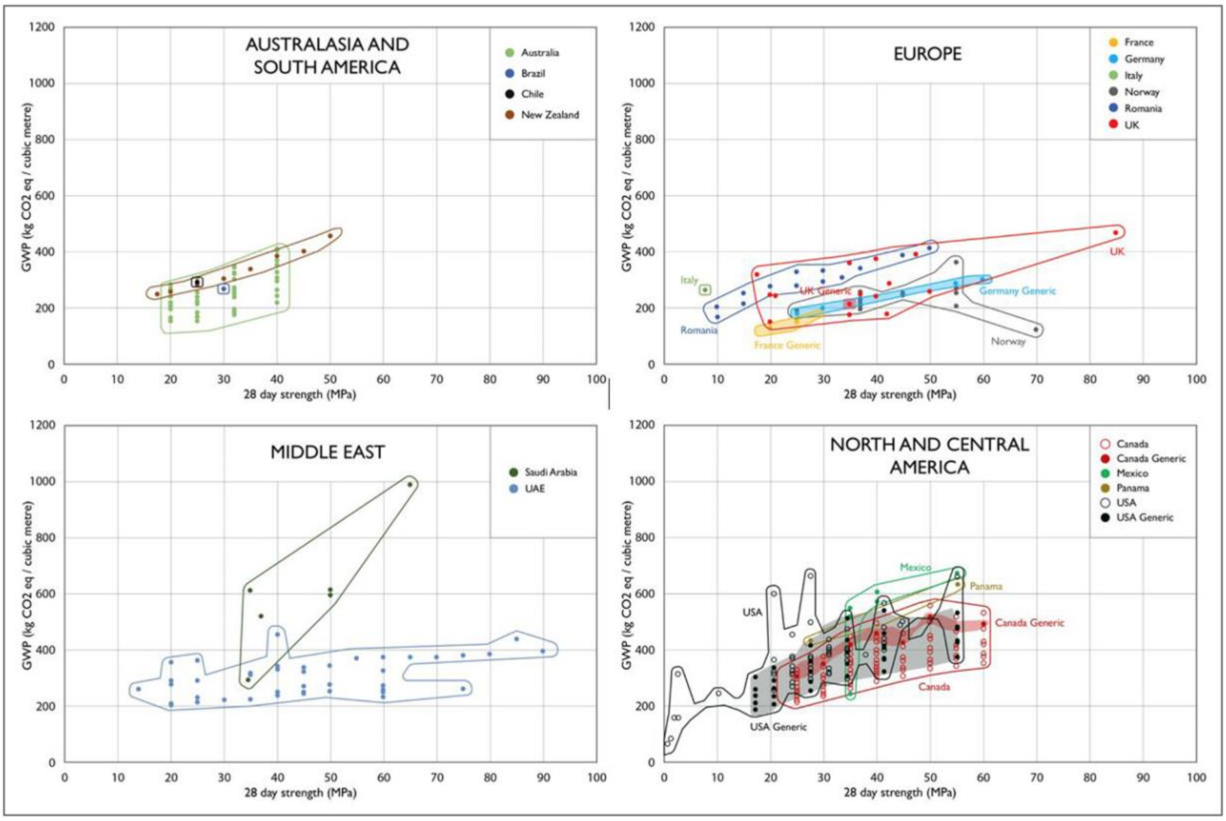


Figure 10: Relationship between GWP and compressive strengths of a concrete by regions. Source: (Anderson & Moncaster, 2020).

5.1.8 From underspecified LCA to the full detail

When specific information on the particular system is not available, as discussed in Section 5.1.6, a structure under specification can be employed for LCA of buildings (Tecchio et al., 2019). Figure 11 Figure 11: Probabilistic distributions of impact metrics (Global warming, Smog creation) for an ICF wall. AL1 to 5 = Assembly level 1 to 5. CV = Coefficient of variation. MAD-COV = median absolute coefficient of variation Source: shows the probabilistic distributions of impact metrics of assembly levels 1 to 5, with AL1 being the most general classification and AL5 being the most specific classification.

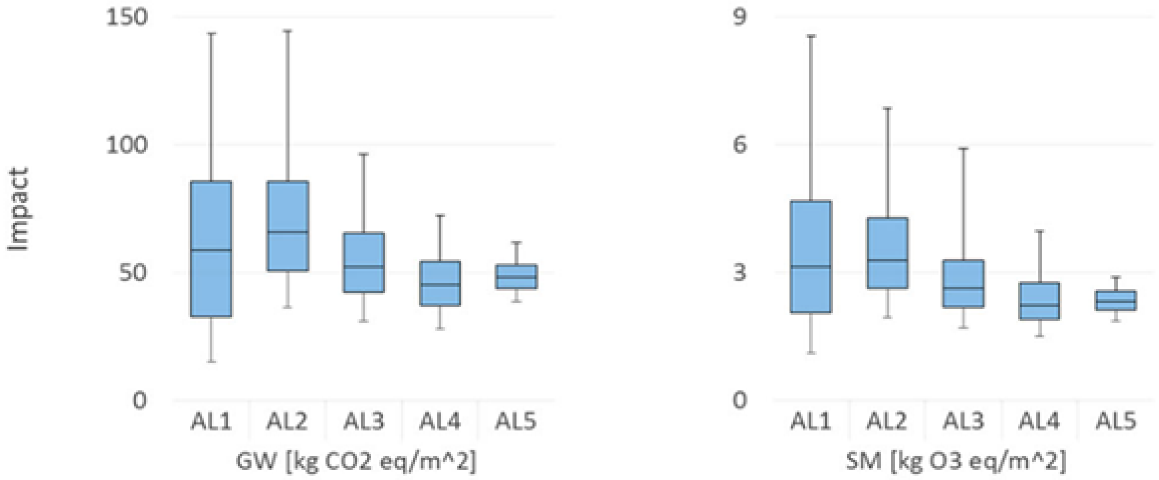


Figure 11: Probabilistic distributions of impact metrics (Global warming, Smog creation) for an ICF wall. AL1 to 5 = Assembly level 1 to 5. CV = Coefficient of variation. MAD-COV = median absolute coefficient of variation Source: (Tecchio et al., 2019).

The authors (Tecchio et al., 2019) declare by their calculations that even though the uncertainty regarding materials decreases in time (as the project phases follow) from Material Level (ML) 1 to 5, a significant amount of uncertainty is still present.

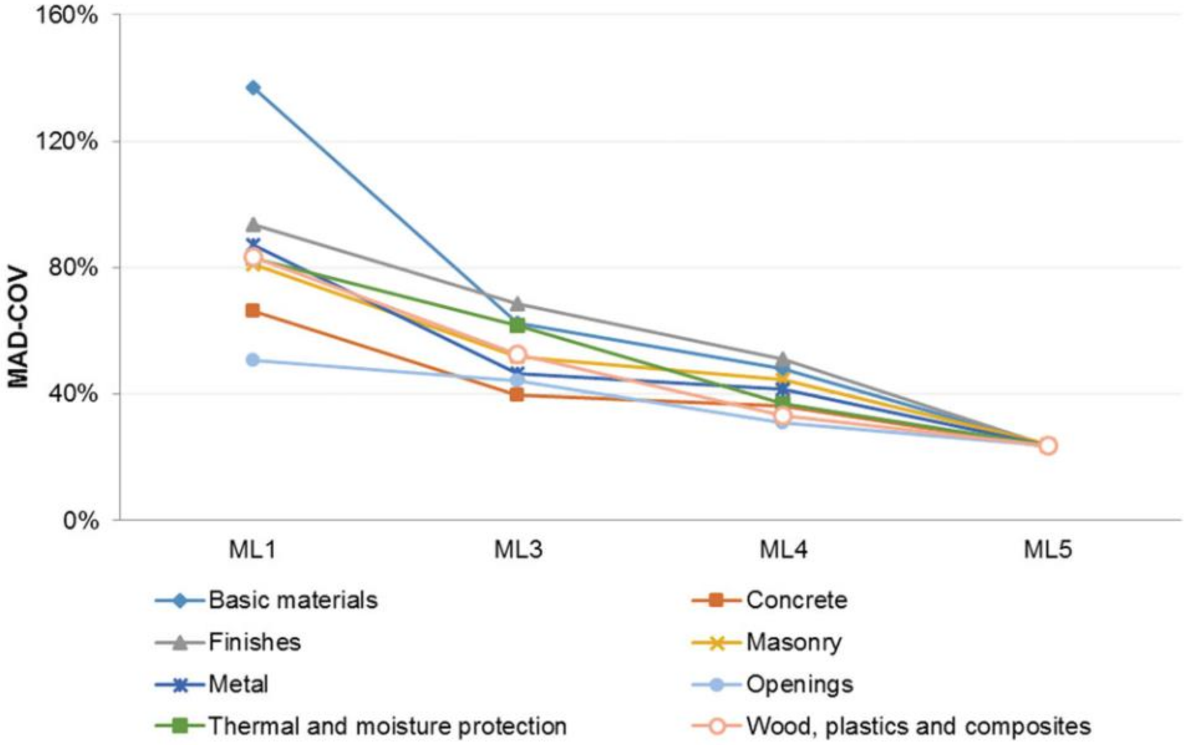


Figure 12: Average median absolute deviation coefficient of variation. Source: (Tecchio et al., 2019).

Another important structure to handle the variability is the one of the Bauteilkatalog. At the difference with working with materials along the design phases, the interest of the Bauteilkatalog (literally, catalogue of building element) is to work with building element. Therefore, depending on the level of details one can have a good knowledge of materials used in structural part of the wall while leaving largely unknown the choice of material for insulation or finishing. It allows to assemble a building from various building element, each having a given uncertainty on the materials depending on the level of knowledge on the funcational aspect of the material. This method has been described in previous section (from building element to building material design strategies) (Pierucci, Dell'Osso and Cavalliere, 2015; Cavalliere et al., 2019).

5.1.9 Link LCA only at detailed BIM level

In the late design phase, much research was done and published recently (Soust-Verdagher et al., 2017) . Even though not much uncertainty is present Figure 12: Average median absolute deviation coefficient of variation. Source: (Tecchio et al., 2019).in the late project phase (as it is shown on Figure 12), it is still necessary to consider it. The detailed model offers several ways for connecting with LCA. In the detailed design, the level of uncertainty is naturally low. The main building parts with the highest environmental impact (load bearing structure, façade, interior structures) as well as materials are already defined. On top of that, currently there are enough environmental data sources for detailed design of material databases or EPDs.

Currently, the problem is still with the Mechanical, Electrical, Plumbing (MEP), as even in the detailed design, the lack of data can be a problem. More about this issue is available in chapter 0

MEP systems.

The most common way is to employ BIM as an inventory (LCIA). The model is usually prepared in the BIM authoring tool (e.i. Revit, ArchiCAD, or similar) and BoQ are exported to the traditional LCA workflow. There are more ways how to combine BIM and LCA; four other approaches are defined by Wastiels and Decuypere (Wastiels & Decuypere, 2019). All the proposed approaches are shown in Figure 13. Based on that conference paper, a systematic literature review (SLR) was published by Obrecht and co-authors (Obrecht et al., 2020). The study investigates how different researches process the BIM-LCA workflow and how much manual work is needed. The authors consider 60 different case studies and the results show that most of the studies are still processed manually (Figure). This approach is time consuming and it creates the potential for uncertainty caused by errors.

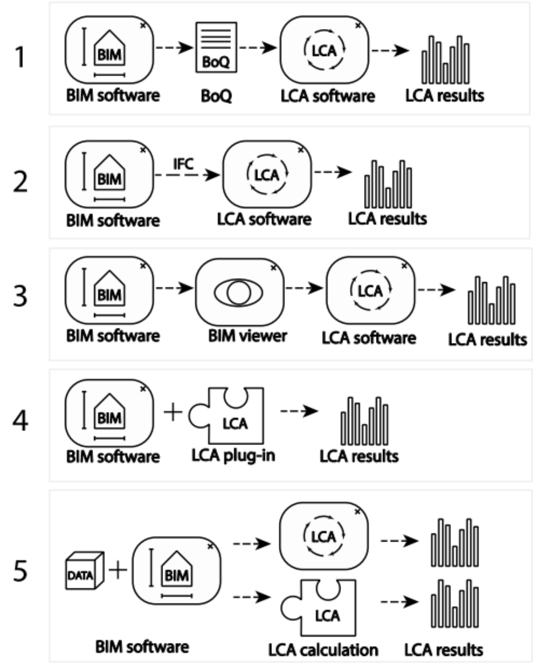


Figure 13: Different BIM-LCA approaches. Source: (Wastiels & Decuypere, 2019).

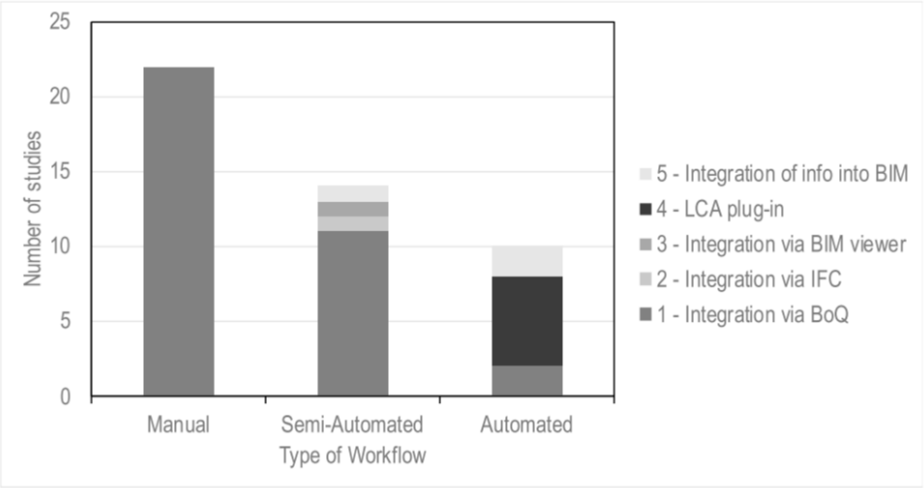


Figure 19: Level of automation in different case studies collected in the systematic literature review. Source: (Obrecht et al., 2020).

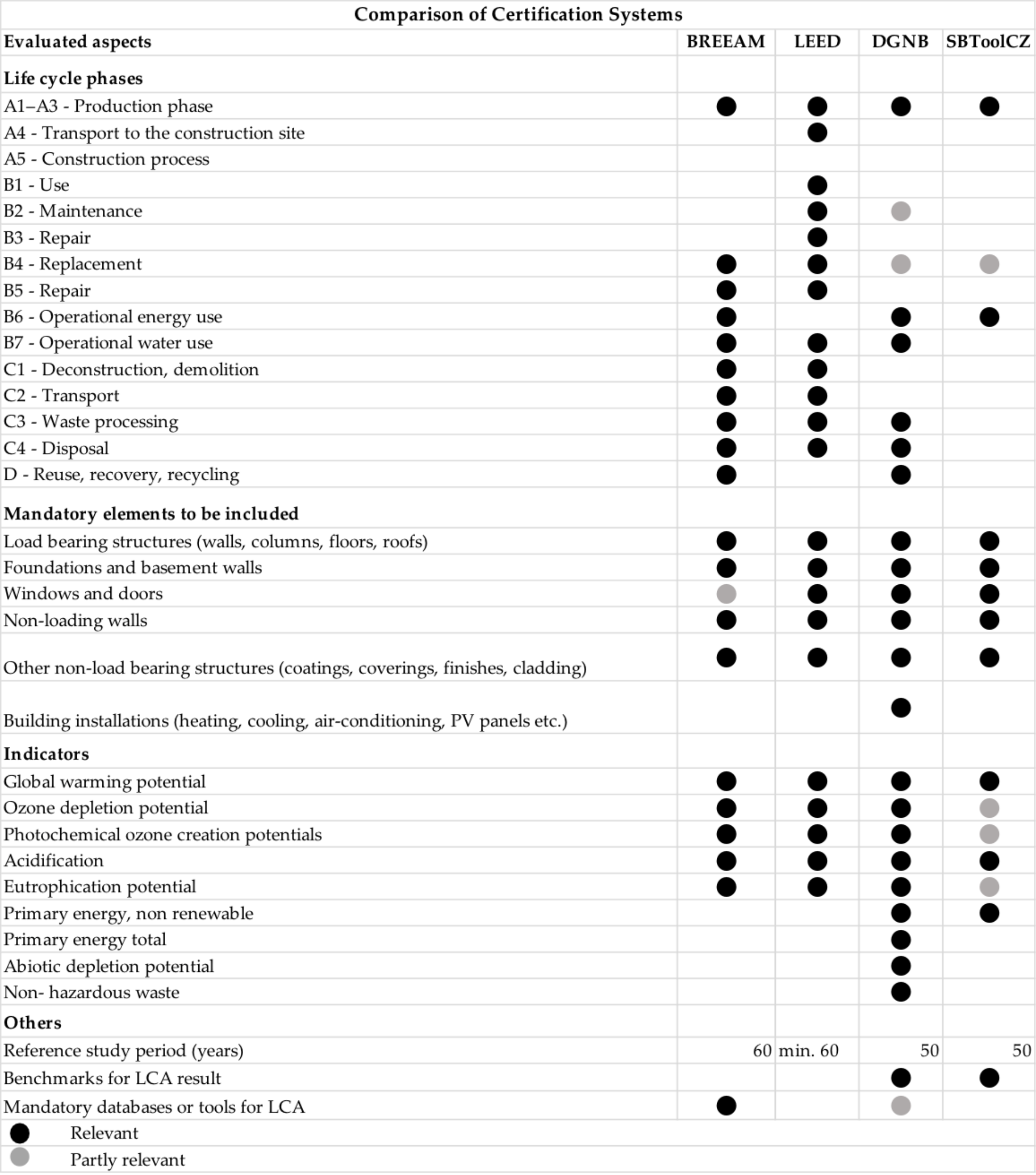
5.1.10 Related BIM-LCA topics having influence for uncertainty

BIM was developed as a place to store all information useful for the building project from design to use phase. It's therefore possible to include environmental information in the BIM. This information is not necessarily used for design purpose as detailed BIM model are used in later design phases when few adjustment can be done, but rather for certification and data storage objective.

5.1.11 Green Building Certifications

As it was presented in chapter 5.1.3, BIM-LCA topic is a relevant topic for research in the last decade. It is highly probable that its importance will also increase in real construction projects, but so far, the full LCA approach is usually is too complex. For this reason, various Green building certification systems have been invented. Those methodologies such as BREEAM, LEED, DGNB and others partly cover some aspects of the LCA, along with other environmental as well as social or economic aspects, and each of them have a demand for the BIM. Mentioned certification systems with their demands on BIM were published by Veselka (Veselka et al., 2020). Figure 14 gives an overview of the different certification systems and their relation to the LCA phases and indicators. Linking data from the model is then similar to other presented studies in this report.

Since green building certifications do not always follow system boundaries, goals and scopes of LCA methodology, results have to be considered separately from the models used for a whole LCA. Otherwise, a high uncertainty will be present.



Comparison of Certification Systems				
Evaluated aspects	**BREEAM**	**LEED**	**DGNB**	**SBToolCZ**
Life cycle phases				
A1–A3 - Production phase	●	●	●	●
A4 - Transport to the construction site		●		
A5 - Construction process				
B1 - Use		●		
B2 - Maintenance		●	○	
B3 - Repair		●		
B4 - Replacement	●	●	○	○
B5 - Repair	●	●		
B6 - Operational energy use	●		●	●
B7 - Operational water use	●	●	●	
C1 - Deconstruction, demolition	●	●		
C2 - Transport	●	●		
C3 - Waste processing	●	●	●	
C4 - Disposal	●	●	●	
D - Reuse, recovery, recycling	●		●	
Mandatory elements to be included				
Load bearing structures (walls, columns, floors, roofs)	●	●	●	●
Foundations and basement walls	●	●	●	●
Windows and doors	○	●	●	●
Non-loading walls	●	●	●	●
Other non-load bearing structures (coatings, coverings, finishes, cladding)	●	●	●	●
Building installations (heating, cooling, air-conditioning, PV panels etc.)			●	
Indicators				
Global warming potential	●	●	●	●
Ozone depletion potential	●	●	●	○
Photochemical ozone creation potentials	●	●	●	○
Acidification	●	●	●	●
Eutrophication potential	●	●	●	○
Primary energy, non renewable			●	●
Primary energy total			●	
Abiotic depletion potential			●	
Non- hazardous waste			●	
Others				
Reference study period (years)	60	min. 60	50	50
Benchmarks for LCA result			●	●
Mandatory databases or tools for LCA	●		○	
● Relevant				
○ Partly relevant				

Figure 14: Overview of the LCA phases and indicators covered in the green building certification systems. Source: Veselka et al.

5.1.12 Methodologies similar to LCA

LCA is not the only methodology used for the environmental assessment. Lu, Kun et al. (Lu et al., 2019) employed models in Boundary of Building's Life Cycle Carbon Emissions (BLCCE) approach instead. The overview of the methodology is shown on **Error! Reference source not found.**. There are similarities with the LCA methodology, therefore results have to be considered separately from a models used for a whole LCA. Otherwise, a high uncertainty will be present.

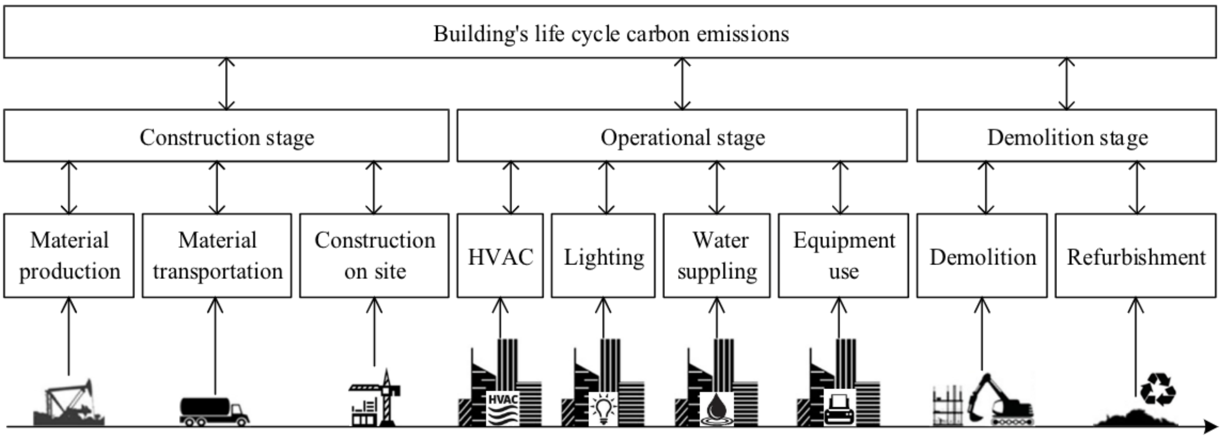


Figure 15: Schema of Boundary of Building`s Life Cycle Carbon Emissions (BLCCE) approach. Source: Lu, Kun et al.

5.1.13 Industry Foundation Classes (IFC)

BIM can be processed in various workflows. Two main ways of data exchanges are using (a) models in a native format, or (b) Industry Foundation Classes (IFC). This workflow is also called Open BIM. Both approaches are described on Figure 13, as use cases 1 and 2. When using IFC, relevance of a proper data structure and model classification became very important. A very good overview of BIM2LCA approach is described by Horn et al. (Horn et al., 2020). They point out that BIM has to be prepared for frequent export to IFC (mainly parameters and the Model View Definition (MVD)). On the Figure 16, the data structure is presented. Those facts cause a higher complexity of the whole process and it may conclude to higher uncertainty.

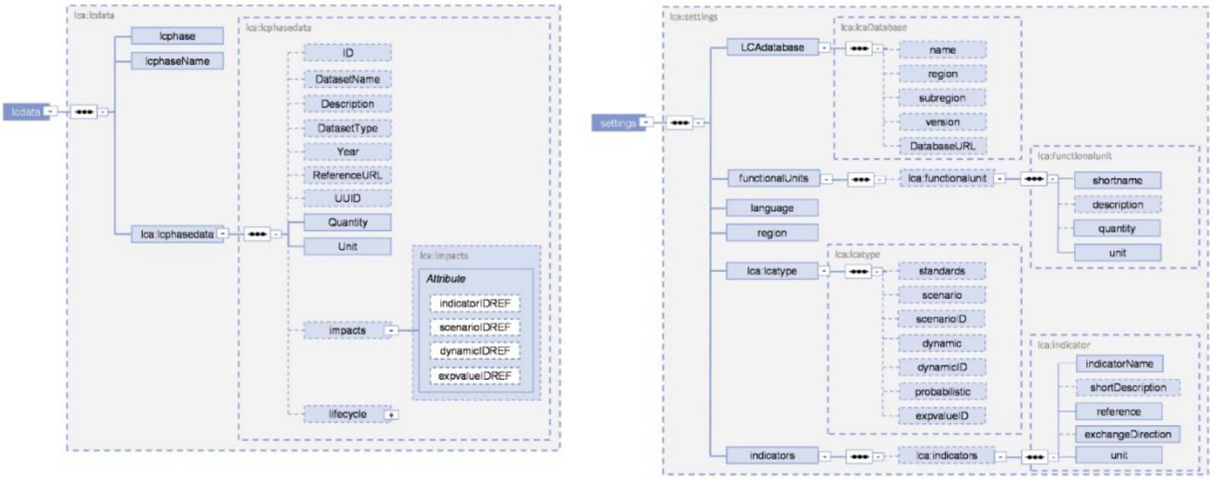
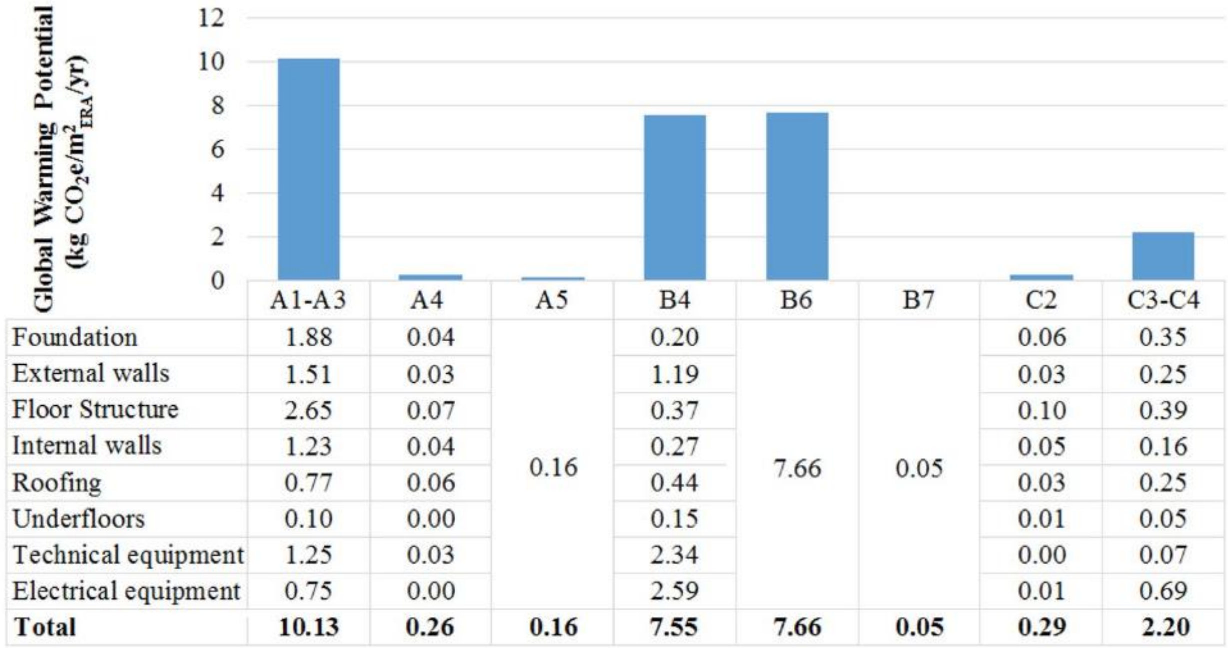


Figure 16: Using LCA in data structure with IFC. Source: (Horn et al., 2020).

5.1.14 MEP systems

Thanks to the employment of BIM, it is possible to quantify the exact impact of the Mechanical, Electrical and Plumbing (MEP) systems. The recent studies show similar trend and clearly point towards the fact that aggregated simplified data initially used in LCA are underestimating the embodied emissions from technical systems. A detailed case study from Hoxha et al. (Hoxha et al., 2021) showed that around 20% of annual environmental impact is caused by the technical installations. Results are presented on Figure 17.



	A1-A3	A4	A5	B4	B6	B7	C2	C3-C4
Foundation	1.88	0.04	0.16	0.20	7.66	0.05	0.06	0.35
External walls	1.51	0.03		1.19			0.03	0.25
Floor Structure	2.65	0.07		0.37			0.10	0.39
Internal walls	1.23	0.04		0.27			0.05	0.16
Roofing	0.77	0.06		0.44			0.03	0.25
Underfloors	0.10	0.00		0.15			0.01	0.05
Technical equipment	1.25	0.03		2.34			0.00	0.07
Electrical equipment	0.75	0.00		2.59			0.01	0.69
Total	**10.13**	**0.26**	**0.16**	**7.55**	**7.66**	**0.05**	**0.29**	**2.20**

Figure 17: Global warming potential indicator. Source: (Hoxha et al., 2021).

Another detailed case study was presented by Kiamili and co-authors (Kiamili et al., 2020). The authors calculated the exact environmental impact of the HVAC system based on very detailed BIM (LOD400). Results are presented in Figure 18.

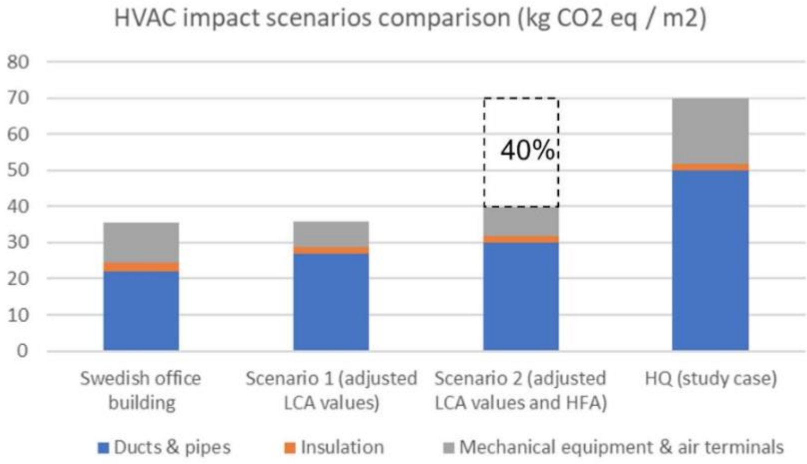


Figure 18: Comparison of different case studies. Environmental impact of HVAC system (per sqm) is significant. Source: (Kiamili et al., 2020).

Both studies show significantly higher impact which are two to seven times higher than previous non-BIM based LCA. Unfortunately, precisely calculated impacts can be processed only in the late phase of the model (LOD350-400). Therefore, it is not possible to optimize the HVAC design. Available generic data underestimate significantly the impact of the technical systems. Further research on early design HVAC quantification is necessary. These initial studies also show that low tech solutions such as the building 2226 from Eberle architects in Lustnau where no technical systems have clear interests from embodied emissions perspective and that classic LCA might not be able to grasp these advantages as they underestimate real environmental impact from MEP.

5.1.15 Risk of relying on BIM data during the design phases

In early design phases, there is an incompleteness of the geometry, such as for instance missing internal walls. It's possible to calculate an expected total environmental impact by adding a percentage of some value as it's done with cost estimation in early design phase of project. However, it is sometimes not an incompleteness which occurs but an overdesign. In a BIM workflow, when multiple stakeholders are working on the same document, some profession can use elements as placeholder in the BIM file which creates an overestimation of the impacts. This is what Hollberg and co-authors have shown (Hollberg, Genova, et al., 2020), by calculating the embodied emissions from a BIM based construction project during all the design phase. The example of this use case is shown in Figure 19. It shows clearly that between the building permit and the delivery of the construction plan the environmental impact of the builidng is devided by 30%, which is good, but before it increases by 150%. So it doesn't follow a regular optimisation process but rather an erratic increase of environmental impact due to very thick concrete wall implementation or placeholder of technical systems, which are then finally refined in the BIM. It means the design has indeed been improved between building permit and construction, but this is due to good construction practice and knowledge from the team and not thanks to the information in the BIM. It is therefore extremely important to elaborate a workflow between the parties to avoid this tendency of placeholder use and to have a regular tracking of LCA in the BIM design.

Figure 19: Evolution of total results for embodied GWP in t CO_2-e throughout the design process. Source: (Hollberg, Genova, et al., 2020).

5.2 Optimizing the design process through LCA

The other method employed to deal with uncertainties during the design process is to directly suggest to the designers the options which would have the lowest environmental impact or the driving decision which should be made in terms of environmental performance. In a way, rather than following the design flow and adapting the LCA to it, another option is to perform an LCA optimisation and to adapt the design workflow to it. The various studies which have been made following this logic are usually dealing with parametric LCA.

5.2.1 Parametric LCA for specific optimisation aspects

Numerous studies are dealing with parametric LCA. These are linked with the development of parametric design in architecture and allow to test different options according to their environmental footprint. This approach has been promoted among other by Alexander Hollberg (Hollberg & Ruth, 2016) and it is shown in Figure 26.

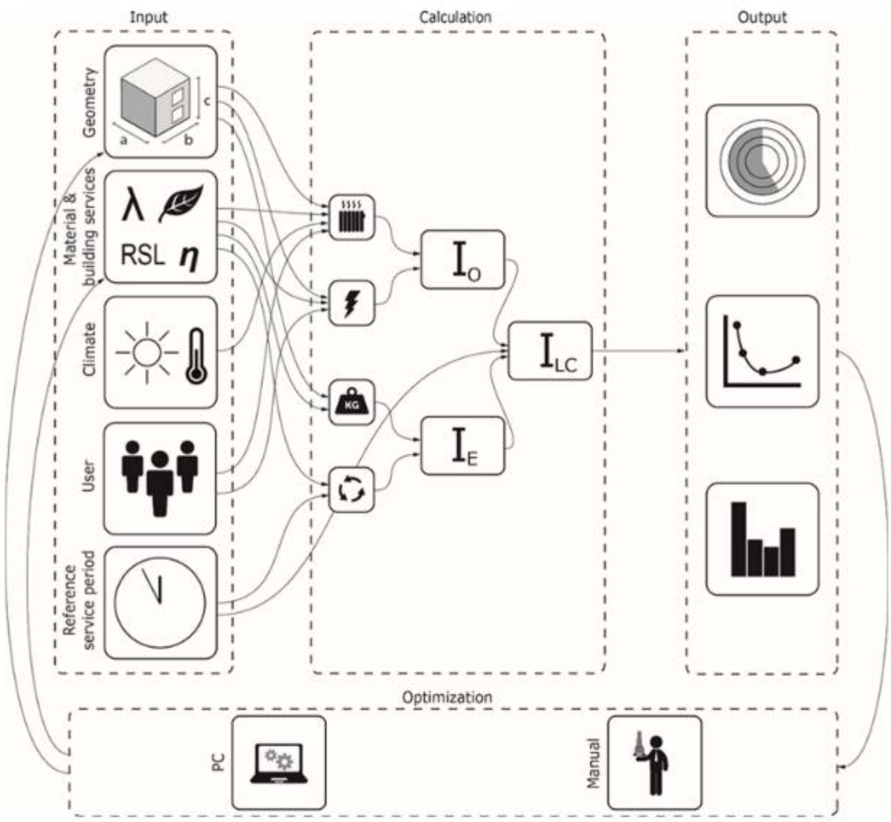


Figure 20: Concept of the parametric workflow. Source: (Hollberg & Ruth, 2016).

It relates to other optimisation strategies in other field such as structural engineering and can use various optimisation methods. Early work related with genetic algorithm and LCA has been performed following these principles (Schwarz et al., 2016). These strategies usually allow to reach the optimal solution once the parameters are chosen. In that sense, most optimisation strategies will not necessarily follow a design workflow, but rather reach an optimal solution than can be implemented directly. The designer is then out of the process as design solutions are taken by optimisation tool, except maybe in the beginning when he can choose the type of parameters that will be assessed and the range of possibilities that can be tested (or not) for each parameter.

Results are usually presented into Paretto front where for instance environment and economic costs have to be balanced (Galimshina et al., 2021). Other example of such approach is shown on Figure 21, where Kiss and Szalay present a process for design a building mass with optimal ratio between embodied and operational cumulative energy demand (Kiss & Szalay, 2020).

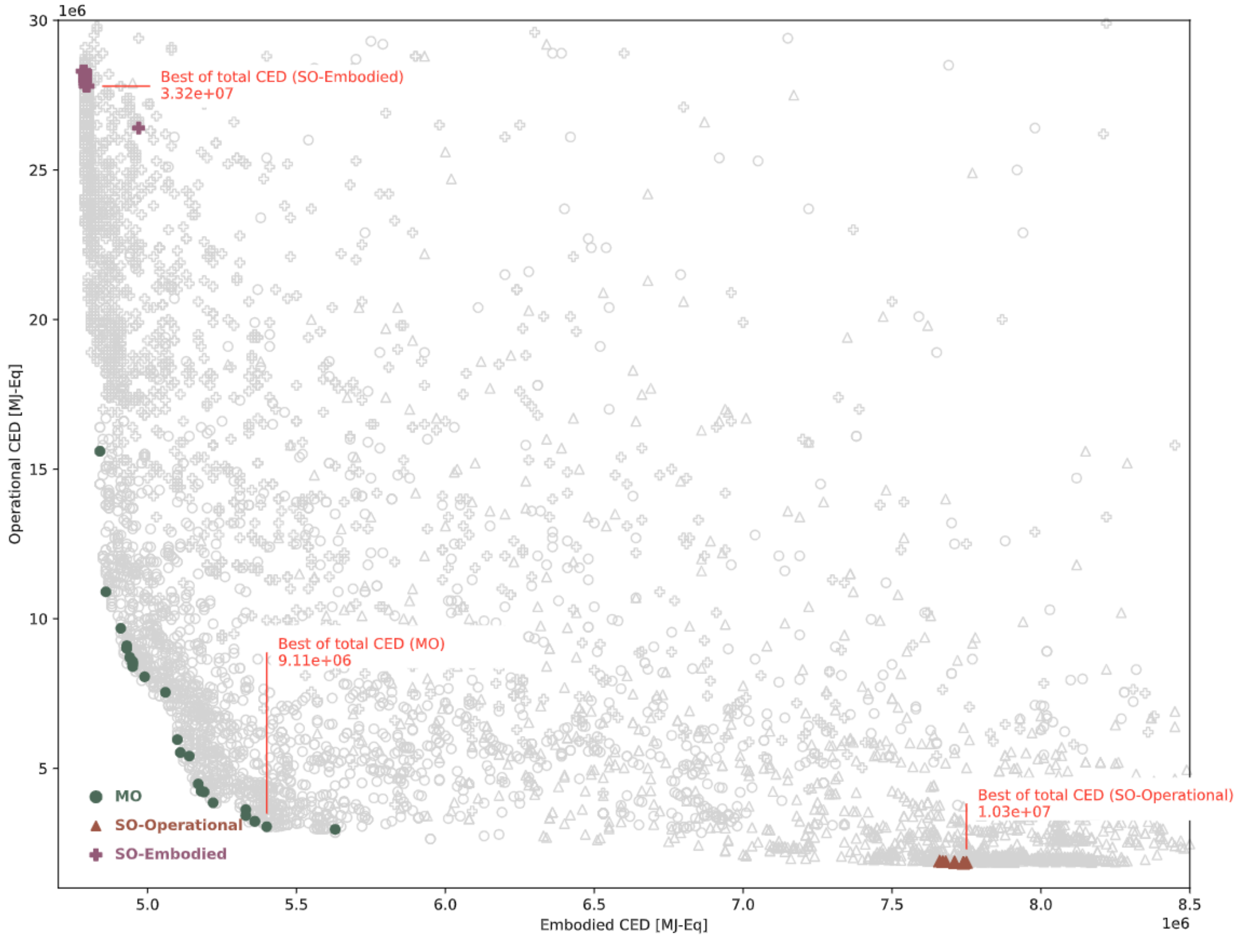


Figure 21: Results of the multi- (MO - green dot) and single-objective (SO-operational - red triangle, SO-operational - purple cross) optimizations on the objective space for cumulative energy demand (heating energy carrier: gas). Source: (Kiss & Szalay, 2020).

5.2.2 Parametric LCA along the design workflow

Another method was proposed by Thomas Jusselme during his PhD at EPFL . The proposed method is based on the novel approach to LCA adapted to the early design context (Jusselme, 2020). Through the extensive literature review and a survey of 500 architects and engineers, the identification of the possible obstacles for the low use of LCA and the possible solutions to overcome this problem, was performed. Afterwards, this was adapted into the data-driven method for low-carbon building design. The possible techniques' difficulties and solutions to them are shown in Figure 22.

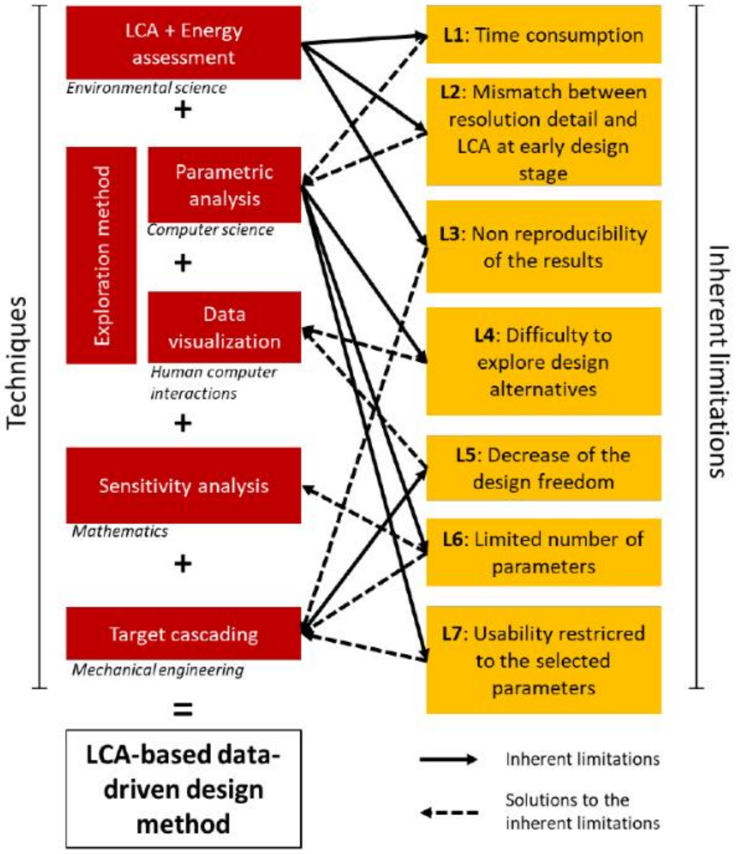


Figure 22: Techniques for increasing LCA usability at early design stages and their identified inherent limitations. Source: (Jusselme, 2020).

In the work of Jusselme the compilation of all design options allow to identify the parameters which will have the most influence on the final Life cycle emissions. From there he will elaborate a decision tree which ask designer to take decision first on the elements which have the most influence. In his case study, it is first the horizontal elements which can be either in wood or concrete, then the HVAC system, then the type and amount of insulation, the choice of PV. This decision tree is not related with a design process but allows to take decision on what will really influence the environmental impact early one.

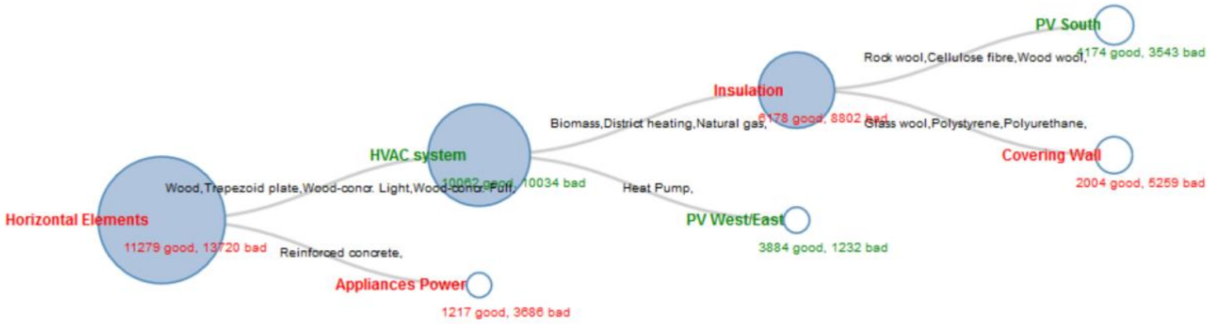


Figure 29: Visualization of the smart living building data set with a Decision Tree. Source: H-IST UNI-FR and (Jusselme et al., 2017)

As a result of this decision tree the amount of uncertainty is gradually reduced and a reliable environmental impact of the project can be provided although it is still in the early design stage as the key decision have been taken and that the rest will have minor influence on the overall result. Actually Jusselme shows that usually 80% of the uncertainty is carried by 20% of decision parameters (Figure 30) (Jusselme, 2020).

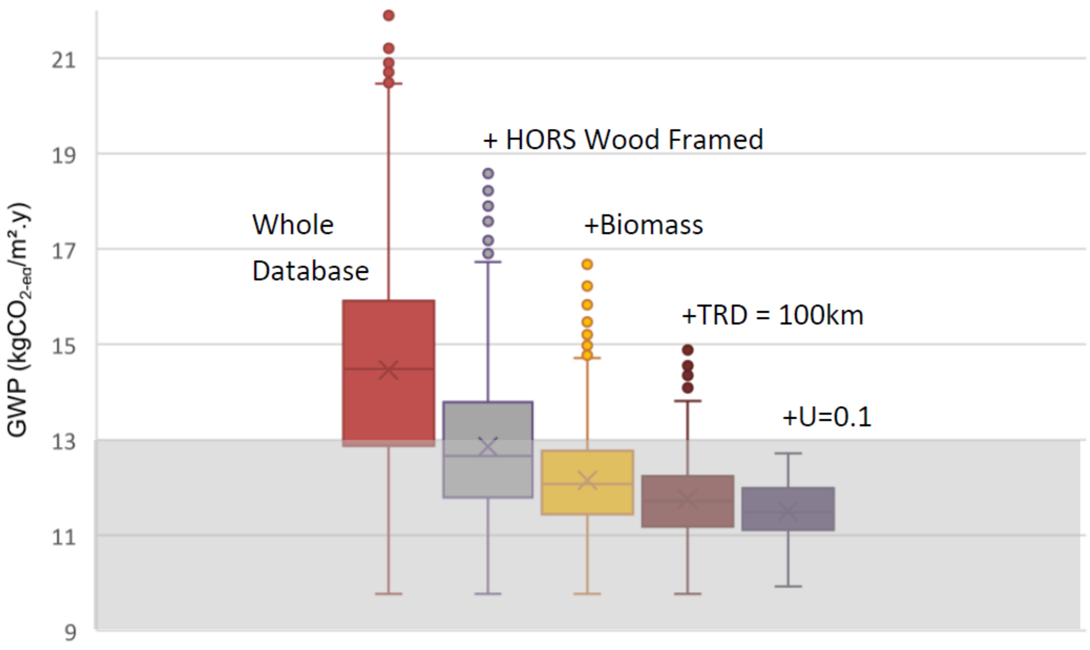


Figure 23: *Distribution of the GWP impacts of the full database (left), and other subpopulations with cumulative constraints by the sensitivity indices of the design parameters. The grey zone represents GWP impacts below the SIA2040 objective. GWP axis starts at 9 kg CO2-$_{eq}$/m$_2$.y.*

6. Conclusion / Recommendations

On the one hand, it is obvious that designer has major influence on the final environmental of a building. On the other hand, a building project is a long process with multiple actors and many small decisions that will be taken during the duration of the project. Therefore the designer has the difficult task of caring the long term and overall vision of the project while being able to take the right multiple decision all along the project. It means that although a large amount of uncertainty remain in the early phase of the project, some key choices taken in the beginning will in fine control the environmental impact of the building. How to take the right decision? When is it possible to take one decisive choice? That's the complex task of the designer.
In order to support the designer during the decision process, LCA experts have to adapt their tool to provide the right level of information depending on the available data at each specific stage of the project.

We have identified two fundamentally different strategies to provide decision support through design process. The first one is to develop LCA that provide reliable results for each stage of the design, the second one is to suggest to the designer to take in the very early stage of the design the key decision that will influence 80% of the uncertainty eventhough a classic design process would not put these decision so early in the design.

In the first workflow, the LCA calculation has to adapt to the level of details available all along the design process. It means that in the early design phase, there is a need for aggregated data which include assumption on typical construction process even if the designer would not specify them. In the very early design stage, the project is described with simple volume and surface. And although a wall is represented only as a plane in 3d or as a line on plan, for the early design LCA, it already mean a given quantity of material assuming typical construction process. This under-specified LCA method (Tecchio et al., 2019; Cavaliere et al., 2019) is key in order to guide designers towards the lowest possible environmental impact considering the choice they are doing. In a later stage, once geometry, heating system, material performance are defined, the designer will choose between two producers which will then influence transport distance. But usually transport has a very minor influence on environmental impact of building and acceptable transport distance are first constrained by economic factors before causing environmental impact differences.

Following this first workflow, where LCA calculation is adapted to the design process, it is recommended to work with aggregated database, calculating building elements rather than specific material quantities. It is also recommended to work with database showing worst and best case for each elements in order to visualize the remaining range of environmental footprint can be achieved depending on the options taken.

In the second workflow, a parametric LCA calculation is done in the very early design phase in order to identify the most influential parameters. This simulation will show to the designers the 5 to 10 parameters they need to fix from the beginning of the design in order to reduce uncertainties to the maximum. The classic rule of 80/20 is valid and usually 80% of the uncertainty are controlled by 20% of the parameters. This decision support approach is very efficient as it allows to fix form the beginning the essential parameters and afterwards, the designer can make detailed choices that will not drastically influence the results. It means that decision can still be taken according to LCA results, for instance choosing the material with the lowest EPD, but somehow even if the choice is not environmentally driven, but aesthetically or economically driven, it won’t have major influence because the type of decision which are taken at that moment haven minor environmental consequences. This is of course because the material choice which have crucial consequences have been in early stage and are then not discussed again.

Following this workflow, the LCA expert is providing to designers in the very early stage the 5 to 10 decision they need to take. It requires tough early decision that will then influence most of the design, but the interest is that the environmental footprint of the building is nearly already fixed which allows to the designer to focus again on what they know how to do, meaning good architecture, which will be within an environmental budget that has been agreed in the beginning.

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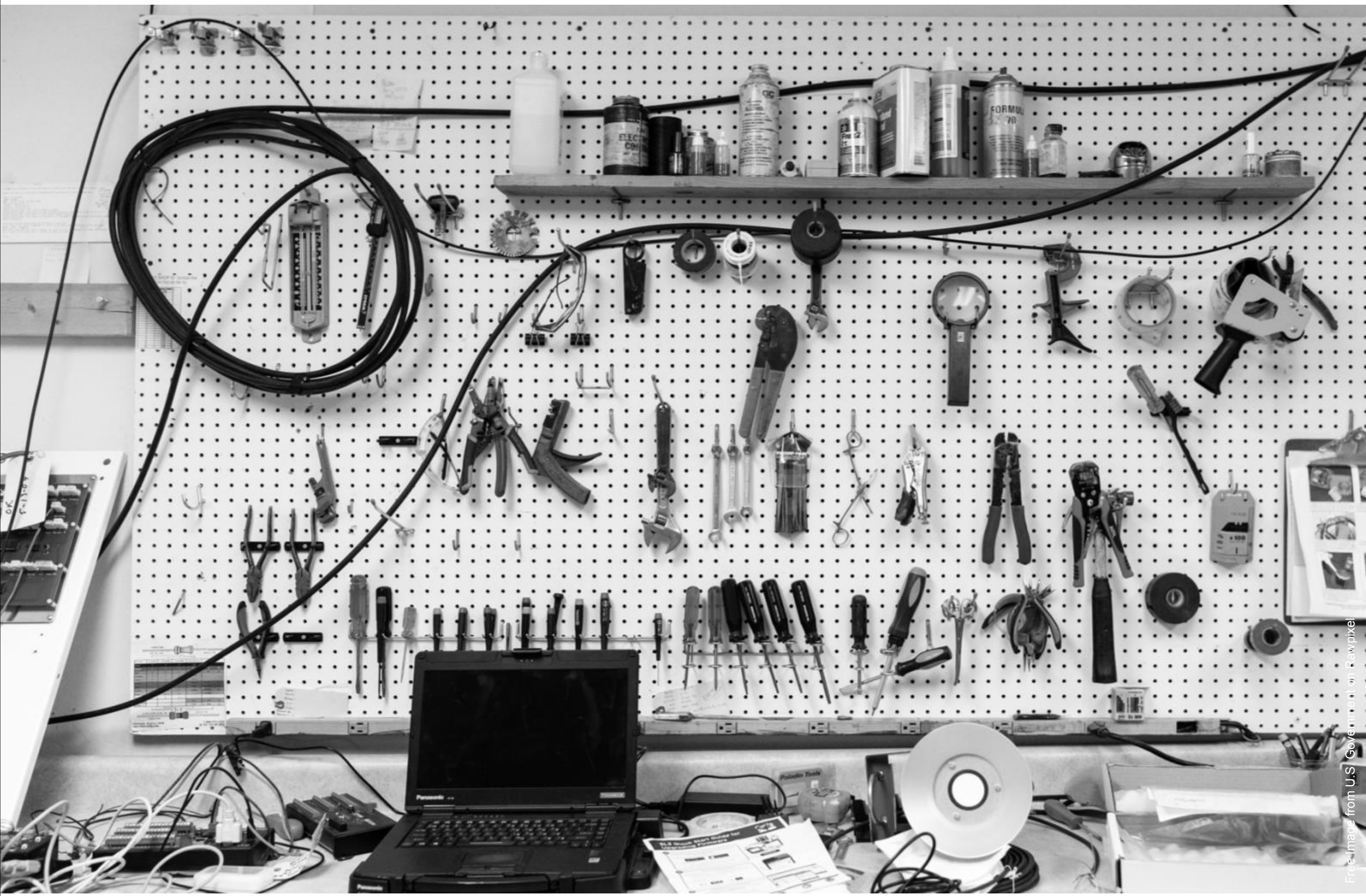
Designer's toolbox for Building LCA

A Contribution to IEA EBC Annex 72

April 2023



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International Energy Agency

Designer’s toolbox for Building LCA

A Contribution to IEA EBC Annex 72

April 2023

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Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_2eq	CO_2 equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House

ST1	Annex 72 Subtask 1: Harmonised methodology guidelines
ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes

Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process
Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Introduction

The perception that life cycle impacts must be considered during the design of a building is common amongst practitioners (Roberts et al., 2020). The need to rely on Life Cycle Assessments (LCA) already in the early design stages drives practitioners to search for tools and data that might support the insertion of environmental performance information on their typical workflows (Nilsen and Bohne, 2019; Potrč Obrecht et al., 2020).

A survey performed within the activities of Subtask 1 showed that, generally, most architects and other stakeholders take environmental aspects into account (more than 90% of respondents), so almost all of them are familiar with the topic. The ones that actually rely on LCA, however, represent only 31% of respondents. 42% plan to use LCA in the medium term, and the remaining 27% do not plan to use it (Balouktsi et al., 2020).

In order to increase the number of design practitioners using LCA in their daily practice, two aspects must be addressed: (i) designers' basic knowledge about LCA and (ii) versatility and ease of use of building LCA tools. Regarding the former, the willingness to acquire knowledge to answer to the increased demand for buildings' environmental performance information will depend on design professionals themselves. A proper use of available tools requires a comprehension about the environmental mechanism measured by relevant indicators, which would allow the ability to interpret calculation results, and a good understanding of how design decisions influence the results (Balouktsi et al., 2020). The latter aspect, on the other hand, depends on the different goals of the tools' developers.

To ensure effectiveness, a tool must be tailored to the planning phase, the user's knowledge, and the concerns of the different stakeholders involved in the design process. Accordingly, either a wide variety of tools are needed, or each tool must be scalable and capable of adapting to the users' needs and knowledge (IEA-EBC, 2004; Millet et al., 2007). The focus of the report is to categorise available tools to make sure the designer can make an informed decision regarding what is (are) the best tool(s) to choose from, according to his or her specific needs.

Objectives

This document relates to activity 2.4 of Subtask 2. It aims to propose a categorisation for building LCA tools currently available for design decision makers.

While building tools number is raising and new products are under development, it is important to document and inform practitioners regarding the available features and options for LCA integration in typical designers' workflows. The report relies on the outcome of a questionnaire, which results are here presented. Within the survey, a group of current available tools participated. Even if the list of mapped tools is not exhaustive, based on this information, the survey activity allowed a building LCA tools' categorisation. The report is expected to help design practitioners in **selecting a building LCA tool** that would best fit their needs and their workflows, but also to provide an overview on **current general** and **ideal next generation tools**.

1. Tools and aids – a typology

LCA databases are used when evaluating the environmental impacts of specific building products, and it is therefore crucial when studying the environmental impact of a product. A various number of LCA databases exist nowadays, and it is acknowledged that the data in the databases varies from database to database because the modelled processes are based on the individual building product manufacturing characteristics (Takano et al., 2014)**Error! Reference source not found.**. A handful of the databases is being used as the underlying data basis in some LCA calculation tools (Soust-Verdaguer et al., 2017). Figure 1 illustrates a selection of databases used in building sector for LCA calculation.

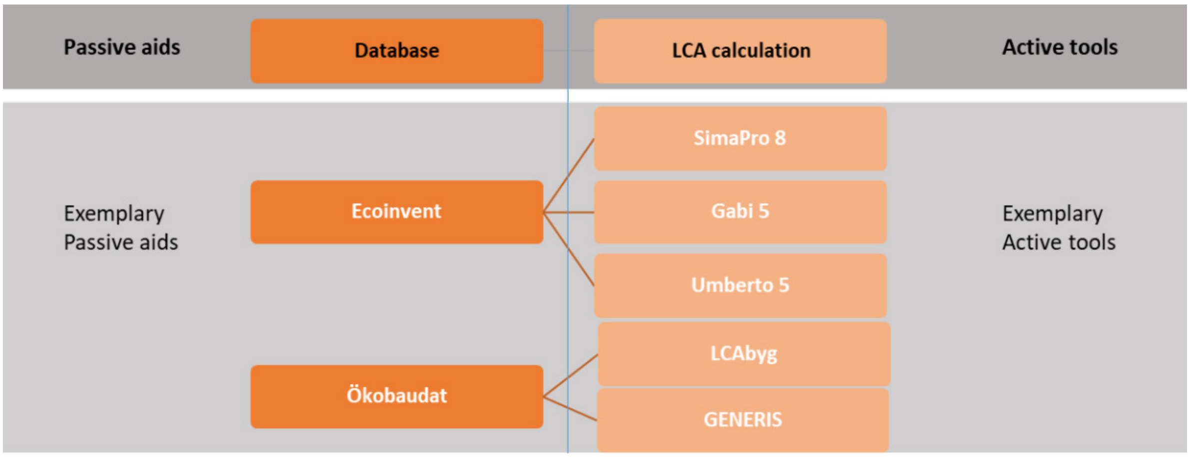

Figure 1 LCA databases used in LCA calculation tools. An example. **Error! Reference source not found.**

LCA databases are needed when calculating a building's embodied emissions. They however collect lifecycle information and document it, oftentimes not allowing the lifecycle modelling of complex processes and materials. Therefore, in this report they are claimed as **passive aids,** in which user is provided with lifecycle environmental information without performing a lifecycle modelling. The actual lifecycle modelling and environmental impact assessment often happens in a LCA calculation tool. LCA calculation tools are thus **active tools**, in which the user *actively* models buildings and buildings parts for deriving lifecycle information. Appropriate LCA calculation tools are needed to value the embodied GHG emissions not only, in a retrospective way, to assess the final environmental performance, but also, during the building design, for decision-making.

This report distinguishes between two main **tool types** (see Figure 2):

- **"pure" calculation tools,** which are specific for LCA calculation. They can equal generic LCA tools for any product (e.g. GaBi and SimaPro).
- **complex planning tools**, which are tools that can be incorporated into the design process or software, such as CAALA, OneClick LCA.

Complex planning tools can be aimed also for a pure calculation.

These are further subdivided into two more: A) **connected** or B) **not to benchmarks** and assessments (see Figure 2). Some LCA calculation tools include also benchmarks to make it easier and help designers to make more informed decisions. Examples of tools, which include benchmarks are Pleiades, CAALA and

OneClick LCA. For insights on building environmental benchmarking, the reader is while referred to Reports "Case study Collection" (Birgisdottir et al., 2023) and "Benchmarking and Target-setting for the Life Cycle-based Environmental Performance of Buildings" of this Annex (Lützkendorf et al., 2023).

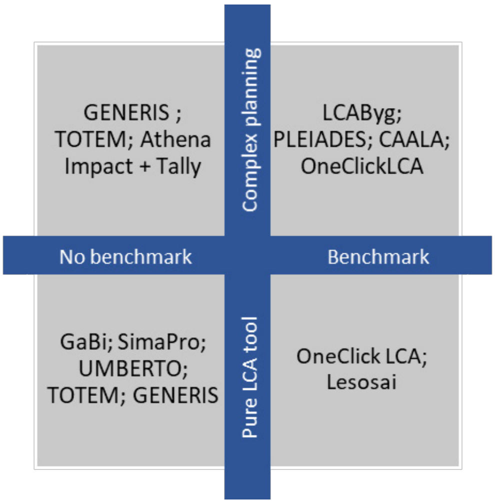

Figure 2 Mapping of the LCA calculation tools. E

When designers consider which LCA calculation tool is suitable for their needs, the following aspects should be considered (1) the designer's needs and constraints (2) the potential and limitations of a specific LCA tool**Error! Reference source not found.**. These factors are crucial when the designer choose the LCA calculation tool.

This report will focus on the selected tools listed in **Figure 3** and map the tools based on five categories, based on quality model standards for system and software products. The purpose of such a mapping is to make it easier for designers to choose between the various LCA calculation tools available on the market today. For a quality critical assessment, this report considers the quality categories, as here below defined and after described in the section 3.1. Definitions are based on ISO 25010 (International Standardisation Organisation, 2011) are adapted for LCA tools.

- **Usability**, which means *"the degree to which the LCA tool is able or fit to be used"*
- **Functionality**, which means *"the degree to which the LCA tool works well, is easy and convenient to use"*
- **Reliability**, which means *"the degree to which the result of a measurement, calculation, or specification in the LCA tool can be depended on to be accurate"*
- **Interoperability**, which means *"the LCA tools ability to exchange and make use of information"*
- **Conformity**, which means *"the degree to which the LCA tool compliance with standards"*.

Figure 3 Overview of the tools included in this report

2. Tools and aids examples

To obtain necessary information for the assessment of available tools in a clear and transparent way, a survey was prepared and submitted to tool providers and users. The main objective of the survey was to create a comprehensive overview of existing LCA software tools dedicated explicitly to buildings or building components and their features. The results have been further analysed, used for a critical assessment of the available tools regarding harmonized features and common issues.

Lastly, based on survey outcomes and their analysis, a procedure for tool identification depending on user needs and requirements will be proposed. The collected information can provide support to designers in the selection of the most appropriate tools for their specified use case and needs (see **Figure 4**).

Figure 4: Overview on provided activities and structure of the chapter

3.1 Methodology for investigating examples

The survey was conducted via the (free and open source) online survey application “Lime Survey” (LimeSurvey GmbH). It entailed 32 questions in six sections requesting:

- **general information,**
- **usability,**
- **functionality,**
- **reliability,**
- **interoperability and**
- **Conformity of the tool**.

The six sections refer to the five categories, as defined in Section 2, together with the **general information** (i.e., tool name and version), which is not a quality category.

A mix of different question types was used, such as dichotomous questions (with only yes or no as optional answers), open-ended questions, closed-ended questions or multiple-choice questions. Most of the questionnaire, i.e., functionality, reliability and interoperability would rather direct to tools’ developers, which own the overview on tools features. However, it is also important to collect information from user’s experience, especially in terms of tool’s usability.

The questions were developed considering the evaluation framework for LCA-based EIA tools presented in Meex et al., 2018. Additionally, quality characteristics for evaluating the properties of a software product as described in ISO 25010 (International Standardisation Organisation, 2011) were taken into account.

The quality characteristics for evaluating the properties of a tool defined in ISO 25010 are represented by two quality models: the *quality in use model* and the *product quality model (International Standardisation Organisation, 2011)*. The models have a hierarchical structure subdividing some quality characteristics further into sub-characteristics.

The **quality in use model** is composed of five characteristics: effectiveness, efficiency, satisfaction, freedom from risk, and context coverage (**Figure 5**). These characteristics relate to the outcome of interaction in a particular context of use of the software product. The impact of the software product on stakeholders is described.

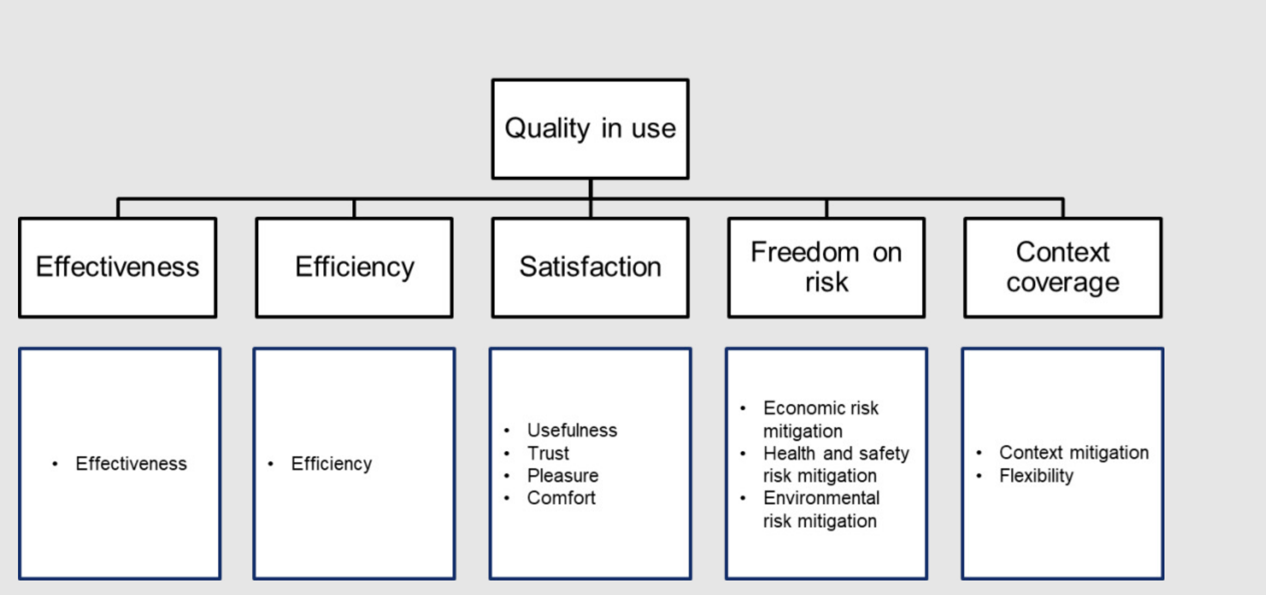

Figure 5 Quality in use model (based on ISO 25010:2011) (International Standardisation Organisation, 2011)

The **product quality model** includes eight quality characteristics: functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability and portability. These are further subdivided into sets of **sub-characteristics** (**Figure 6**).

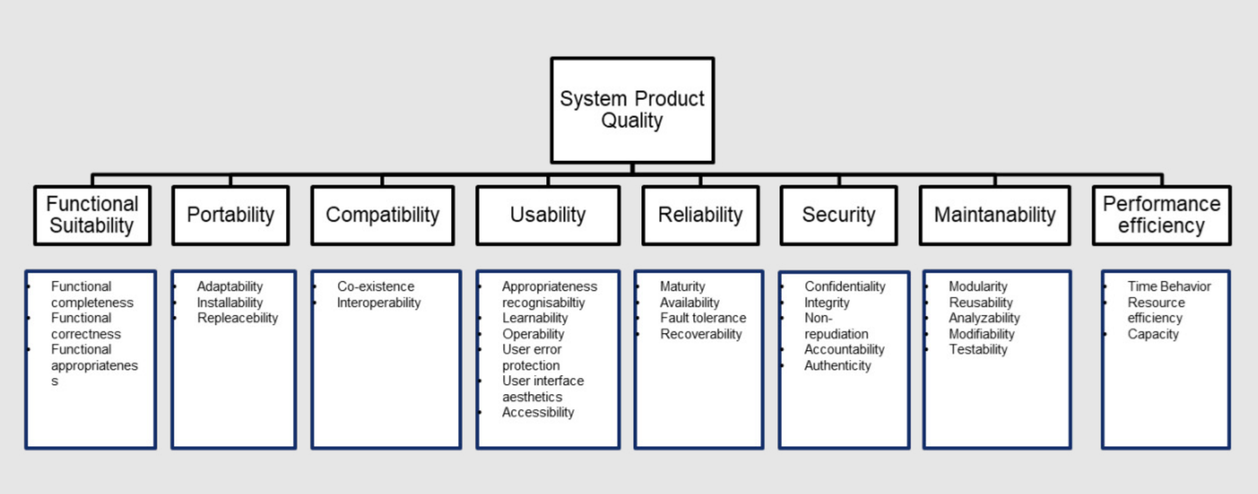

Figure 6 Product quality model (based on ISO 25010:2011) (International Standardisation Organisation, 2011)

Due to the goal of this Subtask in Annex 72 and the focus on the single tool, the quality assessment in use model was not considered in order to evaluate tools more in terms of features, functions and targeted user and applications.

With regard on product quality model, the six selected sections (general information, usability, functionality, reliability, interoperability and conformity) were selected for the survey (see Figure 7). **Usability** equals the definition in standard ISO 25010:2011. The **functionality** equals the functional suitability. Compatibility and portability characteristics are merged into the single **interoperability** characteristic. Differently, from abovementioned standard, **reliability** is defined here as "Reliability of the provided input and output". Lastly, **conformity** (with e.g., standards, guidelines) is considered.

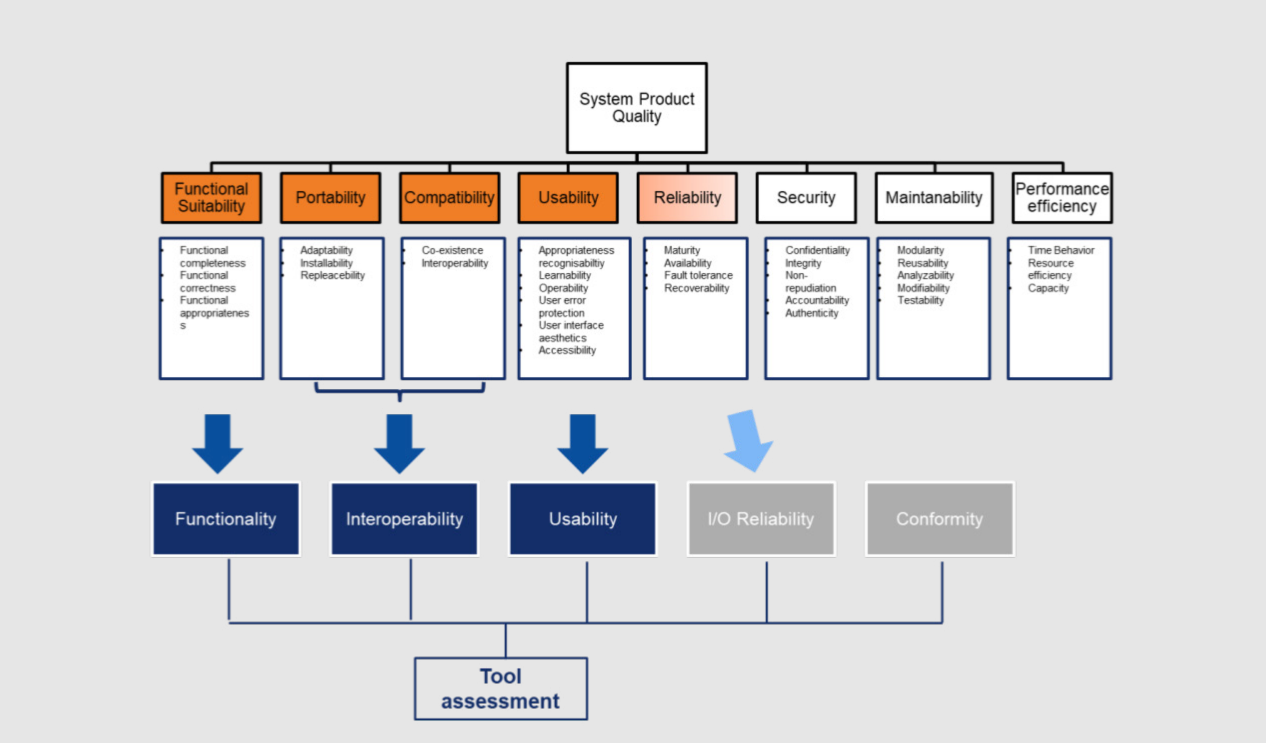

Figure 7: structure of the survey and assessment categories based on ISO 25010:2011 (International Standardisation Organisation, 2011)

Usability

In this section, the respondent was asked to provide information on the context of application. In Figure 8 are listed (on the left side) questions belonging to the "Usability" category. **Sub-categories** are listed on the right side and accompanied by an abbreviation, e.g., Operability (O). Questions in the survey allow the assessment of a specific subcategory. Therefore, each question is accompanied by the subcategory (-ies) (abbreviations) that can be potentially assessed.

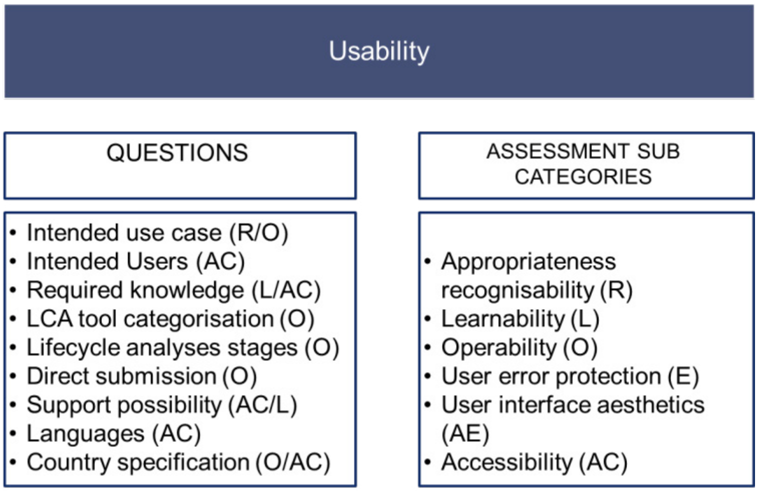

Figure 8: Structure of the survey and assessment categories based on ISO 25010:2011 – Usability section

First, the intended users (target group) should be specified. For example, the tool might be specifically designed to support architects in design phases or to aid LCA experts in the evaluation of a building after the design is completed. A list of intended use cases and users is provided based on the nomenclature of IEA Annex 31 (IEA-EBC, 2004). Please notice that, in the overall Building LCA tools can be addressed to a wider audience, which is not directly involved in the planning process. To get a comprehensive overview of all possible users and to not miss out any tools' target group, the survey included all potential tools users according to Annex 31 (IEA-EBC, 2004). With the intended use target, the questionnaire leads to the evaluation of tool recognisability and operability. By targeting the intended users, the survey evaluates tool accessibility. In this regard, intended use cases can be also outside the design process, e.g. marketing purposes. The questionnaire allows multiple choice, since many tool are targeted for several applications and users.

The list of intended uses based on IEA Annex 31 (IEA-EBC, 2004) entails:

- Assessment of products/building environmental profile
- Choice of products or technical solution
- Improvement of the overall environmental building performance
- Project comparisons
- Comparisons of building environmental profile with a provided reference building
- Marketing
- Labelling/certification
- Meeting standards.

The list of intended users based on IEA Annex 31 (IEA-EBC, 2004) entails:

- Authority
- Auditors
- Product manufacturers
- Building owners
- Building designers
- Consultants
- Financiers

- Tenants
- Researchers
- Service providers.

With the aim to further investigate the tool accessibility, the required level of LCA knowledge is indicated in a closed-ended question that allows respondents to choose between “none, basic or advanced” level of LCA knowledge from a dropdown-list. In this survey:

- "**None**" refers to no knowledge in LCA required,
- "**Basic**" refers to user with some experience in building LCA, and
- “**Advanced**" refers to users with expertise in LCA of building products and buildings. This question can furthermore identify the tool learnability and accessibility.

The tool operability is evaluated by indicating the tool type according to Section 2 and the planning phases, in which the tool can be applied.

The latter is carried out by a multiple choice question that refers to the intended phase(s) of application. The listed phases for selection are consistent with Annex 72 Subtask 2.1, who provided a generic definition of design steps and project phases:

1. Strategic definition
2. Preliminary studies
3. Concept design
4. Developed design
5. Technical design
6. Manufacturing and construction
7. Handover and commissioning
8. Operation and management
9. End of use, recycling

In case the listed design steps and project phases do not represent the intended/specific phase of application that is addressed with the tool, the respondent can add further phases (as a commentary).

The next question concerns the applicability of results delivered by the tool for certification purposes. For instance, the tool might be able to prepare results in a form that is demanded by a specific certification scheme. The tool reduces therefore time and effort for the user to request a certification. Direct submissions of LCA results increases in the final evaluation the tool operability.

Moreover, the respondent is asked to give information on available support options which increases tool learnability and accessibility. This multiple choice question can be answered by selecting one or more options: ***manual***, ***webinar***, ***tutorial***, ***FAQ*** and/or ***hotline***. Hereby, the respondent can specify other offered customer support.

The section on tool usability ends with questions on available languages and country specifications. Both questions are open-ended. The respondent should list the languages available in the tool. The question regarding country specifications aims at identifying the applicability of the tool across national borders and the ability to account for country specific conditions. For example a tool might be able to take into account national regulations, standards, databases or benchmarks. It should be specified whether these country specifications limit the use to only the respective country or whether they are optional (and the tool is generally designed for use across national borders). Both questions identify tool accessibility and operability (country-context operability).

Functionality

With the category functionality the tool input, output and further features for input and output are investigated (Figure 9). As previously, interrelations between questions and "Functionality" subcategories are presented.

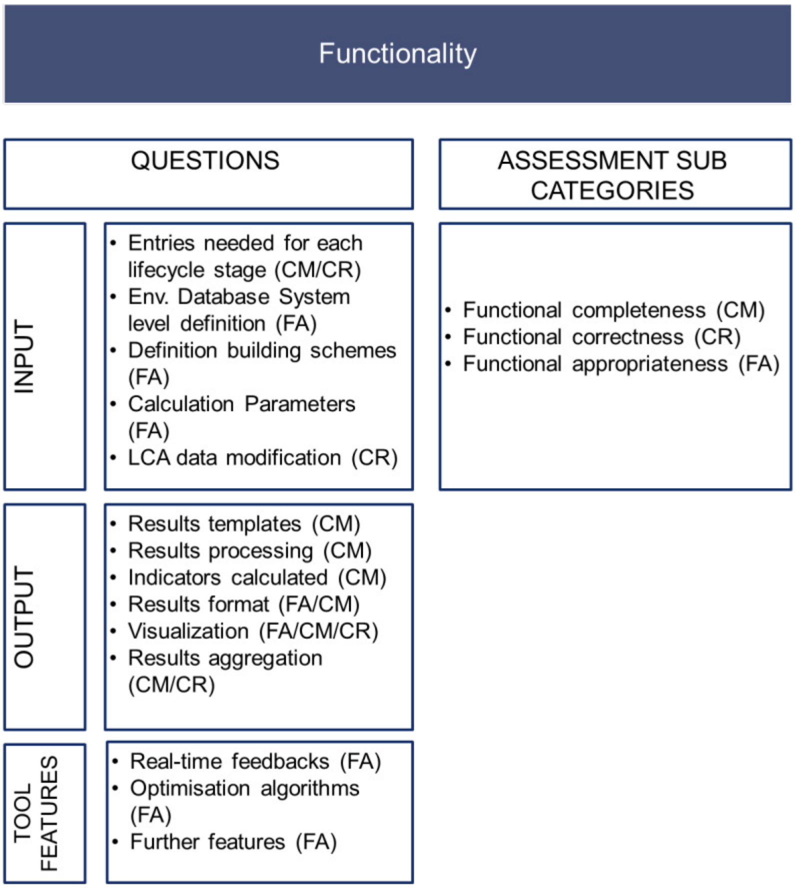

Figure 9: Structure of the survey and assessment categories based on ISO 25010:2011 – Functionality section

In a first instance, the **inputs** and all **required entries** are asked. According to IEA Annex 31 (IEA-EBC, 2004), entries for lifecycle analyses can vary in each lifecycle stage. The survey automatically identifies the considered lifecycle phases and for each of them prepare a list of standard entries. Requested inputs can influence the final completeness and correctness of the tool workflow and of results.

For phases, which entail building and construction elements productions (production phase, renovation and maintenance activities), the required entries can be represented by energy and mass flows. For renovation and maintenance, the tool may require the time interval for elements substitutions, building retrofit or refurbishment. The modelling of construction and erection activities occurs by providing average transport costs/extension and type and extent of building construction processes and use of machinery.

Building and urban systems operational phase requires information on energy performance, which can be provided manually, without any further aid systems with average energy calculations, by referring to building energy regulation, or carrying out energy simulation accounting climate context and daily variations. This information needs to be accompanied by source of necessary energy.

Lastly building end-of-life may require inputs on type and volume of building substances to be demolished, removed and/or destined to disposal, and the specification of recycling and re-use materials and systems.

Another topic, which influences tool functionality in terms of appropriateness, is the underlying data basis. Environmental databases and their version can affect the appropriateness of analysis in specific geographical/temporal contexts. All these issues need to be considered together with designers' need and requirements for building lifecycle analysis. Within the questionnaire, the main and mostly used environmental databases are listed. These encompass Environmental Product Declarations (EPD), which are product- and producers' specific, as well as generic databases, such as Ökobau.dat (building specific) and Ecoinvent and GaBi databases (not building specific).

Further inputs that can specify the LCA analyses are, e.g., characterization methods for the Life Cycle Impact Assessments (LCIA) and parameters for unit conversion. For instance, the user will be supported within the quantity calculation and unit conversions through conversion factors. The functional appropriateness and completeness can be thus increased.

LCA data sources can finally been modified, selected or complemented for a higher correctness of results. An example can be provided by tools, which derive or exploit statistical records for buildings and constructions. The provided inputs are in this case internally processed before the results generation.

The second part of the Functionality category investigates the **output provision**. In this regard, the questionnaire asks about the results data format (spreadsheet document, PDF, Extensible Markup Language - XML, dashboards, HTML document browser). This aspect may dictate user-friendliness and the required informatics knowledge for the tool utilisation, the immediacy of results provision and the visualization flexibility. Visualization possibilities in the context of building LCA is a widely discussed topic. Hollberg et al., 2021 and this Annex, Subtask 2.6 (see Background Report Subtask 2.6), carried out investigation on it. As a results, a list of possible visualisation charts and diagrams was generated. Each possibility must be connected to a specific analysis goal and investigation level. The here abovementioned issues influence the tool appropriateness as well as correctness and completeness of the provided results documentation.

The formal output investigations have been followed by the results contents, i.e., the presented environmental indicators. For many applications, e.g., building environmental certification, more than one single indicator is required, by increasing results completeness. Most of the tools provides core indicators according to European standards EN 15804 (European Commitee for Standardization, 2020).

Last part of the investigation analysed **tools features for design optimisation**. The questionnaire asks about real time feedbacks on design changes and use of optimisation algorithms for solutions suggestions, which enhance the functionality of the tool for proper purposes.

Reliability

As the complexity of models increases, issues on LCA results reliability arise. During recent years a range of tools presented improvement in terms reliability in LCA with the integration of approaches for data quality management, sensitivity and uncertainties analyses.

Such approaches aim to improve data quality and transparency, which in turns enhance the decision-making process. Among all issues related to data reliability, we can mention (Björklund, 2002):

- Data inaccuracy: empirical accuracy of measurements that are used to derive the numerical parameter values
- Data gaps: Missing parameter values in lifecycle modelling
- Unrepresentative data: Data gaps may be avoided by using unrepresentative data (Martínez-Rocamora et al., 2016), typically, data from similar processes, but of unrepresentative age, geographical origin, or technical performance.
- Model uncertainty: Model uncertainty is due to simplifications of aspects that cannot be modelled
- Uncertainty due to choices: Choices are unavoidable in LCA
- Spatial and temporal variability.

Even if such uncertainties can be reduced in a LCA study, some of them still can persist and, due to their effects on LCA results, cannot be neglected. They can involve LCA inventory, which relies on imperfect data, in addition to further uncertainties created by the assessment process itself. It is necessary therefore to evaluate the effects that data and process uncertainty have on the LCA results. Applications of methods coming from statistics, e.g. Bayesian or Monte Carlo Simulation, proved to be effective strategies to track and measure the propagation of uncertainties (Raynolds et al., 1999). Insights on LCA Uncertainties are available in the Background Report 2.3 of this Annex.

Based on such considerations, within the questionnaire asked about possibility of the inclusion of results deviation with sensitivity analysis or uncertainties analysis. When an uncertainties analysis occurs, error propagation possibilities are asked (**Figure 10**).

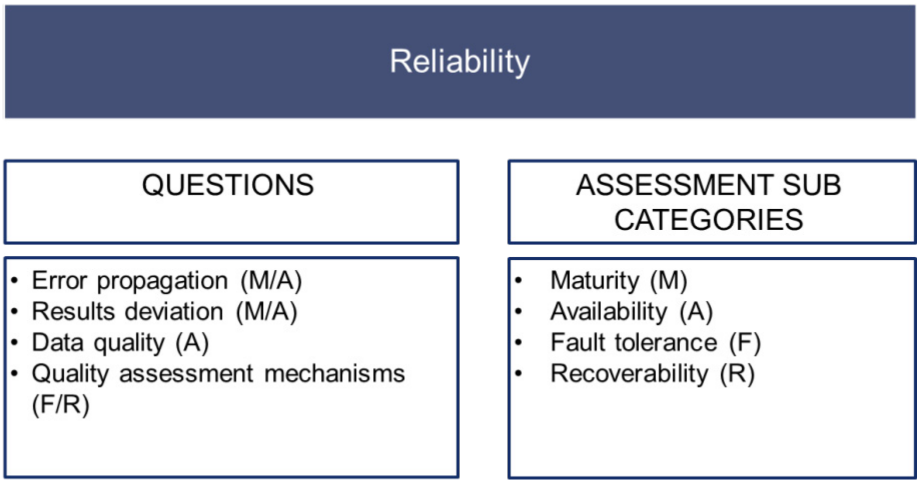

Figure 10: Structure of the survey and assessment categories based on ISO 25010:2011 – Reliability section

Following, data quality is investigated. The participant can declare the data quality (none, regional, verifies, independent) of the tool.

Finally quality assessment mechanisms are asked, e.g., automatic quality check of the information entered for LCA study or certification submission.

Interoperability

An increasing degree of digitalization in construction planning offers significant potential for building life cycle assessment: it reduces the efforts related to data collection as well as barriers (Figure 11). European countries are asked to require and apply digital instruments, especially in the context of public works (European Parlament, 2014).

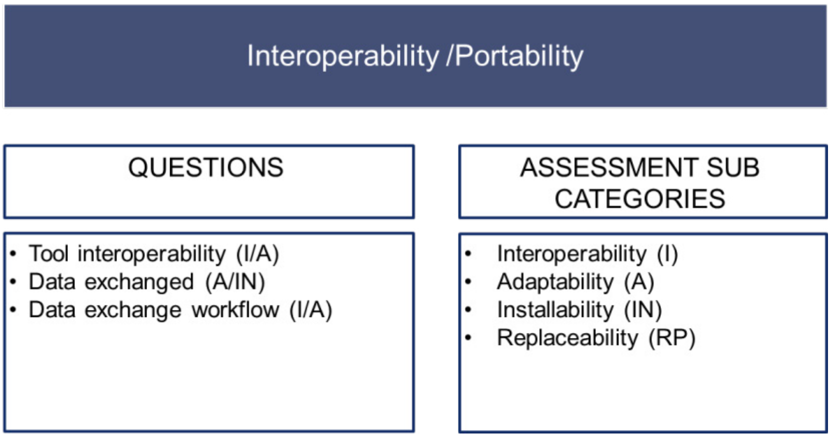

Figure 11: Structure of the survey and assessment categories based on ISO 25010:2011 – Interoperability/Portability section

In the context of the digital planning, BIM is a widely applied and promising workflow in the building sector that aims to enable the collaboration of all involved actors in the planning and design process, through providing accessibility for all, to one single digital building model (European Construction Sector Observatory, 2021; European Parliament, 2014; Horn et al., 2020).

In this sense, the integration of environmental assessment into BIM or any digital integrated planning process or design tool, gained attention. This integration process is also inclined to become continuously more complex resulting in the need for standardization and harmonization of approaches. The application of standardized formats for data exchange enables interoperability throughout the planning and design process and aids the challenge of integrating LCA with BIM through space for implementing environmental impacts information in the overall data structure.

Wastiels and Decuypere, 2019 provided a comprehensive classification scheme of the current strategies and workflows for the interoperability between digital models and LCA tools. Insights on digital workflows for design process are while presented in the background report of this Annex, Subtask 2.5.

Due to the relevance of the topic, the questionnaire includes a section for the investigation of tool interoperability with other tools. Compatibility with other design tools is asked. When this occurs with a specific software, the participant can specify which file format can be exchanged (IFC, gbXML, etc.). This helps the investigation on the tool adaptability. The more tools can be interoperable and the more file can be easy to adapt, the more tools are adaptable and can be installed in different interfaces). As a next step, this portability should be described in detail, particularly with regard to the underlying workflow, by referring to the classification of Wastiels and Decuypere, 2019.

Conformity

The last section of the questionnaire is dedicated to the compliance of the surveyed tool with standards, (International Organization for Standardization, 2006a, 2006b), LCA guidelines and other specific building assessment frameworks (e.g. Level(s) in the European context).

3.2 Overview on tools described by experts

The survey started on the 3rd May and was concluded at the end of September 2021. The collected answers were originally 70 and were analysed, filtered and afterwards selected in order to collect comprehensive results and avoid repetitions. Whereas the same tool was presented more the once in the survey, the provided answers were analysed, in order to check answer inconsistencies, and merged. All results and documentation of the survey can be found in the attached Annex.

As a result, the following tools were investigated.

List of investigated tools

- PLEIADES
- FCBS CARBON
- TOTEM
- GPR Buildings
- CAALA
- LCAbyg
- OneClick LCA
- SimaPRO
- Lesosai
- PHribbon
- GENERIS
- Greg
- BIMELCA
- The ZEB tool
- LCA US
- Enerweb
- Energy Plus; eQuest +Tally
- Athena Impact
- SBToolCZ,
- Envimat
- Sphera GaBi

Usability

Intended Use

Most of the analyzed tools aim to assess product and building environmental performance and improve it. Highly relevant for the final decision-making process is the comparison of products, constructions and projects as well. When the comparison is carried out with a reference building, the tool allows to meet more easily standards. Survey participants declared marketing use case only for the tool "SBToolCZ" (**Figure 12**).

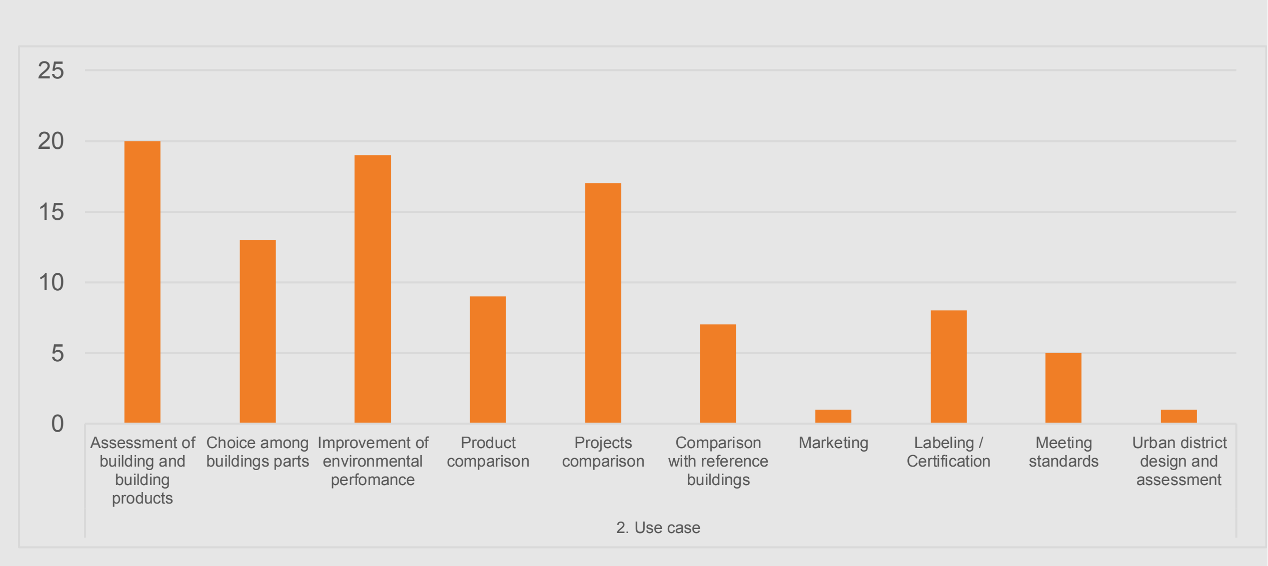

Figure 12: Survey outcomes. Question 2 on intended use case.

Users and Users' Knowledge

In the overall, all tools are intended to be used by building designer or sustainability consultants. Especially in the context of building certification and standards, tools can be used by authority such as auditors. Users belonging to the group of product manufactures, building owners, financiers, tenants and service providers and not prioritized but however included in up to 4 examples (**Figure 13**). For a proper use of the analyzed tools a basic knowledge in field of LCA is required (**Figure 14**). However, there are tools (19%), which are easy-to-understand also for an audience, who does not have experience in LCA.

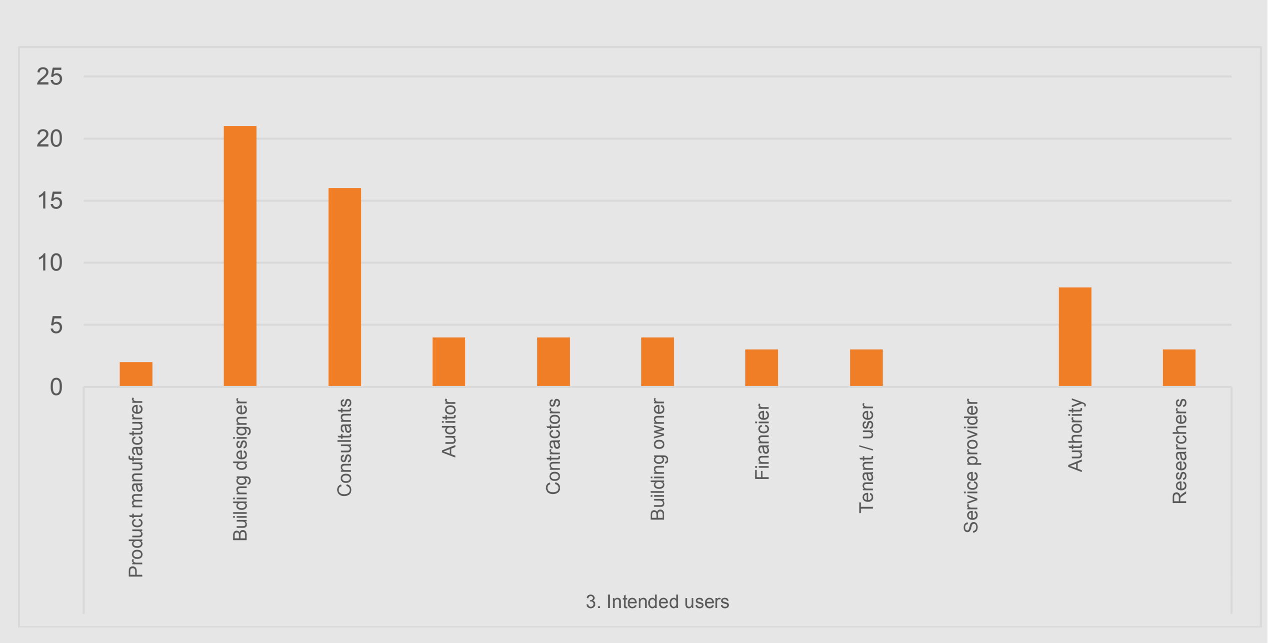

Figure 13: Survey outcomes. Question 3 on intended users.

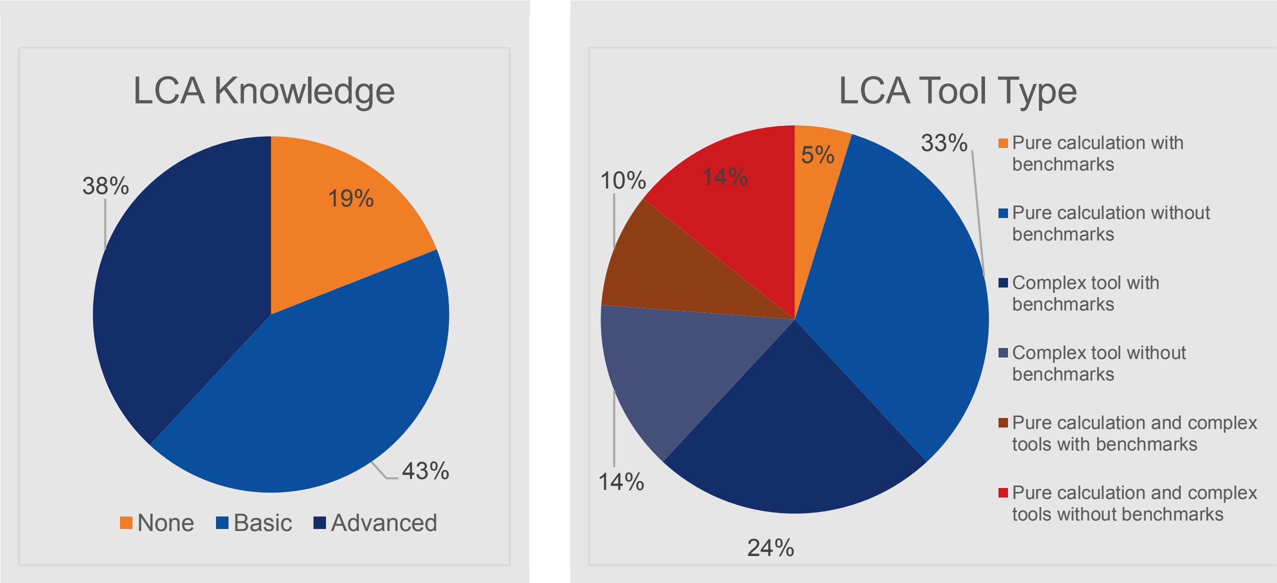

Figure 14: Survey outcomes. Questions 4-5 on required LCA knowledge (left) and tool type (right).

Tool Typology

Most of the tool examples are complex tools for building LCA, which can work also for a pure calculation. More than half of them is accompanied by benchmarks. Pure calculations tool (only) cover totally 40% of the investigated tools and 85% of them are without benchmarks.

By carrying out a cross-reference among all results, it can be noticed that complex tools with benchmarks are targeted for audience with basic knowledge in LCA. When a tool is working as pure calculation tool, sustainability experts and consultants are included in the targeted users. Since the most targeted user is the building designer, not surprisingly the main use case of all exanimated tools is the evaluation and the improvement of the building profile.

Considered LCA Stages

The majority of the analysed tools aim to carry out “cradle to grave” LCA analyses. In this sense, all lifecycle phases are included in the system boundaries. Whereas the tool provides analyses of urban system (2 tools counted), the operational phase will include additional information (**Figure 15**).

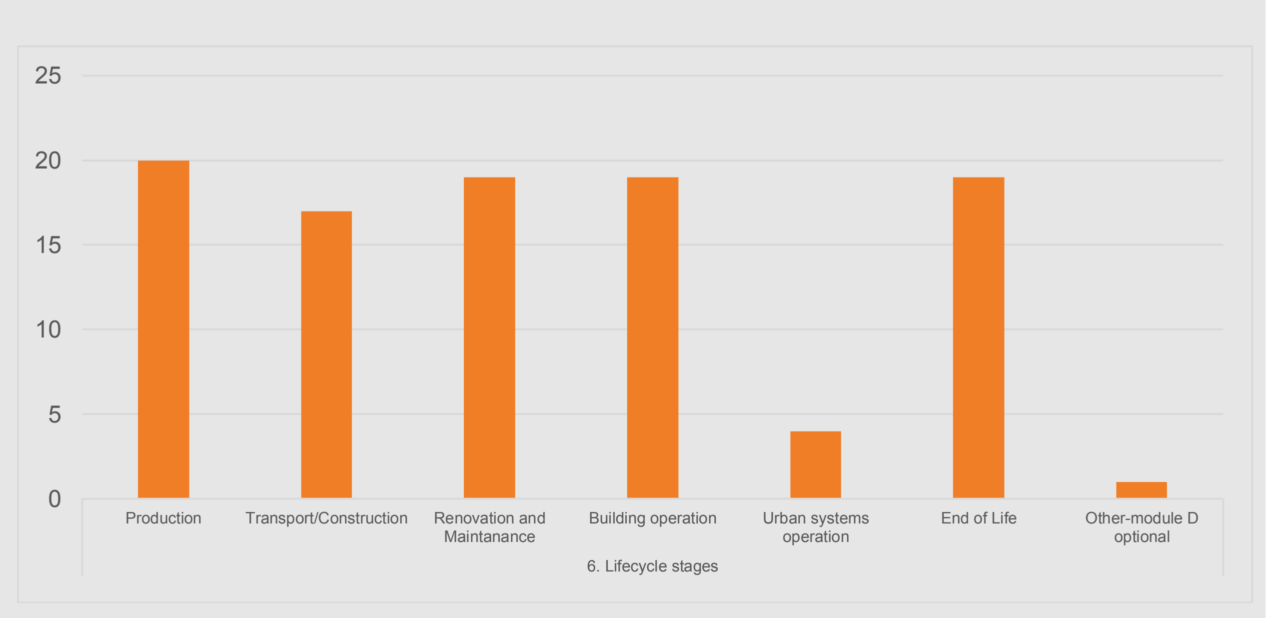

Figure 15: Survey outcomes. Question 6 on considered lifecycle stages.

Intended Design Phases

As a results of this question, most tools are increasingly applicable starting from the preliminary study until the handover. All tools are intended to be applied during the developed design, namely during the latest design stages. The high interest in the application during strategic definition and preliminary studies can be claimed relevant. In this context, the tool needs to derive environmental values starting with few buildings' information. Only 6 tools were intended for Operation and End of Use (**Figure 16**).

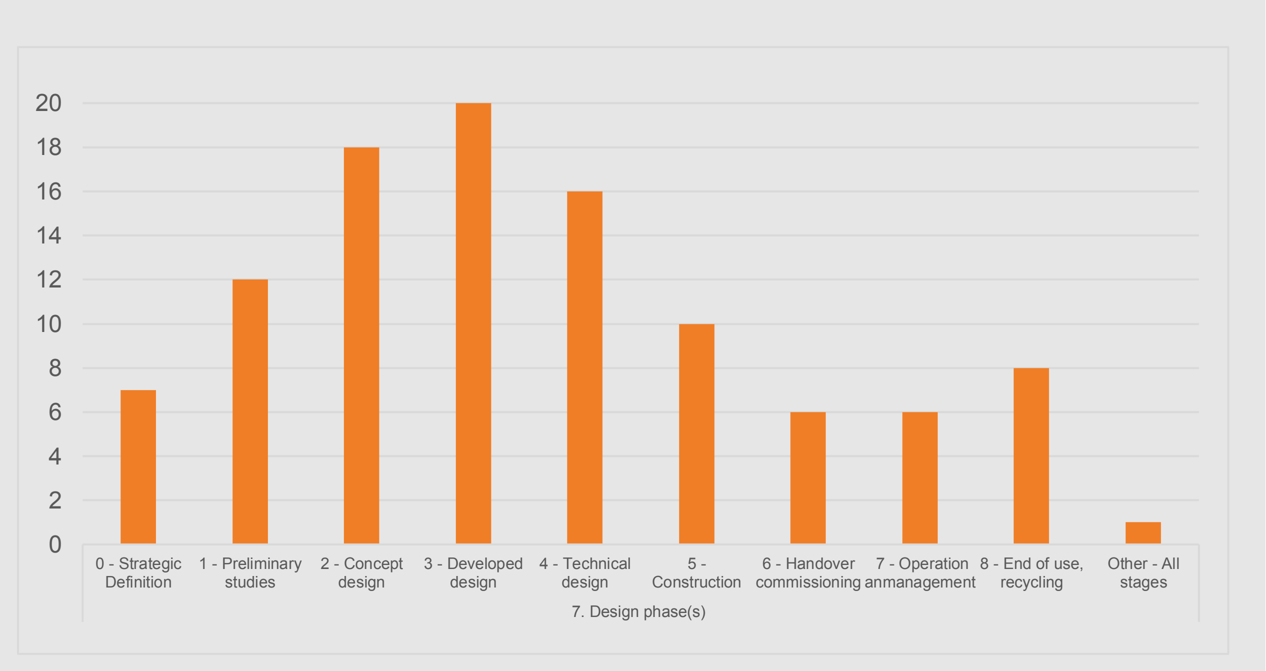

Figure 16: Survey outcomes. Question 7 on intended design phases of tool application.

The cross reference between results on Tool typologies and intended Design phases, showed that tools with link to benchmarks can be at least applied starting from the concept design. Tools like Pleiades, FCBS Carbon, CAALA and OneClick LCA are provided with benchmarks and, according to survey participants, can be applied already during the strategic definition.

Prepared for Submission – Certification schemes

Roughly half of the tools surveyed were intended to help with Submission Preparation. The Certificate Schemes are evenly distributed and the most common certificate scheme is Minergie-ECO (**Figure 17**).

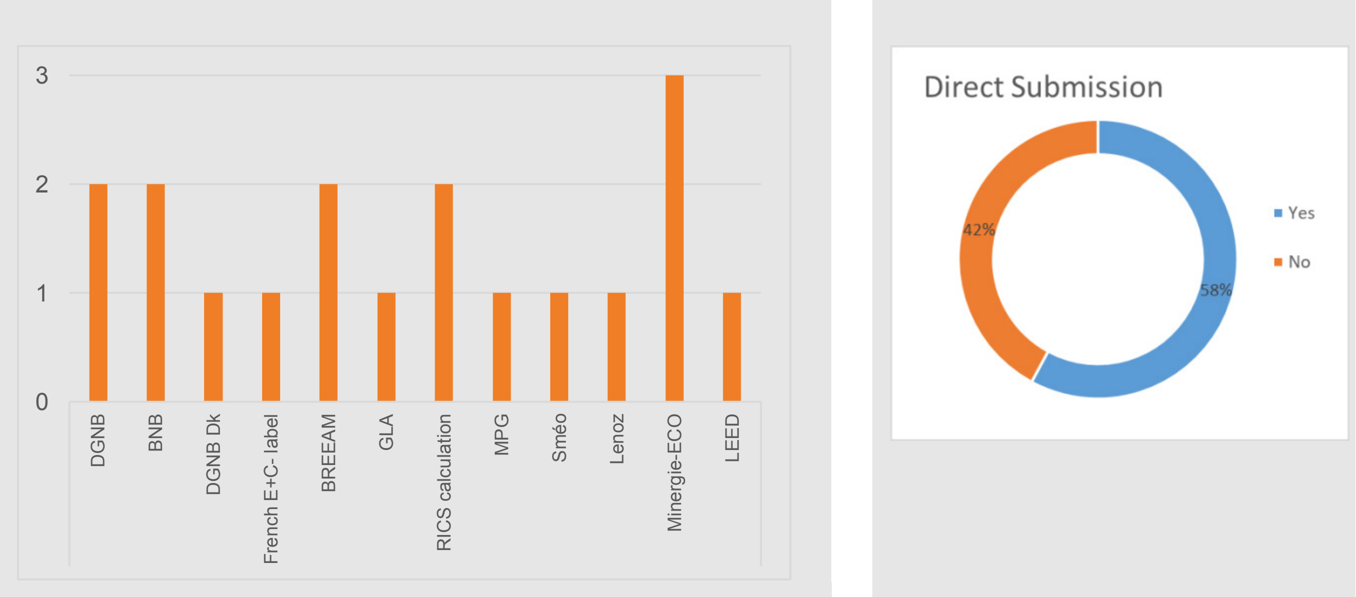

Figure 17: Survey outcomes. Questions 8 on availability of certification schemes and direct submission for building certification.

Support Options Available

The most common Support Option available is the product's manual and online video Tutorials. Roughly half of the products have Webinars, FAQs and Trainings. Only 5 of the products offer Online Support /a Hotline. In this sense "*live support*" is still not for all tool developers manageable (**Figure 18**).

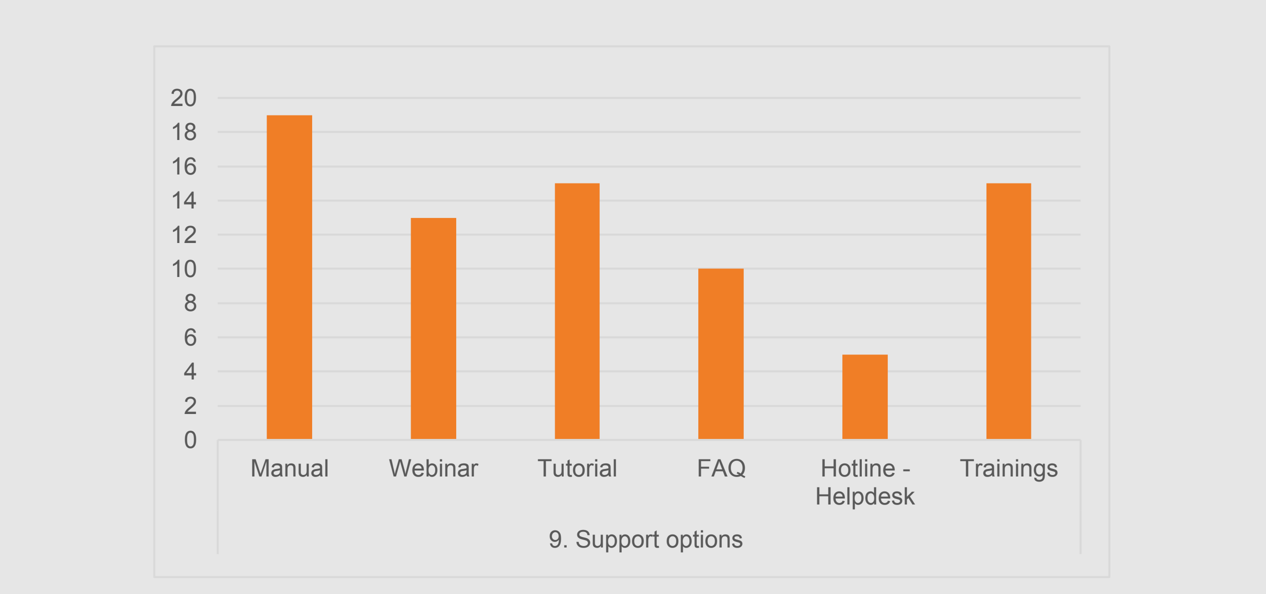

Figure 18: Survey outcomes. Question 9 on support options

Languages Offered

All of the products offered their services in English in order to be fully accessible also outside their country.

This leads to the investigation on tools' country specification. Roughly half of them are country-specified. The cross reference with results on tool typology, confirmed that pure calculation tool (see Section 1) are mostly not country specified. Such tools, in fact, allow higher level of flexibility during the lifecycle modelling (**Figure 19**).

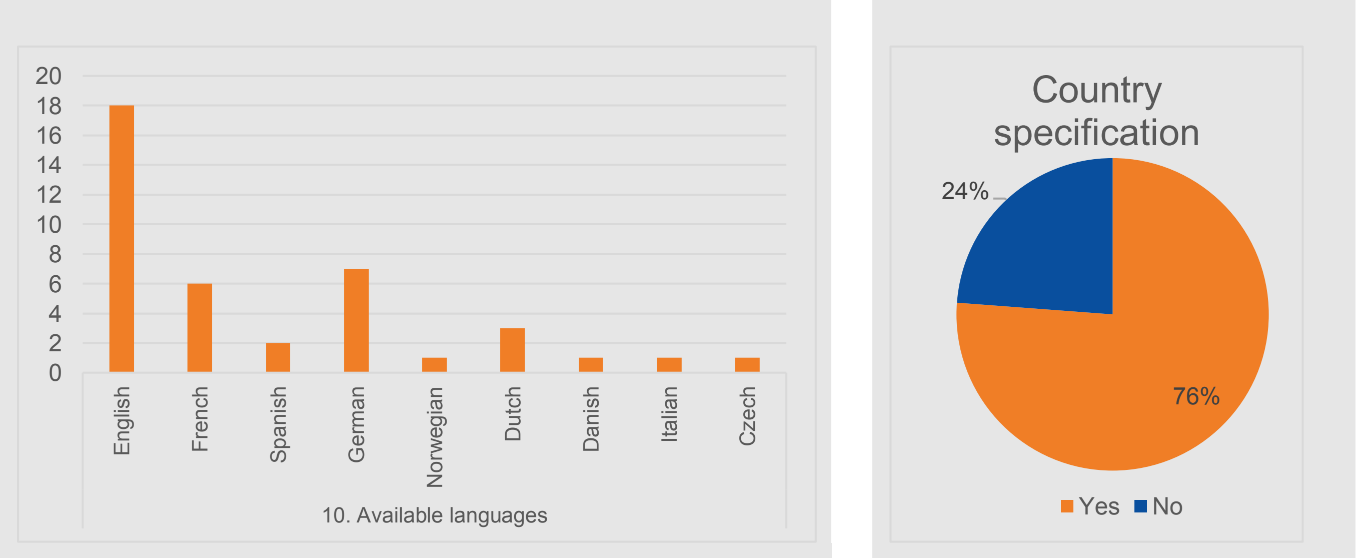

Figure 19: Survey outcomes. Questions 10-11 on available languages and country specification.

Functionality

Production Phase entries

Almost all tools require energy and mass flow of manufacturing, i.e., type and quantities of building materials (**Figure 20**). Four calculation tools allow the possibility of entering energy and mass flow due to provision and manufacture of technical services. Whereas the tool can be linked to a digital model, the building form and the model can be provided as input. The tool will either recognize type and quantities of materials, or this information needs to be entered manually.

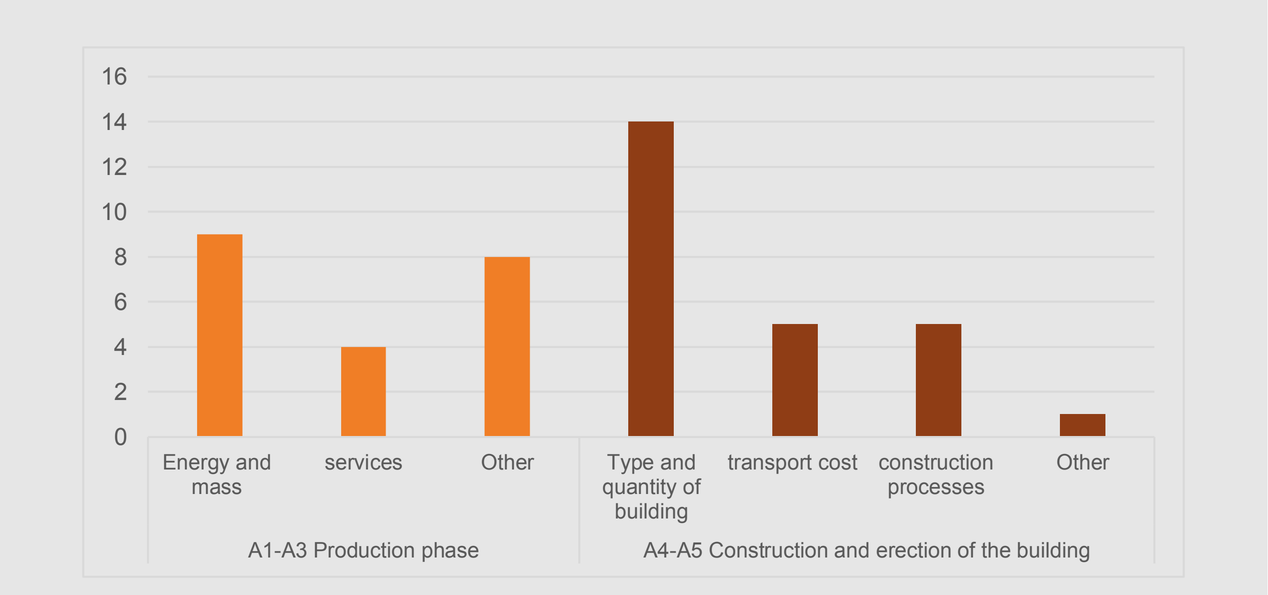

Figure 20: Survey outcomes. Question 12 on required entries for building production and construction process.

Regarding the construction phase, the evaluation is mostly based on type and quantity of building products. Few tools allow the inclusion of transport information and extended specifications about construction processes and machinery use.

Maintenance Phase Considerations

Half of the products consider Time Interval for Maintenance Activities, more than half consider Time Interval for Renovation Activities and less than half consider Mass / Energy Flow for Maintenance or Renovation Activities. If the time interval is not manually entered, the tool can suggest automatically time interval for all renovation and maintenance activities, depending on the building element.

Operational Phase Considerations

Half of the products surveyed consider Building Energy Regulation and Average Energy Calculation (such as “degree day method”) in the Operational Phase. When a link with digital planning is allowed, the tool can consider daily variation (hourly variation) in energy consumption simulation. Totally, five of the investigating tools can derive the quantity automatically. This can be done also, for instance, by calculating the U-values for building constructions and deriving an average value of energy consumption (**Figure 21**).

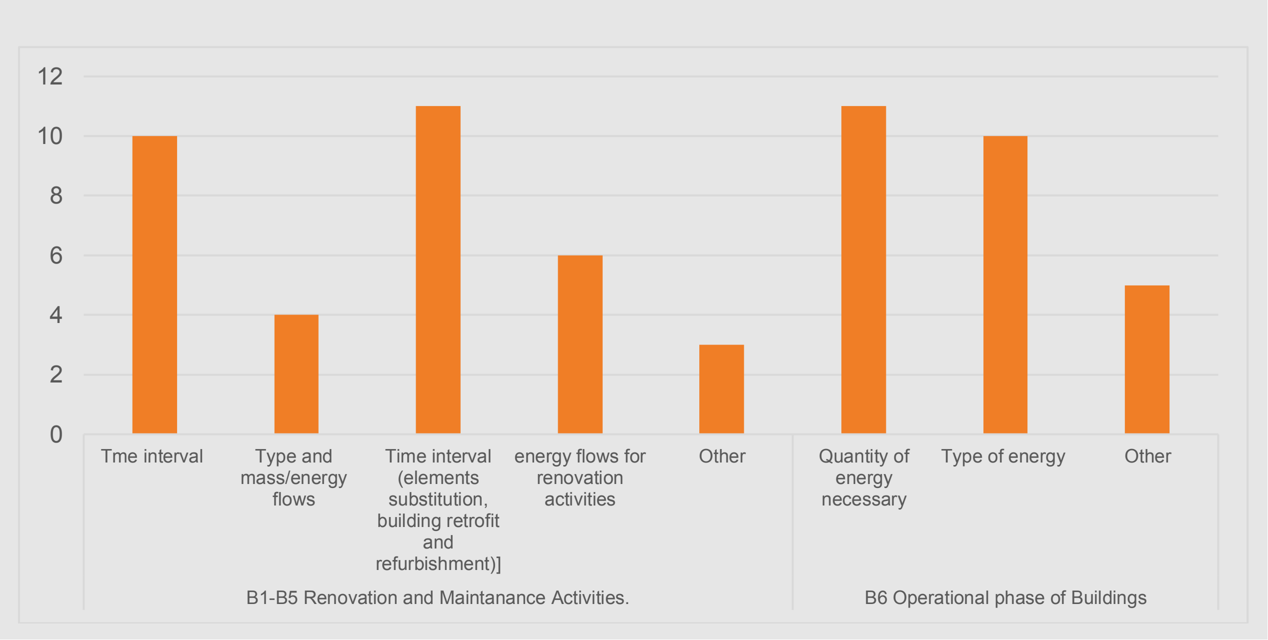

Figure 21: Survey outcomes. Question 12 on required entries for building operational phase.

Urban Systems Considerations

The investigated tools that allow analyses on urban system level have similar entries for the operational phase calculation. Among all the information, water mains leakage, waste sorting system, streets, district heating characteristics, pipes, parks with water needs can be specified (**Figure 22**).

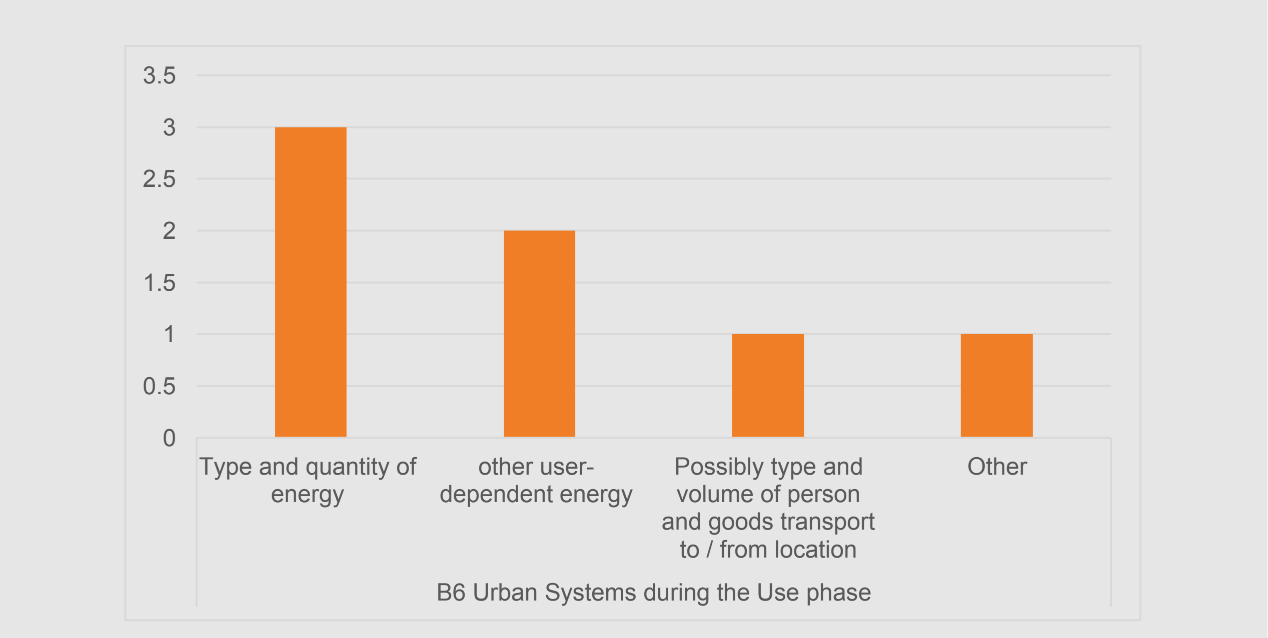

Figure 22: Survey outcomes. Question 12 on required entries for urban system operational phase.

End of Life Considerations

Most products surveyed consider the Type and Volume of Building Substance to be demolished during the removal of the building. Less than half of the products consider Possible Re-Usable Materials / Systems or Possible Recyclable Materials / Systems (**Figure 23**).

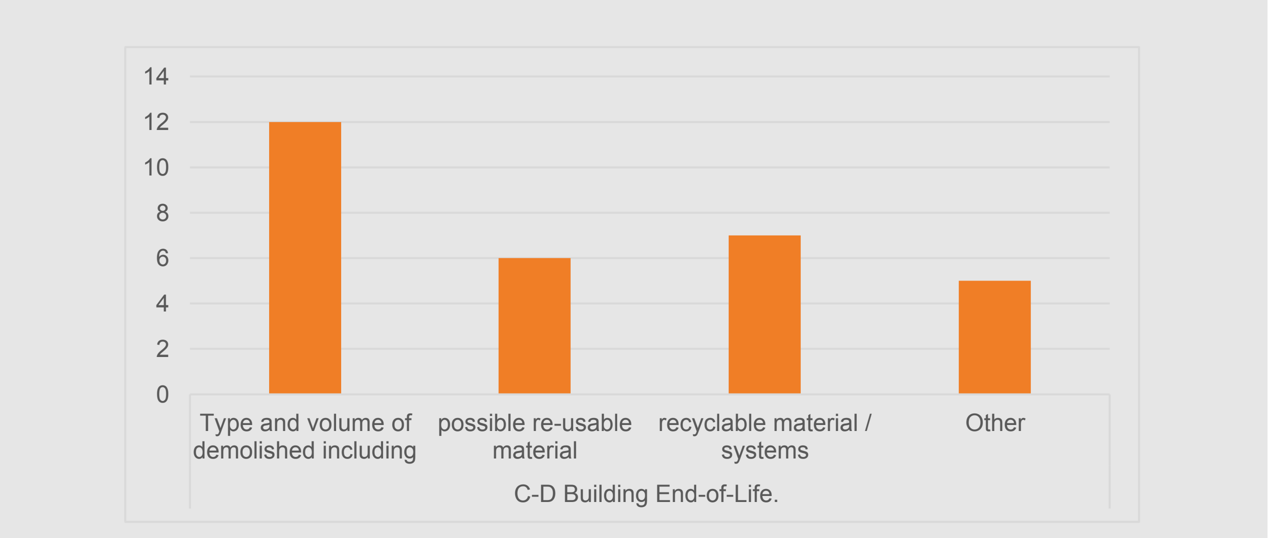

Figure 23: Survey outcomes. Question 12 on required entries for maintenance and renovation activities (left) and building end of life (right).

Environmental Databases

Most of the investigated tools are based on product or manufacturer specific datasets. EPDs and Ecoinvent are prevalent (**Figure 24**). Tools that are country specific in the German context can provide results based on Ökobau.dat, while other tools use ICE database, NMV (for Netherland), ESUCO, kbob list (valid in Switzerland) or envimat.cz (for Czech Republic).

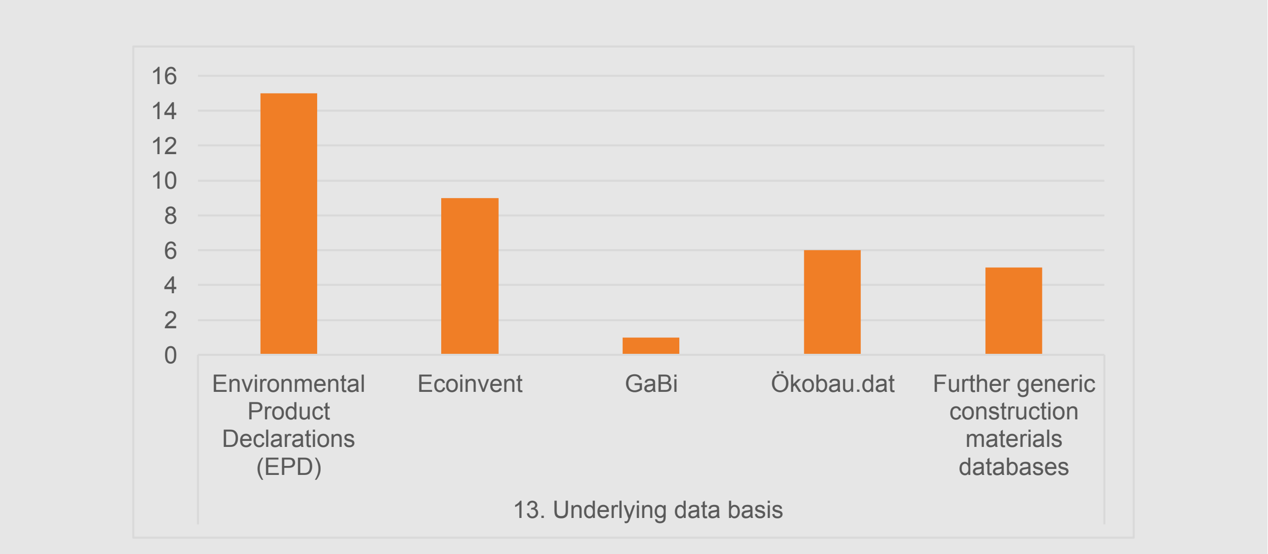

Figure 24: Survey outcomes. Question 13 on underlying databases.

System level

As already noticed in the questions, analyses are mostly carried out for buildings and building elements. Building stock and urban districts are not on focus of the currently available tools (**Figure 25**).

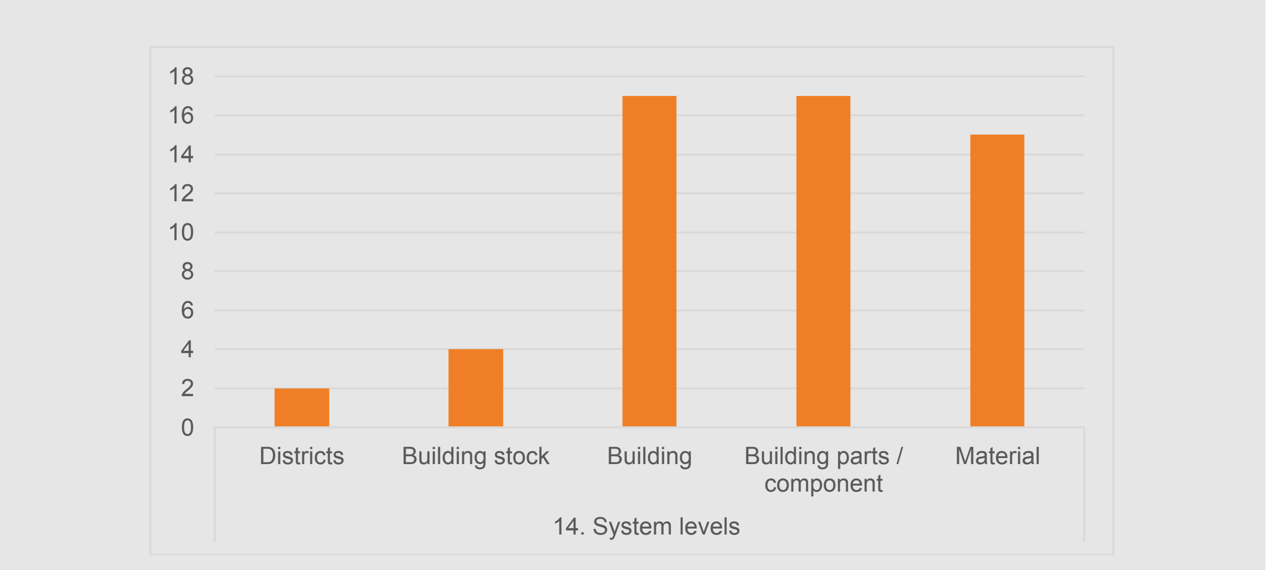

Figure 25: Survey outcomes. Question 14 on system levels.

Templates / Predefined building schemes

All tools' providers agree on the compilation of templates for the collection of LCA results and include predefined building schemes. However, each tool presents several typologies with different features and level of flexibility. Some examples present standard building elements that can be modified by the user. Users can also copy elements from the library and modify or delete existing layers. There are templates for the constructions' comparison or comparison with reference buildings. Some tools are entirely based on standard components and materials, enabling quick design choices to be made at early stages. Direction and magnitude of decision impact is key at the early stages.

Parameters Used for Calculation

Among the 15 investigated tools, nine tools allow a higher level of flexibility through the selection a proper LCA characterisation method. Nine tools provide conversion factors (**Figure 26**). This can be also done with help of an algorithmic generation of building quantities based on basic building parameters (height, footprint, etc.).

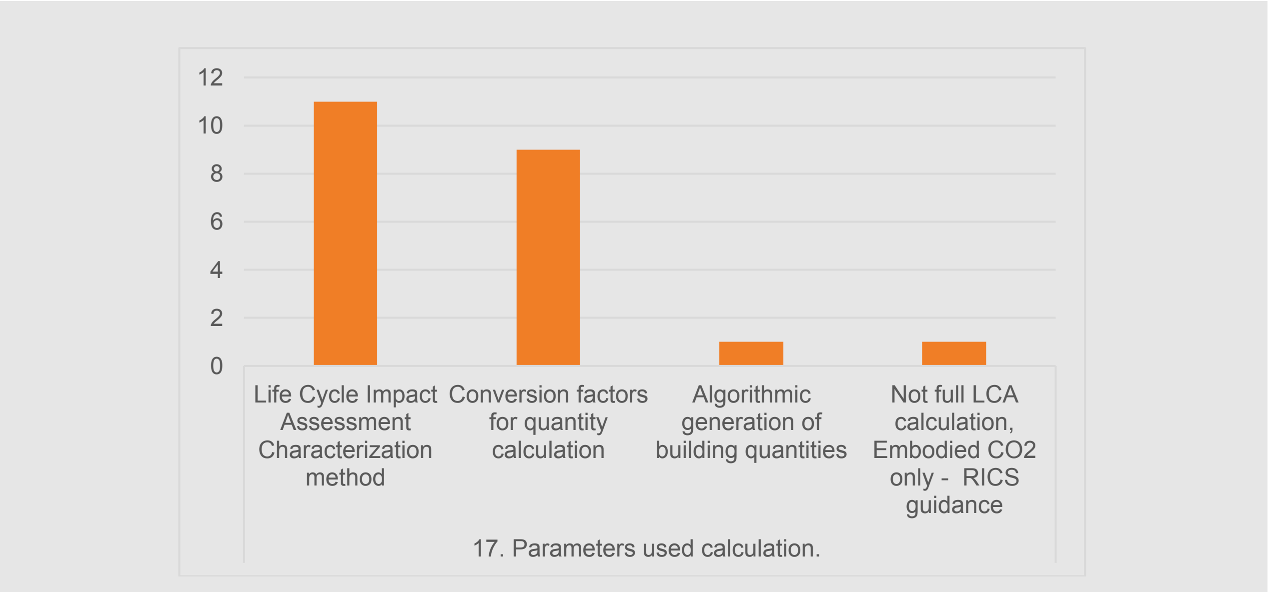

Figure 26: Survey outcomes. Question 17 parameters for calculation.

LCA Modification

Almost 60% (7 tools) of the products surveyed modify the original LCA Data Sources before making them accessible to the users. Contextualisation of products that are mainly national (e.g., concrete), calculation of some indicators not provided in ecoinvent (e.g., CO2 including biogenic according to forest management for wood) are possible. Standard information from EPD can be modified in 2 tools. Units in the EPDs vary widely and can be awkward for the praxis, which allows a crosscheck for consistency too. Sometimes materials are in other units, e.g., per m^2 if the thickness is not generally known, e.g., for carpet, or per m for I-beams. They can also be per kg or per kWh for ASHPs, these are not generally converted from the EPD.

Available Results

The most common visualisation of the LCA Analysis is in a PDF Report. Over half of the products offer Spreadsheets and Dashboards while only a few offers Mark-up Language or HTML/json files. BIMELCA allows a unique visualisation directly in the BIM model (Figure 27).

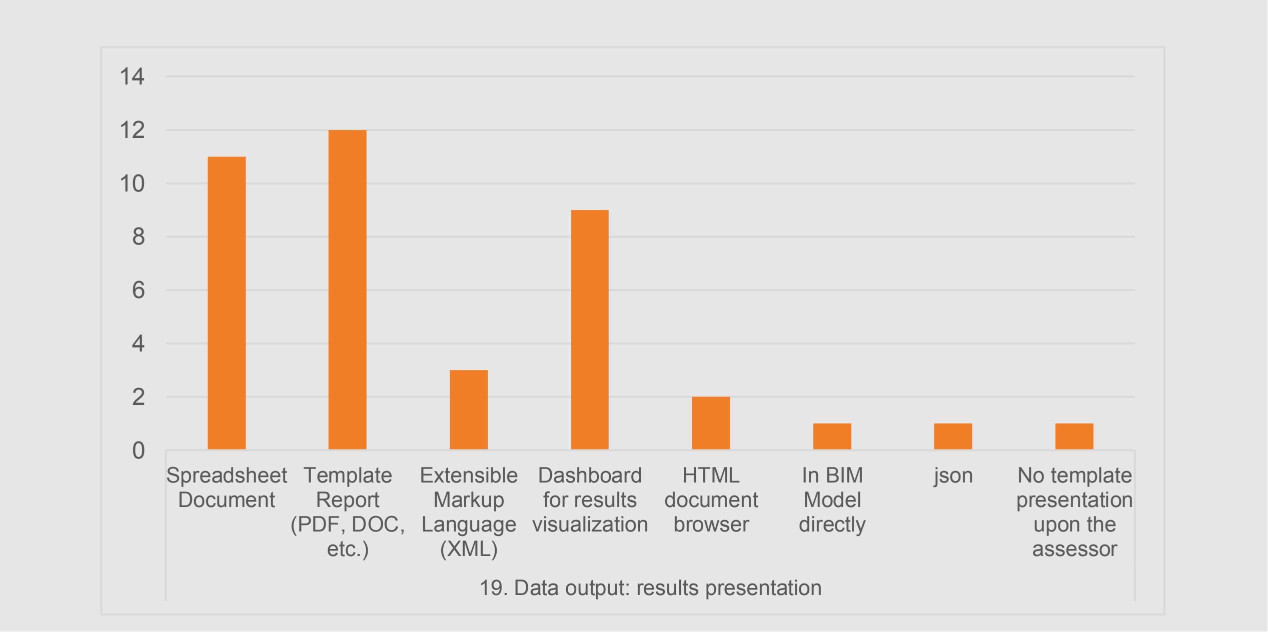

Figure 27: Survey outcomes. Question 19 on data output and results presentation.

Result Visualisation

The most common visualisation available in the products is the Bar Chart, followed by the Pie Chart, the Stacked Bar Chart and Line Chart. However, as shown here in **Figure 28**, there is a variety of uncommon visualisation possibilities that are not considered (see Section 3.1 – Functionality and background report 2.6 of this Annex), such as scatter plat, cluster and colour map. They are in fact to be related to further applications, which are not intended in the investigated tools.

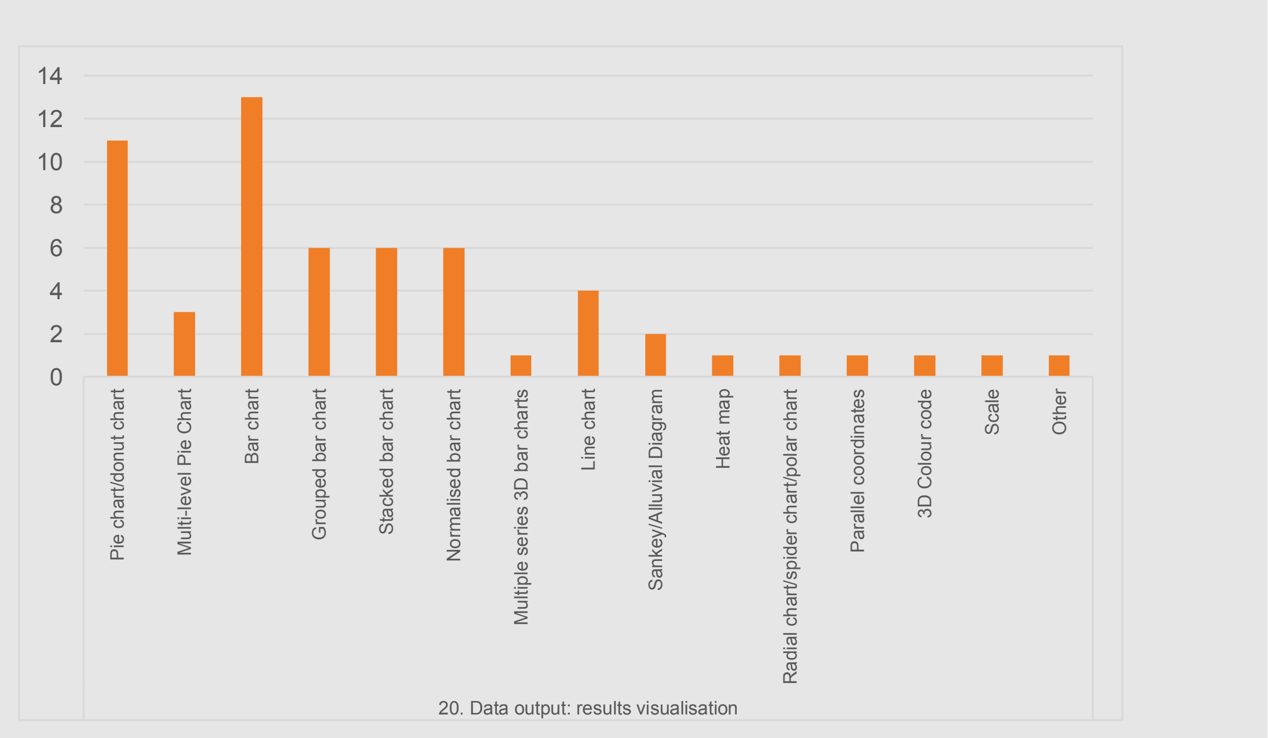

Figure 28: Survey outcomes. Question 20 on data output and results visualisation.

Result Indicators

All tools, except for Enerweb, provide GWP results. Most of the tool calculate all indicators relevant for building environmental certification purposes. Four participants declared a possible derivation of the full set of core indicators according to EN 15804 (**Figure 29**).

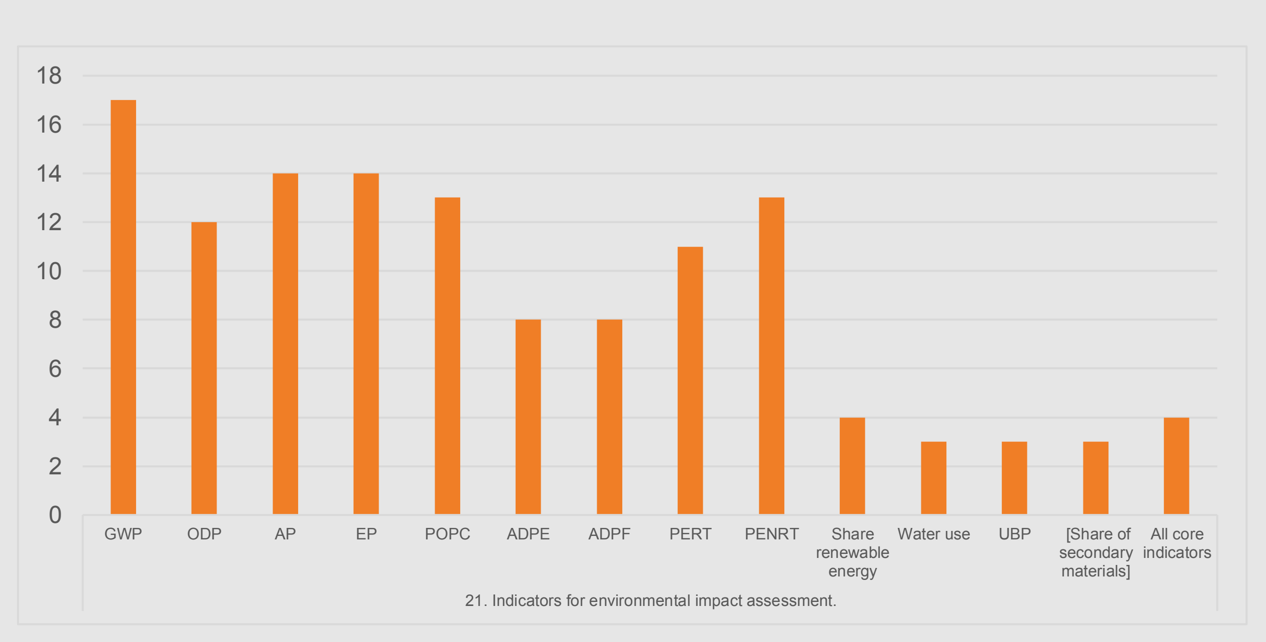

Figure 29: Survey outcomes. Question 21 on calculated environmental indicators.

Aggregation

All the products surveyed aggregate their results in building elements or in the several lifecycle stages. In this sense, results aggregation is an important instrument for allowing different granularities of the lifecycle environmental information and support better the user (**Figure 30**).

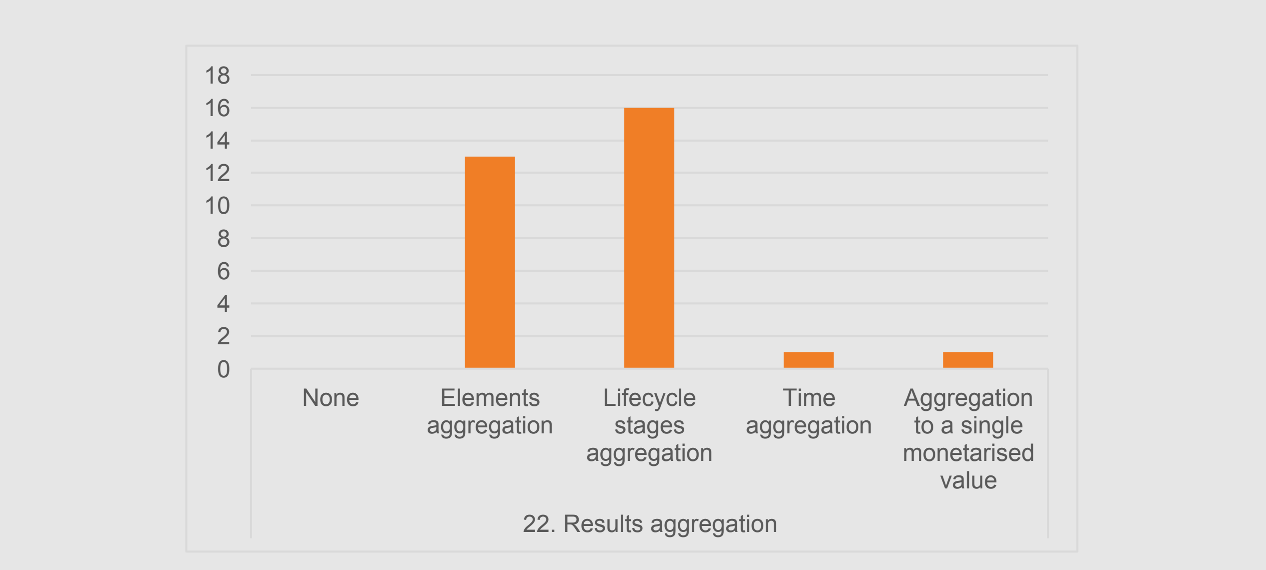

Figure 30: Survey outcomes. Question 22 on results aggregation.

Real-Time Design Feedback / Optimization Algorithms

Due to the different tool maturities, not all products offer Real-Time Design Feedback. For any of them it is not feasible because external energy simulation data are needed. According to participants' answers, some products declare that it is possible, but they have not incorporated it yet (**Figure 31**).

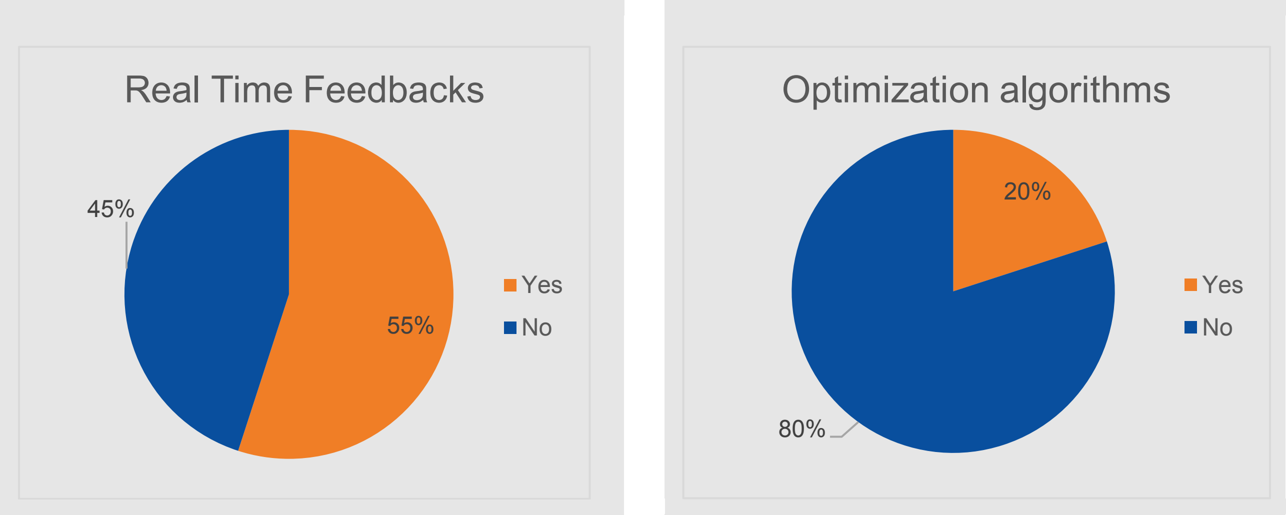

Figure 31: Survey outcomes. Questions 23 -24 on real time feedbacks and optimization possibilities.

With regard on Optimization Algorithms to propose building solutions, only a few of the products are provided with enough resources. Some of the products can be linked to visual programming software like Dynamo and use their results as an objective in optimization.

Other tool features

The FCBS CARBON tool is designed to provide early estimates of the embodied carbon of building at an early stage, when bills of quantities are not yet available. Instead, it uses a standardised algorithm to provide guidance during design about better or worse material/form choices. Components are based on standard build-ups, modelled using EPD and ICE data. Within 30 minutes, it is expected that a building whole life carbon analysis can be undertaken, and then iterated on to find lower carbon solutions.

CAALA links to CAD/BIM model, import and export of gbXML, simplified LCC calculation for variants comparison.

PHribbon integrates with PHPP, the Passivhaus Planning Package. From PHPP, materials and quantities are extracted; operational data serve for the generation of combined Embodied and Operational graphs.

BIMEELCA can work via Revit API and integrates in this way the BIM tool.

The ZEB tool can be used on its own to calculate embodied emissions for materials and has an input to link with simulated emissions from operation. Due to it being excel based, it can be used to model different life cycle modules depending on the availability of generic and, or specific data (EPD). Norwegian EPD are collated and linked in the EPD library in the tool and the user can use a drop-down menu to choose different materials (linked to the EPD). The ZEB Tool can be connected to REVIT using Dynamo plugin.

Reliability

Deviation Analysis

Most of the investigated tools, cannot provide instruments like deviation analysis (Figure 32). Pleiades provide both sensitivity and uncertainties analyses only for energy calculation. SimaPro can carry out sensitivity analyses.

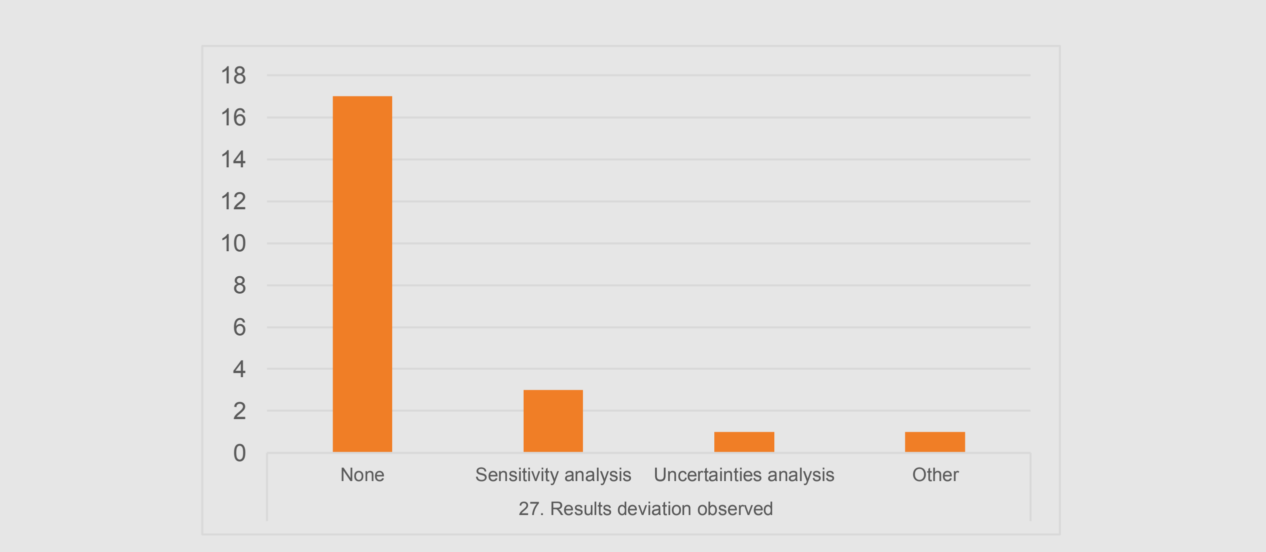

Figure 32: Survey outcomes. Question 27 on tool-observed results deviations.

Data Quality

Most of the products consider data quality. According to underlying databases, roughly half of the products consider Regional and Verified data quality, while only five consider independent data quality (Figure 33). Three tools do not specify the dataset quality.

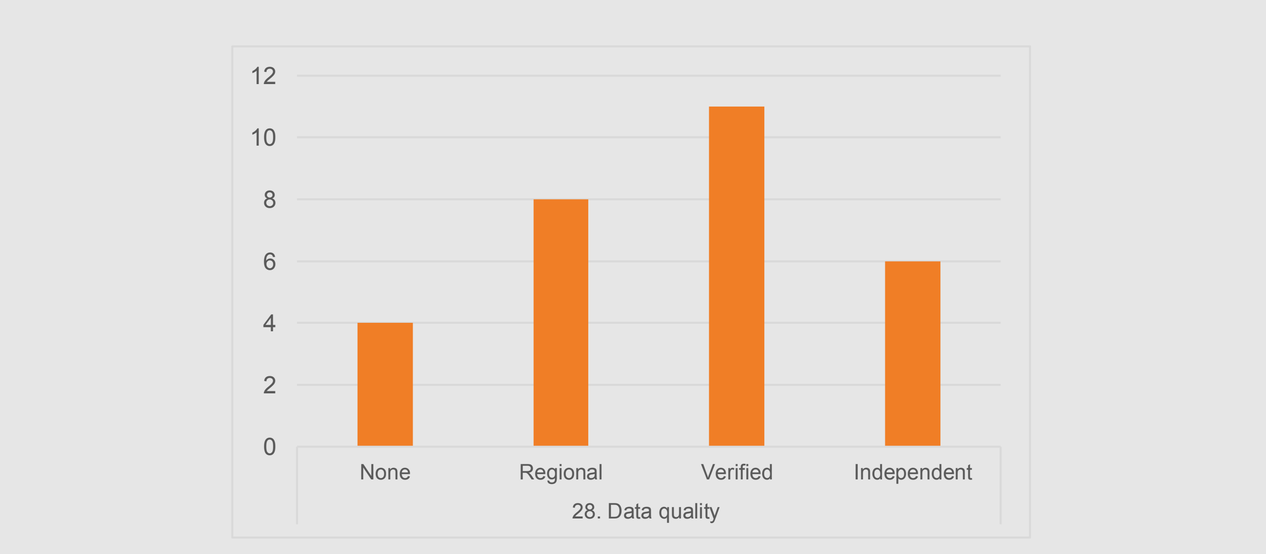

Figure 33: Survey outcomes. Question 28 on data quality.

Quality Assessment Mechanism

Quality assessment is offered only in few products, i.e., only a third of the products offer a Quality Assessment Mechanism. Mechanisms can however strongly differ. GPR Building provides an optional independent review, in order to receive certificate (GPR certificate). CAALA has a simple model checker to check quantities taken over from CAD/BIM model. Quite similar is the mechanism in GENERIS, which verifies user entries for building environmental certifications. If data are changed, Lesosai shows it in report and checks that all materials are filled with values.

Interoperability

Tool Interoperability

The survey showed a still missing tool interoperability with other products. Most of the tools are able to work with Excel, half of the tools can work with Revit and only 3 can work with other more advanced tools. If the products can work with Excel, other software such as Revit are indirectly accessible (**Figure 34**).

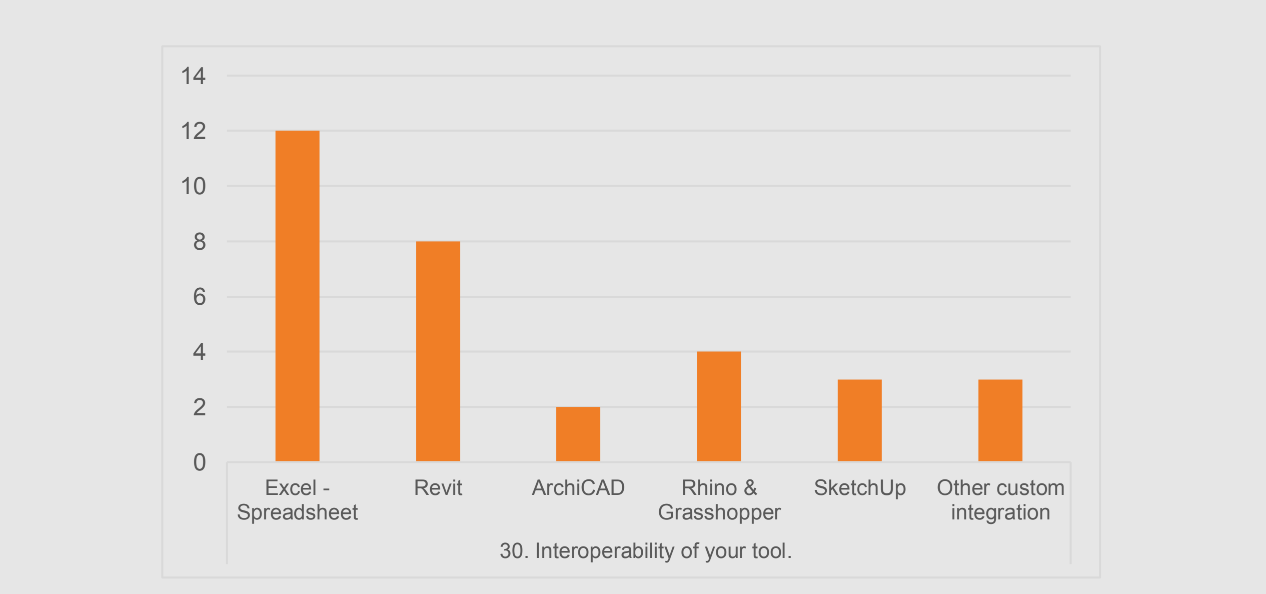

Figure 34: Survey outcomes. Question 30 on tool interoperability.

Workflow

As referenced previously, tools operability occurs mostly with an Excel Spreadsheets. More than half of the products have the ability to produce Bill of Quantities but only a few can work directly within other software (**Figure 35**). Other more sophisticated and automated workflows, such as LCA plugin application or BIM object enrichment) are not widespread.

Instead of IFC, Pleiades and CAALA can possibly use gbXML import/export. Generally, for the PHribbon version the quantities come from the PHPP, the Passive Haus Planning Package model, though additional info is needed for items that are not part of that thermal model, e.g. internal walls, intermediate floors, services, roof finishes etc.

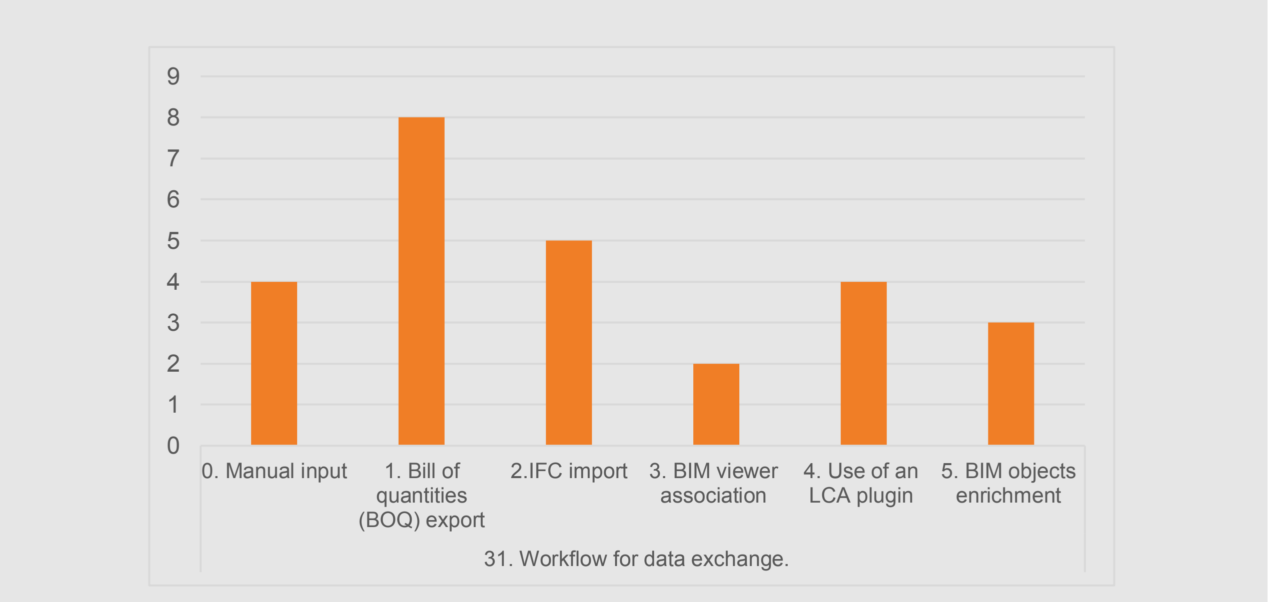

Figure 35: Survey outcomes. Question 31 on workflow for data exchange.

Standards Compliance

The majority of the products comply with the ISO 14040 – ISO 14044, EN 15804 and EN 15978 (in the European context).

PH Ribbon is designed to follow RICS in the UK as close as possible, however it is not an official calculation. Consequently, the document generated as tool-output is based on RICS. FCBS CARBON follows also RICS for a Whole Life Carbon Assessment. ISO 14025: 2010 is included in the ZEB Tool. SIA 2032, Lenoz, SIA 2040 can be included in tools such as Enerweb and Lesosai (valid in the Swiss context) (**Figure 36**).

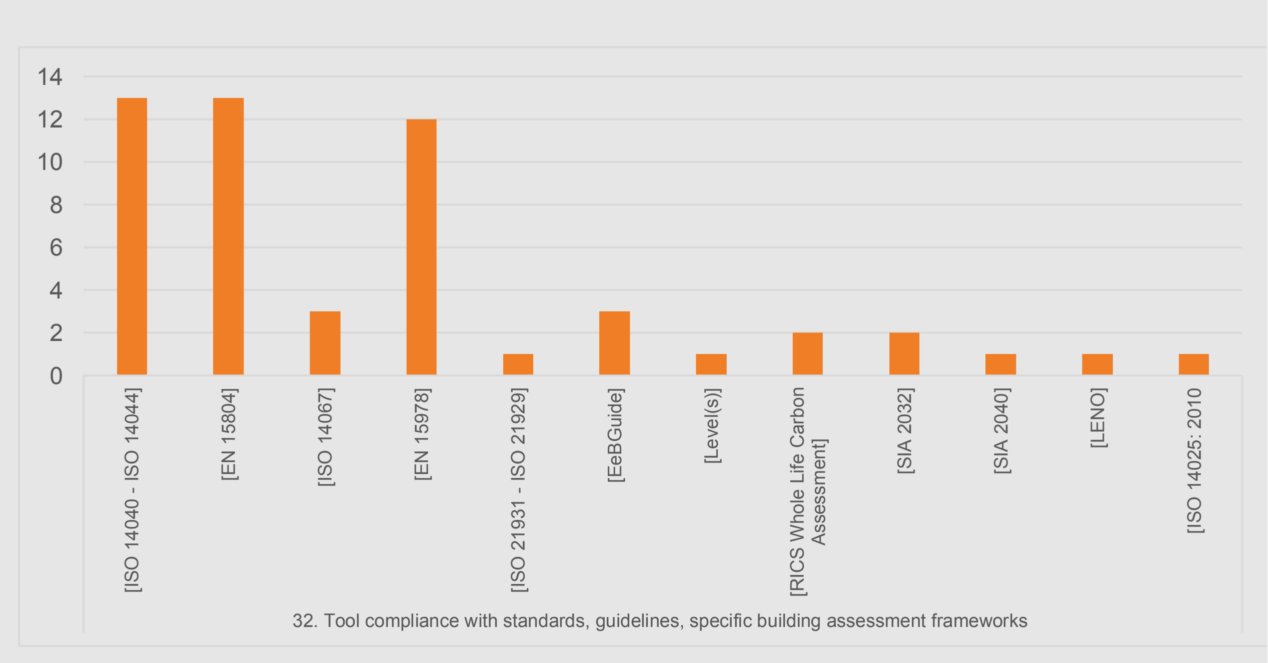

Figure 36: Survey outcomes. Question 32 on standard compliance.

3.3 Synthesis and critical assessment of survey results

The conducted survey served as an instrument to have an overview of tools for buildings LCA. Even if in the market are more tools now available and to still to be potentially investigated, the survey let arise common points and issues.

For the recognition of harmonized and still opened issues, the results were collected the answers counted. Each question has been associated to a specific issue (see Appendix) and the latter has been classified by considering the following criteria:

- Questions which presented at least one answer with counting from more than 75% of participant. “None” – answer is not entailed → **Harmonized issues**. There is an agreement/alignment on such issue
- Questions which presented all answers with counting between 25% and 75% of participants → issues considered **relevant but handled in different way** by tool developers
- Questions in which counting was less than 25% and “none answer” presented higher counting→ open issues. There is an **improvement potential**

Here in Table 1 the results of the critical assessment are provided.

Table 1: Critical assessment. Recognition of harmonized and open issues.

		Harmonized	Handled differently	Open issue
Usability	2. Use case	X		
	3. Intended users?	X		
	4. Level of LCA knowledge		X	
	5 LCA Tool category		X	
	6. Lifecycle stages	X		
	7. Design phase(s)	X		
	8. Direct submission to certification authorities		X	
	9. Support options	X		
	10 country specification	X		

Functionality	11 Language	X		
	12 Tool Entries		X	
	13 Databases		X	
	14 System level	X		
	15. Templates or default values		X	
	16. Predefined building schemes		X	
	17. Parameters used calculation.		X	
	18 Data source modification			X
	19 Predefined building schemes		X	
	20 Visualization		X	
	21 Indicators	X		
	22 Results aggregation	X		
	23 Real Time feedback		X	
	24 Optimization algorithms			X
	25 Tool features		X	
Reliability	26 Error propagation			X
	27 Results deviation			X
	28 Data quality		X	
	29 Quality assessment mechanisms			X
Interoperability	30 Tool interoperability		X	
	31 Workflow for data exchange		X	
Compliance	32 Compliance	X		

The survey reported a harmonized status of the available tools with regard on usability and overall applied LCA methodology.

All tools target similar intended applications, i.e., Building and building parts assessment, comparison, environmental certification and improvement of building environmental performance with an aware choice of products. Intended user are similar as well: tools aim to planners, sustainability consultants and authority. In terms of LCA knowledge, pure calculations tools require a more advanced expertise level, in comparison with complex tools, which, in the other hand, try to support more the user during the building lifecycle modelling.

The variety of languages, the country specification and the several available submissions for environmental certifications demonstrated that building LCA tools target mostly a national audience.

The survey showed furthermore that there is a consensus on applying cradle-to-grave analyses, with few variations for tools that do not consider transport and construction process and the whole building maintenance and renovation activities. There are tools that use building energy simulation, and therefore focus on the building operation. The environmental indicators are derived by core indicators-set according to the EN 15804.

In terms of tools functionality, the survey showed a higher variety in terms of requested inputs, provided templates, visualisation possibilities, results aggregation and tool features. Tool maturity level and the technical/informatics advancements dictate the implementation of more sophisticated features, such as LCA data source modification, real-time feedbacks and optimisation algorithms.

A similar issue can be found in the category “Interoperability/Portability”. Most of the investigated tools show a high interest in data import and export from digital models but prefer working with Bill of Quantities and Spreadsheet. A tools’ coupling is not yet applicable and a limited number of tools achieve higher levels of automation. In this respect, there are also differences in terms of technical advancement and BIM/LCA integration strategies.

3.4 A methodology for tools identification

With the collected answers, it is possible to establish a procedure to identify tool, which can satisfy specific designers' or user needs.

The procedure here suggested consists in systematic pyramidal selection, which starts from the bottom, with a first identification, to the top, where there is a more personalized filtering. Requests belonging to the lower part have higher priority for the tool identification process, but however can provide a lower selection level. Requests on the higher part can select the proper tool with higher level of personalisation. Such requests are related to the survey outcomes that shown more discrepancies.

Five main levels are identified (see **Figure 37**) and a generic example is presented in the following tables.

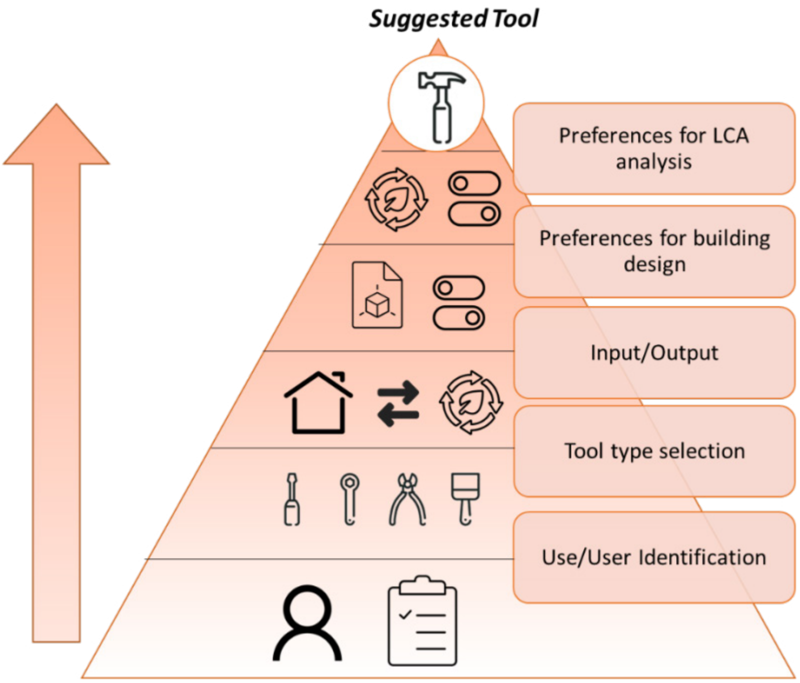

Figure 37: Methodology for Tool identification depending on user's needs.

a) **Use/User Identification**: the application(s) and the intended user(s) need to be targeted and indicated. The country of application is declared. This will automatically select tools with country-specific databases. Furthermore, a preference on languages can be provided (**Table 2**).

b) **Tool type selection**: the potential user selects the tool type, pure calculation or complex tools for the building assessment (**Table 3**).

Table 2: Field 1 - Use and User Identification.

Request	Example
User Type	Designer
User preferred Tool Language(s)	English
Use case	Improvement of environmental performance
Country specification for use case	Yes
Suggested Tools	Pleiades; FCBS CARBON; GPR Building; CAALA; One Click LCA; SimaPro; PHribbon; LCAUS; BIMEELCA; TOTEM tool; Energy Plus; eQuest; Athena Impact + Tally; GENERIS

Table 3: Field 2 - Tool identification.

Request	Example
Calculation tool (Y/N)	Y
Complex tool (Y/N)	Y
With link to benchmarks? (Y/N)	Y
Suggested Tools	Pleiades; CAALA; One Click LCA; PHribbon; BIMEELCA; Lesosai

With this first selection (see Tables -2-3), it is possible to narrow the tool search, but, according to the survey outcomes, this may lead still to different tools. The identification process can therefore continue.

c) **Input/Output**: the lifecycle stages to be investigated, the system levels and, if still necessary, the underlying LCA database are specified. Furthermore, the potential user can declare the environmental indicator under investigation, the preferred template and the data format for results (Table 4).

Table 4: Field 3 - User preferences for tool Input/output.

Request	Example
System level(s)	Building
LCA database	Environmental Product Declaration
Environmental indicator(s)	Global Warming Potential
Output for selected lifecycle stages	Template Report (.doc; .pdf)
Results aggregation	Elements / Lifecycle stages aggregation
Suggested Tool(s)	Pleiades; CAALA; One Click LCA; Lesosai

This further selection can now provide a restricted number of tools. A further level of personalization can be enabled through two last preferences.

d) **Tool features and user's preferences for building design**: this field aim to recognise specific designers' and users' needs, such as provision of results during the early design stages, optimisation algorithms, interoperability with digital planning or tool coupling possibilities (Table 5).

e) **Tool feature and user's preferences for LCA analysis**: preferences about, deviation analyses and quality assessment mechanisms are asked (Table 6).

Table 5: Field 4 - Input and output preferences for building design.

Request	Example
BIM Coupling: Workflow for data exchanges	5 BIM object enrichment
Results provision during design early stages	Yes
Suggested Tool	Pleiades Lesosai

Table 6: Field 5 - Input and output preferences for LCA analyses.

Request	Example
LCA Deviation analysis	Yes
Quality assessment mechanisms for LCA	No
Suggested Tool	PLEIADES

Through the last filtering, based on the survey outcomes, a unique a proper tool has been selected.

3.5 Discussion and outlook on building LCA tools: General and Ideal case

The survey on building LCA tools outlined features and aspects for which a harmonization has been mostly reached. However, certain issues are still challenging. While previous investigations focused mostly on the general usability and functionalities, this report and the related survey included additional aspects, such as optimisation algorithms, data exchange, related to informatics advancement.

According to the survey, LCA tools in a general case (Figure 38), as pure calculation tools do not include benchmarks, or, as complex tools, include them. They are capable to support the design process, but not the early stages. They are applied for building and building parts assessment, comparison, environmental certification and improvement of building environmental performance, but do not integrate benchmarks. Intended users are planners, sustainability consultants and authority with at least basic knowledge. Country specification, which is mostly occurring, and dictates languages, underlying databases and the submission for environmental certifications. LCA analysis are carried out cradle-to-grave and under consideration of core environmental indicators.

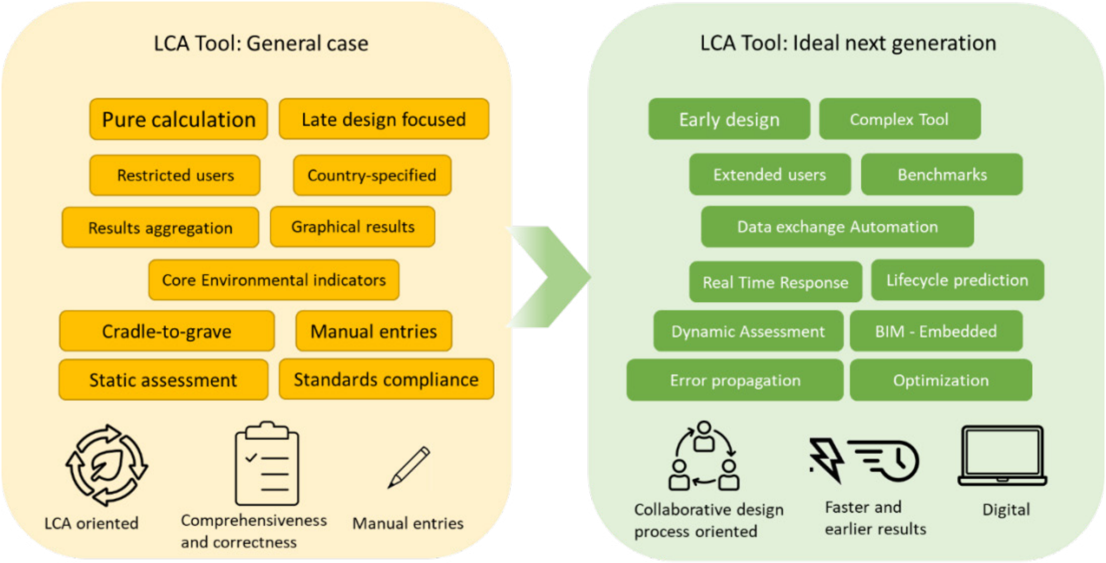

Figure 38: LCA Tool. General and ideal-next generation tools

Input data are often manual. A data exchange is possible: however, users are requested to provide some entries manually, and this may lead to re-entering or errors. Tool outputs are while provided in form of report, pre-formatted templates and with both numerical and graphical options. Results are aggregated in several ways, by considering different level of details or lifecycle stages. Bar charts and/or pie donuts are the most frequent visualization possibilities.

Advancements in tools entails the implementation of functions for earlier and faster evaluation of the environmental profile. These requirements are in line with the increasing collaborative design and digitalization in the building sector.

In this sense, the next generation of tools or currently “ideal” tools should support more the early decision making. The intended users should include all stakeholders involved in the building planning, even those who may not have knowledge in the field of LCA, in order to increase all stakeholders’ awareness towards environmental quality. The usability of the LCA tools needs to be increased with consideration of more environmental information, i.e., including transport, construction processes and renovation/end-of-life scenarios. Databases need to be extended with statistical records, in order to allow for benchmarks derivation and predictive lifecycle modelling. It is important to communicate variations and uncertainties on LCA analysis in a transparent way. This may be feasible with the implementation of results deviation and error propagation.

As a next generation tool will be faster, it is also important to implement real time feedback mechanisms and workflows with higher level of automation, e.g., plug-in or IFC object enrichment and import/export. High efforts need to be addressed to BIM portability, which increases collaborations between different fields.

4 Conclusion

Within this background report an overview on designers' need and tool set is provided.

In particular, the tool set has been prepared with help of a questionnaire, in which 70 participants provided information on LCA tools usability, functionality, reliability, interoperability and conformity. Based on this, a process for tool selection has been established.

The survey represents the core part of this report, which allowed some reflections on a general status quo of currently available building LCA tools as well as ideal next generation tools and upcoming developments. Constraints of the analysis and of the critical assessment are due to the restricted number of participants, which did not cover the whole Building LCA tools market. Despite such a limitation, the survey demonstrated an alignment on tools usability and conformity, but also high variability in terms of tools functionality. Most of the open issues and future potentials entails tools' results reliability and interconnectivity. Tools' development focus was on results comprehensiveness and correctness.

All inhere presented issues are belonging to the current requirements and necessary developments in the context of a more integrated and digitalized planning process. Based on designers' need as well, Ideal LCA tools should be in the future more oriented to the design process. As digitalization in the building sector and life cycle assessment is receiving also more attention, approaches and their respective interfaces need be further developed aiming at a faster and a more robust LCA. The market is still open and new interfaces are fostered. New products will support environmental decisions within building development, by allowing higher level of interoperability with other interfaces, e.g., BIM, geospatial information (GIS) and similar. This makes possible faster and robust statements already in the early design stage under limited information basis and uncertain boundary conditions. This will require a higher and a more effective provision of benchmarks (Björklund, 2002).

It is important to underline that in the construction industry, in comparison with other sectors, the adoption of digital instruments has been slower, and typically only focused on isolated aspects of the building process due to the fragmented nature of the construction sector and a compartmentalised field. National and local governments in this context aim in following years to facilitate the uptake of digital technologies in the construction sector by providing, e.g., e-services or by issuing building permits and keeping the repository of building data.

Tool developments need therefore to follow changes in the design process, which is now requested to become more collaborative. In this regard, tools' evolution should focus also on direct and support the environmental assessment to all the stakeholders involved. With the establishment of such new approaches, next generation products will aim to frame the building and design process, as a whole, in a holistic way.

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Appendix

I) Survey: comprehensive answers

In the following tables, all outcomes are collected. All comments provided by participants are reported as well.

	2. Use case										3. Intended users?											4. Level of LCA knowledge			5 LCA Tool category		
	Assessment	Choice	Improvement	Product comp	Projects comp	Buildings Comp	Marketing	[Labeling / Certification]	standards]	urban designs]	Product manufacturer	[Building designer	[Consultant	Auditor	[Contractor	[Building owner	[Financier	[Tenant / user	[Service provider]	[Authority]	[Researchers]	None	Basic	Advanced	[Pure calculation]	[Complex tool	With benchmarks
Pleiades	X	X	X	X	X	X		X		X		X	X	X	X	X		X		X	X		X			X	X
FCBS CARBON		X	X									X	X				X			X		X			X		X
GPR Building	X		X		X			X				X	X							X		X			X		
CAALA	X	X	X		X							X	X	X		X		X				X				X	X
One Click LCA	X		X	X	X			X				X	X											X	X	X	X
SimaPro	X		X	X		X			X			X	X											X	X	X	
PHribbon	X	X	X		X	X						X	X											X		X	X
LCAUS (n.r.)	X	X	X		X	X						X									X		X		X		
BIMEELCA	X	X	X									X	X										X			X	X
The ZEB tool	X	X		X	X							X	X											X	X	X	
TOTEM tool	X		X		X							X											X			X	
Energy Plus; eQuest; Athena Impact + Tally	X	X	X		X							X	X											X		X	
LCAbyg	X		X	X	X	X		X				X	X	X	X								X			X	
Enerweb	X		X		X				X			X			X								X		X		
Lesosai	X	X	X	X	X				X			X	X							X			X		X	X	X
GREG	X	X	X		X			X	X			X	X											X	X		
SBToolCZ, Envimat	X	X	X		X		X	X	X		X	X	X			X	X	X		X			X			X	X
TOTEM	X		X		X							X			X					X		X			X		
GENERIS	X		X	X	X	X		X				X	X	X									X			X	X
LCA_US	X	X		X	X							X												X	X		
Sphera GaBi	X	X	X	X		X		X			X	X	X			X	X			X				X	X		

	6. Lifecycle stages							7. Design phase(s)										8. Direct submission to certification authorities															9. Support options					
	A1A3	A4-A5	B1-B5	B6	Urban system	C+D	[Other-module D optional]	. [0 - Strategic Definition]	[1 - Preliminary studies]	[2 - Concept design]	[3 - Developed design]	[4 - Technical design]	[5 - Construction	[6 - Handover commissioning]	[7 - Operation Management]	[8 - End of use, Recycling]	[Other - All stages]	Available	[DGNB]	[BNB]	[DGNB Dk]	[French E+C- label]	[BREEAMM	[SNBS]	[GLA]	[RICS calculation]	[MPG]	[Sméo]	[Lenoz]	[Minergie-ECO]	[LEED]	[Manual]	[Webinar]	[Tutorial]	[FAQ]	[Hotline - Helpdesk]	[Trainings]
Pleiades (+ EQUER)	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X				X										X	X	X	X	X	X
FCBS CARBON	X	X	X	X	X	X		X	X	X								X							X	X						X		X			
GPR Building	X	X	X	X		X			X	X	X	X	X			X		X									X					X	X	X	X	X	X
CAALA	X		X	X		X	X	X	X	X	X	X						X	X	X												X	X	X	X		X
One Click LCA	X	X	X	X	X	X		X	X	X	X	X						X														X	X	X	X		X
SimaPro	X	X	X			X		X	X	X	X		X			X																X	X	X			X
PHribbon	X	X	X	X		X				X	X															X						X	X				
LCAUS (not regist)	X	X	X	X		X					X	X	X	X	X	X																					X
BIMEELCA	X	X	X	X		X				X	X	X	X																			X					
The ZEB tool	X	X	X	X	X	X			X	X	X	X				X	X															X					
TOTEM tool	X	X	X	X		X				X	X	X																				X	X	X	X		X
Energy Plus; eQuest; Athena Impact+ Tally	X	X	X	X		X				X	X	X			X																X	X	X	X	X		
LCAbyg	X	X	X	X		X			X	X	X		X		X	X		X			X											X	X	X			X
Enerweb		X							X	X	X							X												X		X			X	X	X
Lesosai	X	X	X	X		X			X	X	X	X						X										X	X	X		X		X	X	X	X
GREG	X			X		X				X	X	X						X												X		X		X			
SBToolCZ, Envimat	X		X	X							X	X	X	X	X			X														X	X	X			X
TOTEM	X	X	X	X		X					X	X	X	X									X									X	X	X	X		X
GENERIS	X		X	X		X				X	X	X		X		X		X	X	X			X									X	X	X	X	X	X
LCA_US	X	X	X	X		X		X	X	X	X	X	X																								X
Sphera GaBi	X	X	X	X		X		X	X	X	X	X	X	X	X	X																X	X	X			X

	12 Production phase.			12 Construction and erection of the building.				12 Operational phase of Buildings.		
	[Energy and mass	services]	[Other]	[Type and quantity of building	transport cost	construction processes	[Other]	[Quantity of energy necessary	[Type of energy	[Other]
Pleiades (+ EQUER)			according to the geometry (possibly BIM), energy calculation etc.				% material surplus and transport distance (not cost)	No	X	the quantities (heating, cooling, hot water, lighting, ventilation...) are calculated by the associated energy simulation tool
FCBS CARBON			Building form only, and selection from pre-curated list of components	X				X	X	
GPR Building	X	X		X	X	X		X	X	Operational energy is evaluated, but is excluded from MPG performance assessment
CAALA			link to CAD model or import of existing building					Yes		calculation done by tool
One Click LCA	X			X	X			X	X	
SimaPro	X			X	X	X				
PHribbon	X			X				X	X	
LCAUS (not regist)	X			X			Distances from factories to site. Mean of Transport.	X	X	
BIMEELCA	X			X				X		
The ZEB tool	X	X	depending on the availability of generic and/ or specific data	X				X		
TOTEM tool										
Energy Plus; eQuest; Athena Impact+ Tally										
LCAbyg			Included in the phase data	X		X				Included in the phase data
Enerweb				X						
Lesosai			Data come from database	X		X			X	energy are calculated
GREG										
SBToolCZ, Envimat	X	X						X	X	
TOTEM			type and quantity of materials	X						the energy demand based on the U-values

GENERIS			Mass of products				X	X
LCA_US	X	X		X	X	X	X	X
Sphera GaBi			Default avaragae	X	X	X	X	X

	12. Urban Systems during the Use phase.				12. Renovation and Maintanance Activities.					12. Building End-of-Life.			
	[Type and quantity of energy	*other user-dependent energy*	*[Possibly type and volume of person and goods transport to / from location]*	*[Other]*	*[Time interval*	*[Type and mass/energy flows*	*[Time interval (elements substitution, building retrofit and refurbishment)]*	*energy flows for renovation activities]*	*[Other]*	*[Type and volume of demolished including]*	*possible re-usable material /*	*recyclable material / systems]*	*[Other]*
Pleiades (+ EQUER)	X	X	X	water mains leakage, waste sorting system, streets, district heating characteristics, pipes, parks with water needs etc.			X	X	derived from the geometry and life spans	X	X	X	derived from geometry, the input is the type of EoL process
FCBS CARBON	X						X			X			
GPR Building								X	maintenance is included				EOL mostly included
CAALA					X				RSLs integrated	X			calculated by tool
One Click LCA	X	X			X		X			X	X	X	
SimaPro					X	X	X	X		X	X	X	
PHribbon							X			X		X	GIA based, materials assessed at disposal by the proportion of recycling, incineration and landfill.
LCAUS (not regist)						X		X		X	X	X	
BIMEELCA					X		X			X			
The ZEB tool				more in The ZEN tool	X					X			
TOTEM tool													
Energy Plus; eQuest; Athena Impact+ Tally													
LCAbyg					X		X						
Enerweb													

Lesosai	X	X	X	X					by default value
GREG									
SBToolCZ, Envimat									
TOTEM					automatically calculated				automatically calculated
GENERIS	X		X			X			
LCA_US	X	X	X	X		X	X	X	
Sphera GaBi	X		X			X	X	X	

	13. Underlying data basis														14. System levels				
	[Environmental Product	[Comment}	[Ecoinvent]	[Comment]	[GaBi]	[Comment]	[Global LCA Data Access (GLAD)]	[Comment]	[Ökobau.dat]	[Comment]	[Further generic construction materials databases]	[Comment]	[Other]	Other comment]	[Districts]	[Building stock]	[Building]	[Building parts / component]	[Material]
Pleiades (+ EQUER)	X	French EPDs INIES	X	v2.2 will soon be replaced with 3.4											X	X	X	X	X
FCBS CARBON	X										X	ICE database					X	X	X
GPR Building	X		X	v 3.6							X	NMD 3.0 (National Environmental Database)					X	X	X
CAALA	X								X					upload possible	X		X	X	
One Click LCA	X																X	X	X
SimaPro	X		X													X	X	X	X
PHribbon	X	around 300 entries											ICE database and Building Transparency.org.	additional 141 entries from ICE.			X		X
LCAUS (not regist)			X	V2.0												X	X	X	

BIMEELCA	X	European	X	Version 3										X	X
The ZEB tool	X		X			X							X	X	X
TOTEM tool															
Energy Plus; eQuest; Athena Impact+ Tally															
LCAbyg	X	The user can inset EPDs				X	2020						X	X	X
Enerweb										KBOB-List	Official KBOB list of Switzerland		X	X	X
Lesosai	X	Customer data				X	2016	X	kbob list	materialsdb.org	different LCA databases	X	X	X	X
GREG															
SBToolCZ, Envimat	X		X					X	Envimat.cz				X	X	X
TOTEM	X	will be included in the course of 2021	X										X	X	
GENERIS	X					X	2021	X	ESUCO 2011				X	X	X
LCA_US			X	v2.0										X	X
Sphera GaBi	X				X	X								X	X

	15. Templates or default values		16. Predefined building schemes (		17. Parameters used calculation.			
		[Comment]		*[Comment]*	*[Life Cycle Impact Assessment Characterization method]*	*[Conversion factors for quantity calculation]*	*[Algorithmic generation of building quantities]*	*[Not full LCA calculation, Embodied CO2 only - RICS guidance]*
Pleiades (+ EQUER)	X	Materials characteristics (e.g. densities), typical life spans, transport distances, electricity production mix, water mains leakage, occupancy profiles (number of occupants, use of electricity, water consumption...)	X	French E+C- label	X	X		
FCBS CARBON	X	Tool is entirely based on standard components and materials, enabling quick design choices to be made at early stages. Direction and magnitude of decision impact is key at early stages.			No	X	X	Algorthimic generation of building quantities based on basic building parameteres (height, footprint, etc.) Standard component list.

GPR Building	X	Reference buildings of different types	X	Building-type specific technical life time	X	
CAALA	X	All default materials are set based on typical variants (e.g timber, concrete). They can be changed and adapted				X
One Click LCA	X	EPDs	X	BREEAM		X
SimaPro					X	
PHribbon	X	There are templates for the comparison constructions, which can be one of the options shown.				X
LCAUS (not regist)					X	
BIMEELCA	X	From EPDs and Ecoinvent			X	
The ZEB tool					X	X
TOTEM tool						
Energy Plus; eQuest; Athena Impact+ Tally						
LCAbyg	X	Library	X	DGNB DK	X	
Enerweb						X
Lesosai	X	coming from standard SIA2032, label Minergie ECO and Lenoz			X	X
GREG						
SBToolCZ, Envimat			X		X	X
TOTEM	X	standard building elements that can be modified by the user. User can copy elements from the library and modify or delete existing layers				
GENERIS	X		X	DGNB; BNB ; BREEAM International NC 2016		
LCA_US					X	
Sphera GaBi	X	Lots of default values for practically everything	X		X	

	18. Are the LCA data sources modified, selected or complemented prior to their provision to the user?		19. Data output: results presentation							
		[Comment]	*[Spreadsheet Document]*	*Template Report (PDF, DOC, etc.*	*[Extensible Markup Language (XML)]*	*[Dashboard for results visualization]*	*HTML document browser]*	*[In BIM Model directly]*	*[json]*	*[No template presentation upon the assessor]*
Pleiades (+ EQUER)	X	Contextualization of products that are mainly national (e.g. concrete), calculation of some indicators not provided in ecoinvent (e.g. CO2 including biogenic according to forest management for wood)	X	X	X	X				
FCBS CARBON	X	Standard material EPD data is converted to workable building elements, that are then presented as components for use within the tool.	X	X						
GPR Building				X		X				
CAALA				X		X	X			
One Click LCA			X	X		X				
SimaPro	X	Nationalized.	X							
PHribbon	X	Units in the EPDs vary widely and can be awkward, so they are generally converted to kgCO2 per m3, that allows a crosscheck for consistency too. Sometimes materials are in other units, e.g. per m2 if the thickness is not generally known, e.g. for carpet. Or per m for I-beams and Easi-joists. They can also be per kg or per kWh for ASHPs, these are not generally converted from the EPD.	X							
LCAUS (not regist)				X						
BIMEELCA								X		
The ZEB tool			X	X		X				
TOTEM tool										
Energy Plus; eQuest; Athena Impact+Tally										
LCAbyg			X	X		X			X	
Enerweb	X	It is possible to modify the data but not the default way to use Enerweb.		X		X				
Lesosai	X	For example: reinforced concrete	X	X	X	X				
GREG										
SBToolCZ, Envimat										X
TOTEM	X	ecoinvent data is combined and modified	X	X						

GENERIS			X		X
LCA_US	X				
Sphera GaBi	X	X		X	

20. Data output: results visualization	[Pie chart/donut chart]	[Multi-level Pie Char]	[Sunburst]	[Bar chart]	[Grouped bar chart]	[Stacked bar chart]	[Normalized bar chart]	[Multiple series 3D bar charts]	[Line chart]	[Stacked area chart]	[Sankey/Alluvial Diagram]	[Tree map]	[Heat map]	[Radial chart/spider chart/polar chart]	[Parallel coordinates]	[Pictorial unit chart]	[Scatter plot]	[Cluster]	[3D Scatter plot]	[3D Color code]	[Bubble map]	[Color map]	[Scale]	[Other]
Pleiades (+ EQUER)	X	X		X	X	X	X							X										
FCBS CARBON	X			X					X															
GPR Building	X	X																						
CAALA	X			X	X																		X	
One Click LCA	X			X		X	X																	
SimaPro	X	X		X					X						X									
PHribbon							X						X											
LCAUS (not regist)				X	X	X																		
BIMEELCA																				X				
The ZEB tool				X																				
TOTEM tool																								
Energy Plus; eQuest; Athena Impact+ Tally																								

LCAbyg		X		X	X		X							
Enerweb	X	X												
Lesosai	X	X	X	X		X		X						
GREG														
SBToolCZ, Envimat														result upon the assessor
TOTEM	X													
GENERIS	X	X	X		X									
LCA_US		X								X				
Sphera GaBi	X	X	X	X	X		X	X	X	X	X	X	X	

	21. Indicators for environmental impact assessment.														22. Results aggregation is possible?					23. Real time feedback		24. Optimization algorithms	
	GWP	ODP	AP	EP	POPC	ADPE	ADPF	PERT	PENRT	Share renewable energy	[Water use]	UBP	[Share of secondary materials]	[All core indicators]	[None]	[Element' s aggregation]	[Lifecycle stages aggregation]	[Time aggregation]	[Aggregation to a single monetarized value]		[Comment]		[Comment]
Pleiades (+ EQUER)	X		X	X	X	X			X		X			X		X	X				one minute computation time for energy simulation; real time feedback imprecise	X	
FCBS CARBON	X															X	X	X		X	Designed to enable enhanced design, so feedback is key.		Not currently.
GPR Building	X	X	X	X	X	X	X	X	X				X			X	X			X			
CAALA	X	X	X	X	X			X	X							X	X			X			under development, prototype working
One Click LCA	X	X	X	X												X	X						
SimaPro	X	X	X	X	X		X	X	X							X	X						
PHribbon	X															X			X	X	Results update instantly with any change		

LCAUS (not regist)	X	X	X	X	X	X	X	X	X							X					
BIMEELCA	X	X	X	X	X	X	X	X	X						X	X		X			
The ZEB tool	X															X		X	at different stages of design to provide feedback on different material and design choices	X	Dynamo/Revit for dynamic parametric approach.
TOTEM tool																					
Energy Plus; eQuest; Athena Impact+ Tally																					
LCAbyg	X	X	X	X	X	X	X	X	X				X		X	X		X	Comparison of elements		
Enerweb								X	X			X			X			X	Calculation after every change.		
Lesosai	X		X	X	X			X	X			X			X	X				X	
GREG																					
SBToolCZ, Envimat	X	X	X	X	X				X	X	X					X			SBToolCZ is an open method, real-time feedback possible.		
TOTEM	X	X	X	X	X	X	X							X		X	X	X			
GENERIS	X	X	X	X	X	X	X	X	X	X				X	X	X					
LCA_US	X	X	X	X	X			X	X	X						X					
Sphera GaBi	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					

	25. Special features.	26. Does the tool incorporate error propagation?
Pleiades (+ EQUER)		
FCBS CARBON	The tool is designed to provide early estimates of the embodied carbon of building at an early stage, when bills of quantities are not yet available. Instead, it uses a standardised algortihm to provide guidance during design about better or worse material/form choices. Components are based on standard build-ups, modelled using EPD and ICE data. With in 30 minutes, it is expected that a building whole life carbon analysis can be undertaken, and then iterated on to find lower carbon solutions.	
GPR Building		
CAALA	link to CAD/BIM model, import and export of gbXML, simplified LCC calculation, variant comparison	
One Click LCA		

SimaPro		
PHribbon	It integrates with PHPP, the Passivhaus Planning Package. It uses quantities of materials from that and also generates a combined Embodied and Operational graph that uses operational data from the PHPP.	
LCAUS (not regist)		X
BIMEELCA	Developed via Revit API and integrated in that BIM tool.	
The ZEB tool	The ZEB tool can be used on its own to calculate embodied emissions for materials and has an input to link with simulated emissions from operation. Due to it being excel based, it can be used to model different life cycle modules depending on the availability of generic and, or specific data (EPD). Norwegian EPD are collated and linked in the EPD library in the tool and the user can use a drop-down menu to choose different materials (linked to the EPD). The ZEB Tool can be connected to REVIT using Dynamo plugin/	
TOTEM tool		
Energy Plus; eQuest; Athena Impact+ Tally		
LCAbyg		X
Enerweb		
Lesosai		
GREG		
SBToolCZ, Envimat		
TOTEM		
GENERIS	Dynamic entries Comparison of constructions and buildings	
LCA_US		
Sphera GaBI		

	27. Results deviation observed				28. Data quality									29. Is a quality assessment mechanism integrated?
	[None]	[Sensitivity analysis]	[Uncertainties analysis]	[Other]	[None]	[Regional]	[Comment]	[Verified]	[Comment]	[Independent]	[Comment]	[Other]	[Other comment]	[Comment]
Pleiades (+ EQUER)		X	X	only for energy calculation		X		X	ecoinvent review process					
FCBS CARBON	X				X									

GPR Building	X			X	For building product available on Dutch market	X				cat 1, 2 and 3	Two categories for verified data: cat1 for producer-specific, cat 2 for sector-specific. Andt cat 3 for generic, unverified data (mostly ecoinvent)	X	optional independent review for GPR certificate
CAALA	X			X	ökobau.dat	X	EPDs					X	simple model checker to check quantities from CAD/BIM model
One Click LCA	X					X	EPDs						
SimaPro		X		X		X						X	
PHribbon	X							X	The quality of the data is assessed according to source. the ICE database less good because less product specific.				
LCAUS (not regist)	X		X										
BIMEELCA	X			X	Only verified generic (Ecoinvent) or site-specific (EPD) datasets are considered.								
The ZEB tool	X					X	Ecoinvent and EPD					X	Database third party verified.
TOTEM tool													
Energy Plus; eQuest; Athena Impact+ Tally													
LCAbyg	X			X	DK			X	Own data				
Enerweb	X					X	KBOB	X	User specified				
Lesosai	X					X	KBOB, Ökobaudat, lenoz	X	KBOB, Ökobaudat, lenoz	user value	Epd	X	Changes showed in report: check materials values
GREG													
SBToolCZ, Envimat	X			X		X		X		.	Data sources are: EPD, Envimat.cz, Ecoinvent		
TOTEM	X		X										
GENERIS	X					X						X	check for information required for LCA or for DGNB and BNB certification submission
LCA_US	X		X										
Sphera GaBi		x		X		X		X				X	Conservation of mass automatically checked per process. Saturation of process input/outputs visual. Computability of

linear equation system automatically checked.

	30. Interoperability of your tool.												31. Workflow for data exchange.						
	[Excel/Spreadsheet]	*[Comment]*	*[Revit]*	*[Comment]*	*[ArchiCAD]*	*[Comment]*	*[Rhino & Grasshopper]*	*[Comment]*	*[SketchUp]*	*[Comment]*	*[Other custom integration]*	*[Comment]*	*[0. Manual input]*	*[1. Bill of quantities (BOQ) export]*	*[2.IFC import i*	*[3. BIM viewer association*	*[4. Use of an LCA plugin*	*[5. BIM objects enrichment*	*[Other]*
Pleiades (+EQUER)	X		X	plugin to export or directly use Pleiades in Revit			X	export a gbXML file that can be imported in Pleiades			X	own 2-3D modeler	X		X	X	X	X	possible use of gbXML instead of IFC
FCBS CARBON											X	Manual input of 7 variables. Agnostic of software.	X						
GPR Building																			integrated visualization of building element and completeness
CAALA			X				X		X		X	Open Street Map		X			X		gbxml import
One Click LCA	X		X											X	X		X		
SimaPro	X													X					
PHribbon	X																		quantities come from the PHPP, though additional info is needed for items that are not part of that thermal model
LCAUS (not regist)	X													X					
BIMEELCA	X	Data input	X	Tool developed via Revit API													X		
The ZEB tool	X		X											X	X				
TOTEM tool																			
Energy Plus; eQuest; Athena Impact+Tally																			
LCAbyg	X		X				X							X					
Enerweb																			

Lesosai	X	X	X	X	X	Bausoft		X	X	X	X
GREG											
SBToolCZ, Envimat	X							X			
TOTEM											
GENERIS	X	X IFCxml	X IFCxml		X IFCxml				X		X
LCA_US	X						X				
Sphera GaBi							X				

32. Tool compliance with standards, guidelines, specific building assessment frameworks	[ISO 14040 - ISO 14044]	[EN 15804]	[ISO 14067]	[EN 15978]	[ISO 21931 - ISO 21929]	[EeBGuide]	[Level(s)]	[RICS Whole Life Carbon Assessment]	[SIA 2032]	[SIA 2040]	[LENO]	[ISO 14025: 2010
Pleiades (+ EQUER)	X	X		X			X					
FCBS CARBON	X			X				X				
GPR Building		X										
CAALA	X	X		X								
One Click LCA	X			X								
SimaPro	X		X									
PHribbon								X				.
LCAUS (not regist)	X	X	X	X								
BIMEELCA		X		X								
The ZEB tool	X	X		X								X
TOTEM tool												

Energy Plus; eQuest; Athena Impact+ Tally									
LCAbyg		X							
Enerweb		X					X		
Lesosai	X			X			X	X	X
GREG									
SBToolCZ, Envimat	X	X		X	X	X			
TOTEM	X	X		X					
GENERIS	X	X		X		X			
LCA_US	X	X		X					
Sphera GaBi	X	X	X			X			

II) One-pager template draft for an exemplary tool

LCAbyg	Short description of the tool

Usability	***Functionality***	***Reliability***	***Interoperability***	***Compliance***
Intended use	**Data input**	**Error propagation**	**Data exchange**	**Compliance**
Assessment of building and building products/Improvement of environmental performance/Product comparison/Projects comparison/Comparison with reference buildings/Labelling / Certification/	A1-A3 Production phase: Included in the phase dataA4-A5 Construction and erection of the building: Type and quantity of building/construction processes /B6 Operational phase of Buildings: Included in the phase data B6 Urban Systems during the Use phase: B2-B5 Renovation and Maintenance Activities.: Time interval /Time interval (elements substitution, building retrofit and refurbishment)]/C-D Building End-of-Life. :	error propagation incorporated	Excel - Spreadsheet /Revit /Rhino & Grasshopper /	[EN 15804]/
Intended user	**Underlying data basis**	**Results deviation**	**Workflow for data exchange**	
Building designer/Consultants/Auditor/Contractors/	Environmental Product Declarations (EPD) The user can inset EPDs/Ökobau.dat 2020/	None/	1. Bill of quantities (BOQ) export/	
Level of knowledge	**System levels**	**Data quality**		
Beginner	Building/Building parts / component/Material	Regional DK/Independent Own data/		
X Basic				
Expert				
Tool type	**Parameters**	**Quality assessment mechanism**		
Complex tool/without benchmarks	Life Cycle Impact Assessment Characterization method/	Not integrated		
Life cycle modules/phases	**LCA data modified?**			
Production/Transport/Construction/Renovation and Maintenance/Building operation/End of Life/	n.a.			
	Data output			
	Spreadsheet Document/Template Report			

	(PDF, DOC, etc.)/Dashboard for results visualization/json/		
Design stages	**Visualisation**		
1 - Preliminary studies/2 - Concept design/3 - Developed design/5 - Construction/ 7 - Operation and management/8 - End of use, recycling	Bar chart/Stacked bar chart/Normalised bar chart/Line chart/		
Certification scheme(s)	**Indicators**		
Direct Submission to certification authorities//DGNB Dk//////////	GWP/ODP/AP/EP/POPC/ADPE/ADPF/PERT/PENRT/ [Share of secondary materials]/		
Support	**Aggregation**		
Manual/Webinar/Tutorial/Trainings	Elements aggregation/Lifecycle stages aggregation/		
Languages	**Real life time feedback**		
Danish/	Real time feedbacks available: Comparison of elements		
Country specification	**Optimisation algorithms**		
Country specified	n.a.		

LCA-BIM workflows in the design process

A Contribution to IEA EBC Annex 72

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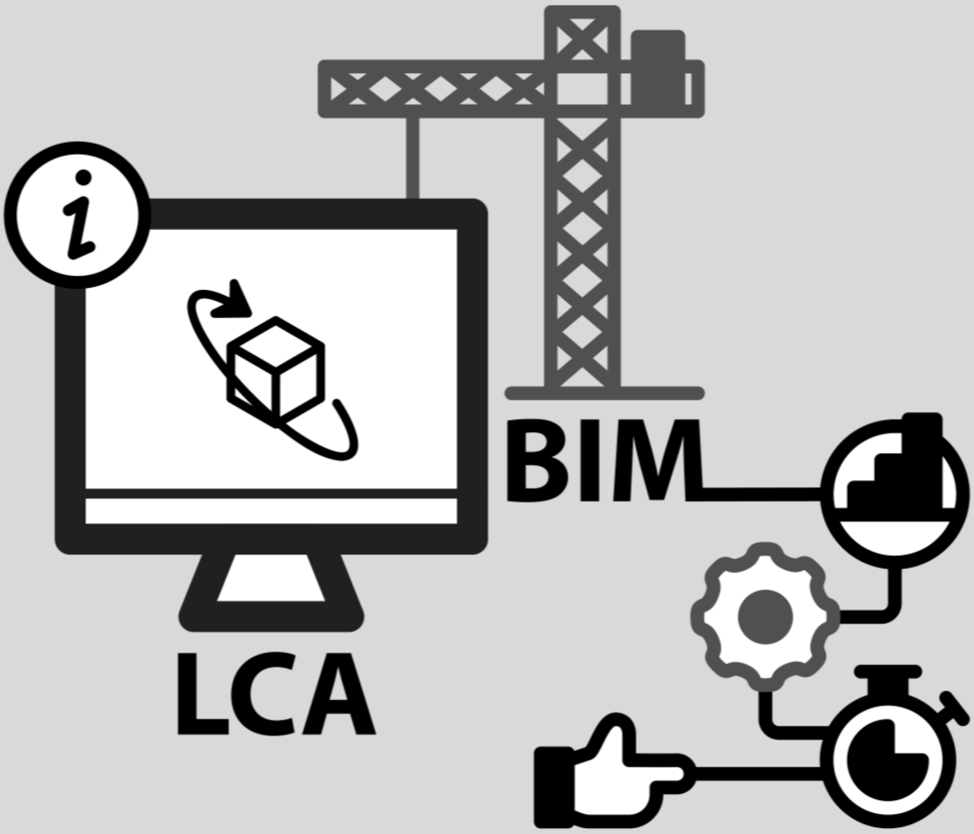

International Energy Agency

LCA-BIM workflows in the design process

A Contribution to IEA EBC Annex 72

June 2023

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Table of content

Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO$_2$eq	CO$_2$ equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
LCCO$_2$	Life Cycle CO$_2$ equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines

ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process

Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Introduction

This report provides an overview of building LCA frameworks and workflow structures and a generalization of the BIM approach in building LCA based on existing solutions.
In this section:

- We introduce a conceptual modular framework that generalizes the typology of systems for building LCA calculation. This can serve as a starting point for designing tools for building LCA.
- We present the results of an internal survey about the calculation structures applied by experts in 10 countries.
- The results of an LCA-BIM exercise performed as a part of the IEA EBC Annex 72 is presented.

1. A modular framework for building Life Cycle Assessment

1.1 Literature review on BIM-LCA

The application of LCA for buildings' environmental assessment has been of increasing interest for more than 5 years in the literature. However most of the papers were focusing on the applicability of BIM for building LCA (Nizam, Zhang, & Tian, 2018) or the extension of BIM (Dupuis, April, Lesage, & Forgues, 2017) to include environmental data. Soust-Verdaguer and colleagues (Bernardette Soust-Verdaguer, Llatas, & García-Martínez, 2017) evaluated the limitations of BIM-based LCA in a comprehensive review. They identified three levels of integration, from which only the third level includes automated data exchange. It is also recognized that this is not the current practice yet. On the other hand Hollberg and Ruth (Hollberg & Ruth, 2016) applied a different approach focusing on the parametric definition and optimization of the model instead of starting from a predefined BIM geometry model. They emphasized the advantages of a parametric model in optimization processes and in early design stages. Other studies were focusing on the data management to bridge the gap between the input requirements of an LCA and the data availability in BIM. Cavalliere et al. (Cavalliere, Dell'Osso, Pierucci, & Iannone, 2018) defined the minimum requirements to include environmental data in BIM models. They developed an "architecture of variables" so that the various parameters can be included depending on the life cycle stage and the available data. Tecchio et al. (Tecchio, Gregory, Ghattas, & Kirchain, 2018) on the other hand described a hierarchic decomposition structure for building model data and proposed a method to conduct LCA even if the data availability is low and the information is underspecified. Further studies applied LCA on case studies (Fernanda, Rodrigues, & Pinto, 2018; Mora, Bolzonello, Peron, & Carbonari, 2019; Soust-verdaguer, Llatas, García-martínez, Carlos, & Cózar, 2018), most of them facilitated some features of BIM (e.g. extract material quantities, visualization of 3D building model, etc.), but they either use some self-developed tools (e.g. Excel spreadsheet) (Soust-verdaguer et al., 2018) or apply commercial plug-ins (Mora et al., 2019) to evaluate the environmental impacts. Both approaches have their limitations that is discussed later in this paper. Some papers were focusing on the evaluation of LCA results through different visualization techniques by using the capabilities of a complex 3D building model (Cerdas, Kaluza, Erkisi-Arici, Böhme, & Herrmann, 2017; Benedek Kiss & Szalay, 2019; Röck, Hollberg, Habert, & Passer, 2018a).

The extended integration of LCA into the design practice (Jusselme, Rey, & Andersen, 2018) and into certification systems (Lee, Tae, Gong, & Roh, 2017) is also in focus of recent research.

1.2 Analysis of existing practice

Based on the literature review, there has been increasing interest in the last few years focusing on the application of LCA in building design practice. However, no common practice or exact specification has been developed yet that facilitates the implementation of different software independent from the used methodology. There is an increasing number of existing software tools, and each of them is based on the own considerations of the developer team.

There are two major different approaches to achieve the integration of LCA into design practice. The first one has evolved from the traditional practice of design that is based on human interaction between stakeholders supported by CAD drawings and text documents (legacy method). Throughout the years, usually import and export possibilities have been developed to speed up manual work, or automation facilitates the fast processing of the input data. This approach has the advantage that full control over the calculations is in hand of the expert. The other approach is the extension of BIM solutions to include LCA in the workflow. This is a more straightforward solution to support information exchange between stakeholders, but on the other hand the exact specification of the calculations is usually out of the hand of the LCA expert if a deep integration is achieved.

The following major requirements can be expressed against a platform for building LCA: *Transparency*, that covers both the background data that the assessment is working with (original source, presumptions, uncertainties) as well as the calculation methodology (bill-of-quantities, replacement, energy demand, etc.). *Interchangeability*, that allows the integration of external solutions such as BIM, and finally *automation*, so that the assessment does not need too much manual work, and as a consequence it might be accessible for a wider audience.

1.3 Definition of the modules of the framework

There is a high need for the integration of Life Cycle Assessment into design practice (Jusselme et al., 2018). However, there are some challenges that need to be faced before implementing such a system. First, the steps of the calculation need to be interchangeable, which means that alternative solutions should be easy to apply for each component. Second, the framework should be interoperable so that many external existing solutions (e.g. BIM software) can be connected to provide input to the calculations. Third, the system should be scalable in terms of the level of detail of the calculation. In an early design stage low information granularity is available, but after construction the calculation can be done based on much more specific information. The framework should be able to handle this problem.

Additionally, there is high focus in current research (Jusselme et al., 2018) on how the calculation can be transparent for externals. This includes the transparency of the source data, the way how the bill of materials is extracted, as well as the consideration of time-specific issues of the environmental impact or the application of generic or manufacturer-specific construction products, etc.

The following concept is based on own considerations concluded from the analysis of the current practice and the requirements of the experts (Jusselme et al., 2018). The structure of a building LCA calculation can be generalized to four major modules: background data, modelling, calculation and postprocessing. The main data flow is represented on Figure 1. In the usual case input is provided to the background data and to the modelling module, however, the background data is established prior to and independently from a single calculation (e. g. database), on the other hand the input to the modelling is given specifically for each calculation (usually manually). Output is provided either directly after calculation (e.g. raw data for further use in other systems), or after post-processing (e. g. visualization). The splitting of the latter two modules is necessary because both incorporate various methodological questions that are independent from each other (e. g. how to account for the replacement of the building elements in the calculation component, or how to aggregate the results into a single indicator in the postprocessing component). Each module consists of components that are described in the following.

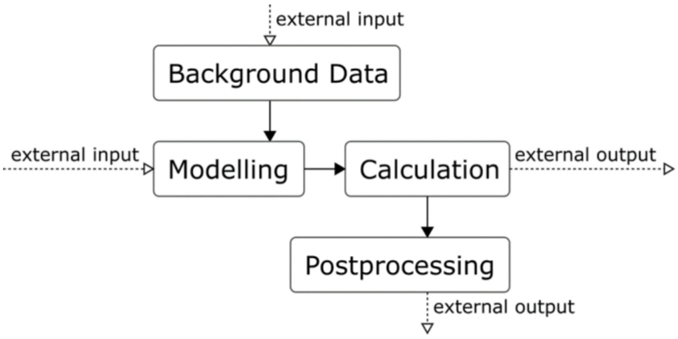


Figure 1 Conceptual representation of the modules and the data flow in the framework

1.3.1 Background Data module

The first separate major module of the framework is called the background data module. This incorporates all the predefined information that is established independently from an assessment case. A component in this module is represented usually by a database (or a table in a simple case) that holds static data. The module includes five optional components (Figure 1).

Material Environmental data

First and most important is the database for material environmental data. There are two different options for this component. The first and most commonly used is a collection of environmental impact information for a wide variety of building materials and for multiple environmental indicators. The impact is quantified on a per mass/volume/piece basis and the characteristics of the impact assessment method (e. g. weighting) is hardcoded into the results. This is called a Life Cycle Impact Assessment (LCIA) database. An example for this case is an EPD database. The other option is a link to a full LCA database, including all unit processes and elementary flows (e. g. ecoinvent processes). In this case the impact assessment method can be later incorporated in the calculation and is not limited to the predefined impact categories. This option also facilitates the update of other related processes in the database (e. g. electricity mix) during calculation.
A further issue related to this component is the inclusion of time- and geographical dependency for the environmental impact associated to the material. Time is an important factor since the reference service period of buildings is most of the times estimated to be longer than the service life of the building components, so replacement is necessary. But the impact associated with the production of the replacement component is going to happen in the future when the available technological circumstances may be different from the current situation. The geographical location is also an important factor since many construction materials are locally produced and may rely on different technology and may use different energy resources (e. g. electricity mix). There are two proposals to overcome this issue: the use of a multi-dimensional database (time and geolocation as the second and third dimension), or the use of an adaptive database, where the environmental impact can be recalculated based on the time and location variables.

Material life cycle data

The second component of this module hold information on the life cycle properties of the materials that are independent from the environmental impact. The most important property is the service life of the materials, but other life cycle related data could be included such as transport and disposal scenario as well.

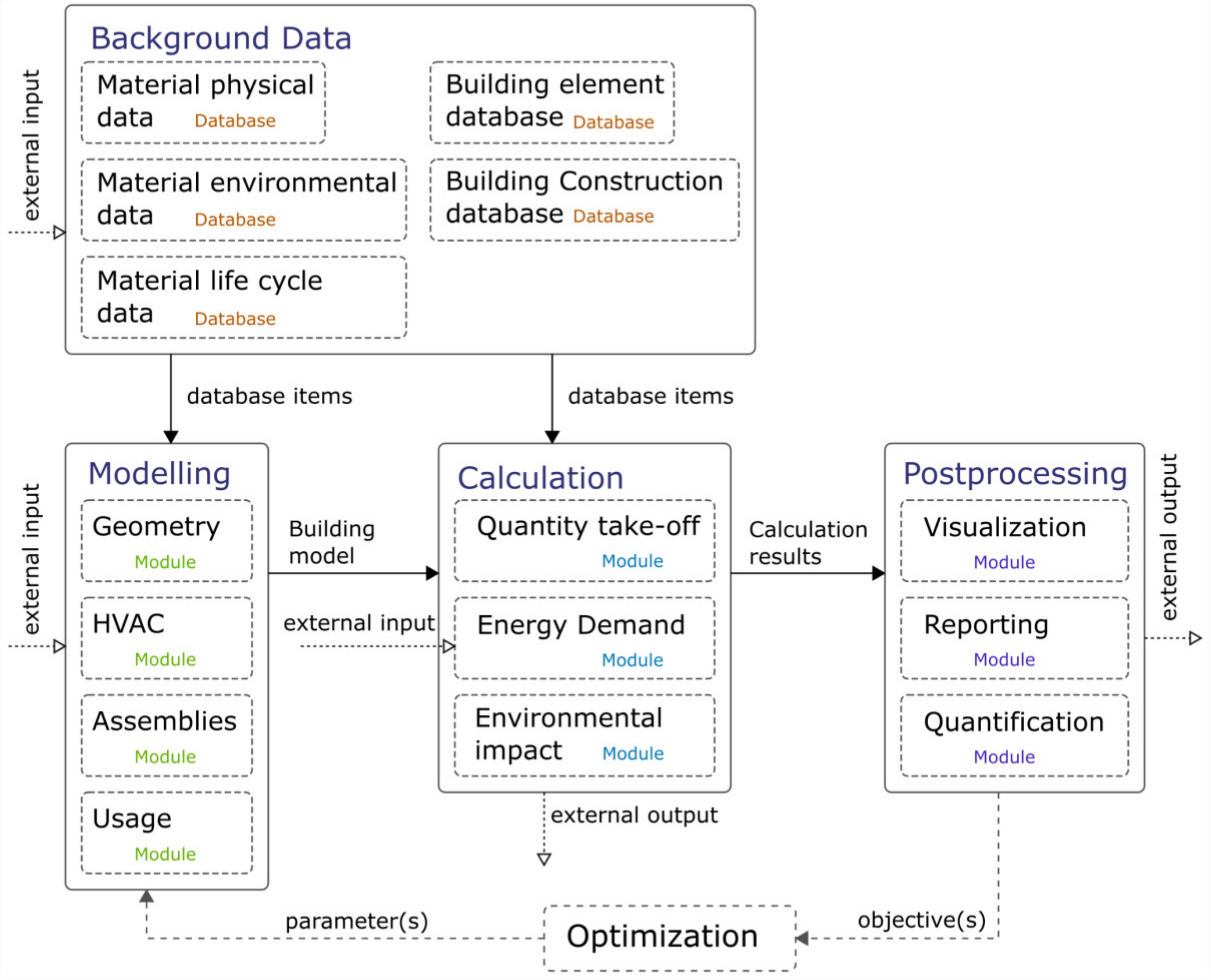


Figure 1. Visual representation of the framework structure and components

Material physical data

The third component incorporates all physical data related to the materials such as density, thermal conductivity (λ) or specific heat capacity. Depending on the type of energy and building physics calculation, the entries can range from a single number to complex temperature- and humidity-dependent functions.
Building element and Building construction data
The last two components facilitate the use of the system in early design stages and for decision support (Röck et al., 2018a). In this case the environmental impact is associated to a construction (assembly of building materials, e. g. masonry structure) or to a building element (multi-layered construction, e. g. wall). The entries in this database can be established prior to the modelling of a building based on industry practice and existing solutions with help of the Material Environmental Database component.

1.3.2 Modelling module

The second major module is called the Modelling. This incorporates all actions that aim to establish a complete building model that is further used in the calculation module. The granularity of the model can range from the single definition of surface areas (without explicit geometry) and construction assemblies to the parametrically defined full model including geometry and HVAC systems. At this point many external applications can provide an input such as BIM capable systems. There are four major modelling components described in the following.

Geometry modelling
This component provides the geometrical information of the model. In a simplified case, the geometry can be defined implicitly by determining surface areas for different types of building surfaces. In a more favourable case, the geometry is defined explicitly in a 3D space. This option supports the 3D representation of the model that can be further used for different LCA visualization options. A third option is the parametrical definition of the building geometry which further includes the optimization possibility.
We can distinguish between two different options for the structure of the geometrical model. The first is based on the practice of energy models, which is usually a surface model divided into thermal zones. The second approach is the exact geometrical modelling of the building elements which is closer to the BIM practice. The advantage of the former over the latter one is the direct input to the energy calculation, but on the other hand there are many simplifications in terms of the bill of quantities (described later). The inverse is true for the "BIM" type of model.

Assemblies
The "assemblies" component describes all composite structures used in the building including the inhomogeneous materials (e.g. masonry made from brick and mortar) as well as the layered constructions (e.g. wall structure). As a further extension, joints can be defined at this point which represent the connection between constructions, and additionally can include geometrical properties too.

HVAC
The last two components of this module are mostly used if an energy calculation is part of the assessment. The "HVAC" component is used to describe technical systems (heating, ventilation, air conditioning, etc.) installed in the building. The level of specification can range from a single general system (e. g. residential gas heating), to very detailed model including all pumps and pipes.

Usage
The last component of this module includes all user-specific information about the building such as occupancy schedules, door and window opening schedules, temperature setpoints, etc. (depending on the type of energy calculation) as well as life cycle related usage information such as renovation cycle, expected type of usage or expected lifetime of the building.
In most of the cases, all the information that is added to the calculation system in the modelling module can be described in a BIM model, however further attention should be paid to the exchange requirements between the database module as well as with the calculation module, an example is provided in the last chapter.

1.3.3 Calculation module

The calculation module provides the heart of the framework. This module is intended to perform all transformations and evaluations that provide all information which is not included explicitly in the model. The module includes three components described as follows.

Quantity take-off
For a building life cycle assessment, the amount of materials used in the building needs to be quantified in order to calculate the embodied impact as well as other related impacts (transport or disposal). Therefore, this component takes the model of the building as input and provides the bill of quantities (list of materials with amounts) for which the environmental impact can be assigned to.

The required calculations are highly dependent on the type of the model. For example, for the "surface" type of model the volume of material used at the joints needs to be added/subtracted depending on the reference line of the surface in the wall construction (innermost/outermost surface). Inhomogeneous constructions (e.g. wooden roof systems) serve as another good example, as the profile used in the construction may be described indirectly (e.g. beam size and axis distance) without explicit geometry.

The type of output can depend on the purpose and type of the result evaluation. For a simple calculation the list of all materials may be sufficient, but if the assessment aims to locate the surface of the model with the highest impact, the provided amounts need to include a placeholder (where it is located in the building).
Energy calculations
The highest impact related to the operational phase of the building is usually caused by the operational energy use. To include this in the assessment, an energy demand calculation needs to be done. The type of calculation can range from a simple seasonal steady-state method to a very detailed energy simulation with an hourly resolution. The type of calculation again highly influences the required input from the model. This component can take further external input that may not be included in the model, for example weather data for the specified location of the building.

LCA calculation
This component is used to allocate the impact to the materials and energy that is used by the building during its life cycle. Also, other life cycle specific calculations are performed here, such as the counting of replacement of the building components as well as the calculation of transport and disposal scenarios for each material. The required output of this component depends on the type of applied postprocessing. This component can include methodological options, for example static/dynamic LCA calculation or localized/general evaluation. A static calculation means that all input data (e. g. environmental impact of brick production per kg) is expected to remain the same during the life cycle of the building. On the other hand, in a dynamic calculation the environmental impacts of the unit products assumed to change over time (e. g. because of the change in the electricity mix), and therefore they need to be updated during calculation. Depending on the available information, the localization of the building may also influence the results of the assessment (through transport distances and available manufacturing technology).

1.3.4 Post-processing module

The structure of the framework implies that all manipulation of the raw output of the calculation module is processed in the postprocessing module. This module aims to provide a range of options to communicate and interpret the results of the assessment. In a simple case the output can be a simple aggregated number based on a corresponding environmental impact indicator. In a more detailed case further visualizations can be performed (in graphs or on the 3D model of the building), examples are available in the literature (Cerdas et al., 2017; Benedek Kiss & Szalay, 2019; Lamnatou, Motte, Notton, Chemisana, & Cristofari, 2018; Röck, Hollberg, Habert, & Passer, 2018b). In some cases (e. g. certification) a full report needs to be created based on the results of the calculation, which can be done with a designated component. These three components cover a good range of possible postprocessing options, but the list is not limited to them.

1.3.5 Optimization

In the favourable case of an automized model generation an optimization module can be introduced in the system. The module takes one or several well quantified outputs of the postprocessing module, they serve as objective(s). It modifies the designated variables of the modelling module which act as parameters in the optimization. This way any optimization algorithm can be implemented in the workflow that is independent from the type of problem (e.g. evolutionary algorithms or other derivate-free algorithms). This structure does not support the application of derivate-based optimization processes, because derivates are not available in the mathematical problem associated with building LCA, since many parameters are discrete and non-numeric (e.g. type of material).

2. Annex 72 assessment workflow survey results

In the framework of this task, we conducted a short survey among the Annex 72 participants to improve our understanding on the calculation procedures and environmental assessment workflows applied in the daily practice. Thirteen partners from 12 countries filled in the survey. The answers are summarised in the following sections. The participating countries were Austria, Canada, China, France, Germany, Hungary, New Zealand, Portugal, Slovenia, Spain, Switzerland and the UK.

The survey contained three major parts. First information was collected about the software types and development options (what existing software is used, what is self-developed in which framework and what is the background data for the calculations). Second, a series of questions was focusing on the structure of the calculations based on predefined modules and information exchange options. Finally, questions were asking the participants about the visualization options available within their framework incl. examples.

2.1 Environmental assessment tools

Figure 3 shows that the 13 respondents are using many different software tools in their practice for environmental assessment. Most participants have different workflows for different purposes, and as a result use different tools or combine these tools in various ways. The application of Excel spreadsheets is widespread: people use Excel either in a standalone way for all the calculations or only for documentation purposes. Five respondents use dedicated LCA softwares with a Graphical User Interface (GUI) and three apply an LCA plug-in for a general CAD software. Many people develop their own LCA calculation in a general framework with scripting capabilites like Grasshopper or in Matlab/ Python. Only one respondent has a complete software package that covers all calculations. None of the respondents use an LCA plug-in for a building energy calculation software, nor a software with Command Line Interface. The questions and possible answers were formulated as:

- What kind of software do you use in your practice for the calculation of Life Cycle impacts?
    - ○ I use a Spreadsheet-based calculation (e.g. MS Excel)
    - ○ I use a plug-in for a general CAD software (e.g. Revit + Tally)
    - ○ I use a plug-in for a building energy calculation software (e.g. DesignBuilder + OneClickLCA)
    - ○ I use a complete software package that covers all calculations
    - ○ I use a standalone software with a GUI (Graphical User Interface) (e.g. SimaPro, OpenLCA)
    - ○ I use a standalone software with a CLI (Command Line Interface) (e.g. BrightwayLCA)
    - ○ I use a general framework with scripting capabilities (e.g. Rhino3D + Grasshopper)
    - ○ I do not use any software

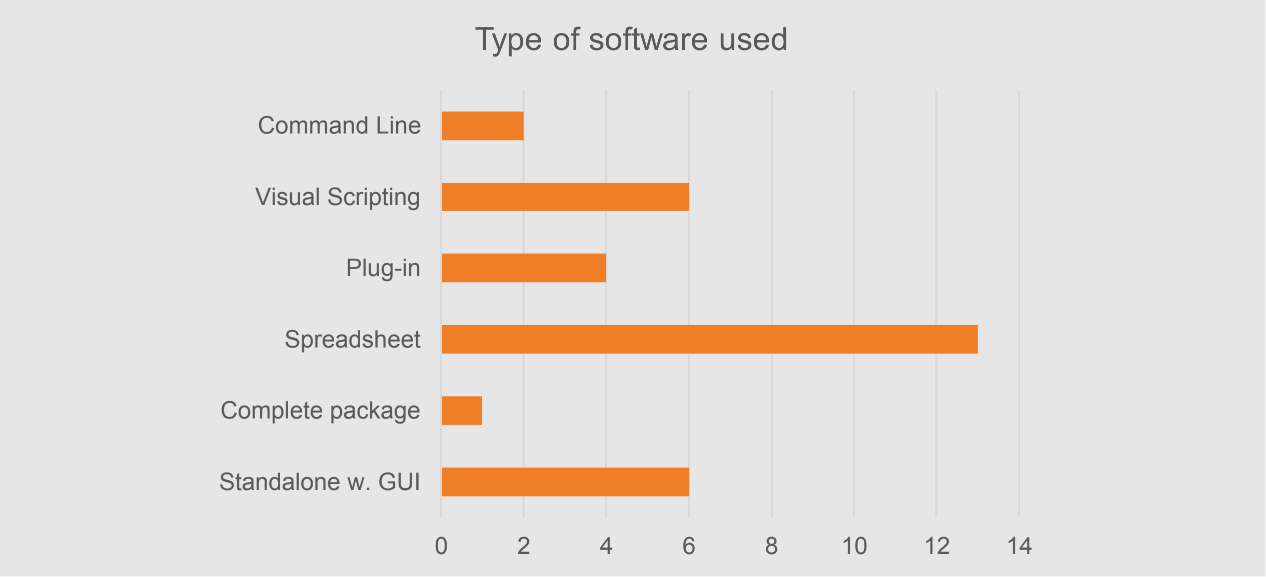


Figure 3: Answers to “What kind of software do you use in your practice for the calculation of Life Cycle impacts?”

As most Annex partners are coming from universities or research institutes, it is not surprising to see that many respondents develop their own LCA software from scratch, either in Excel or in a programming language (Figure 4a). From the 13 answers, only 3 are using independently developed solutions. The popularity of scripting languages shows growing tendency among design professionals, which is also reflected in the survey. 6 respondents use some kind of scripting capability within their framework. None of the respondents are in close contact with the external software developers.

– Do you (your institution) develop your own software (including Excel spreadsheet)?

  ○ Yes, I develop my own software from scratch
  ○ Yes, I use the scripting capabilities of a general framework (e.g. Revit Dynamo)
  ○ No, I use independently developed solutions
  ○ No, but I'm in close contact with the software developers
  ○ No, I don't use any software

Regarding the background LCA database, most respondents use a combination of databases, mostly ready-made LCIA results combined with industry data or LCI databases, such as ecoinvent (Figure 4b). One applies only ready-made LCIA datasets and three only an LCI database. Nobody uses EPD data alone, and two respondents use the combination of datasets without EPDs.

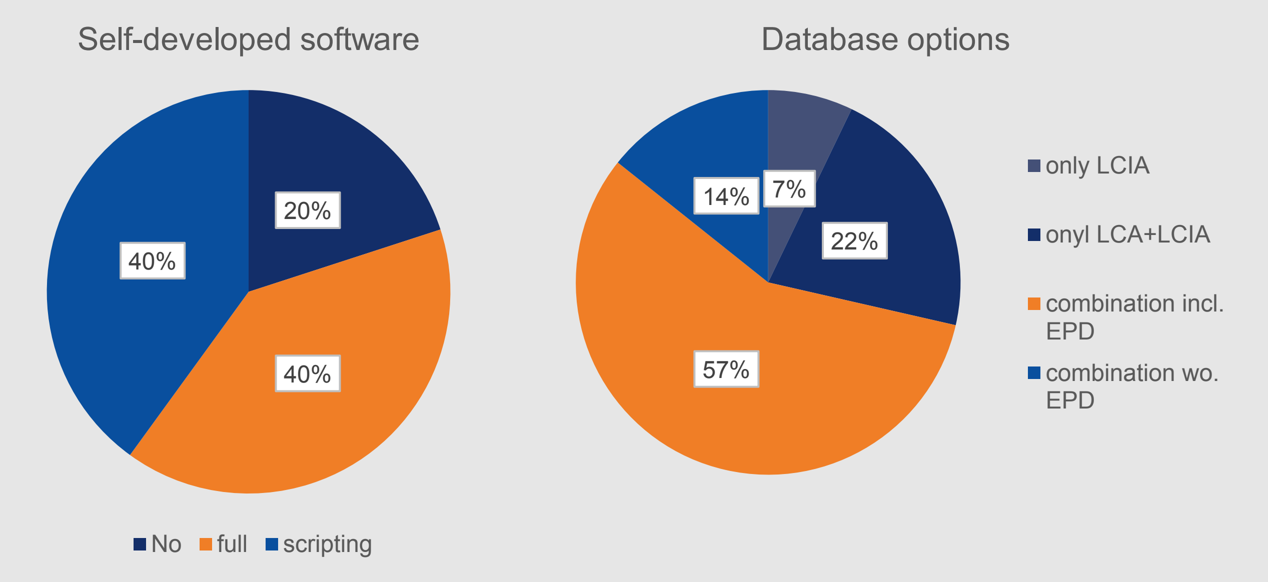


Figure 4: a) Answers to “Do you (your institution) develop your own LCA software (including Excel spreadsheet)? b) Answers to “What kind of LCA data does your software use?”

2.2 Software applied in the environmental assessment workflow

The survey respondents use a wide range of software tools and their different combinations in their building environmental assessment workflow (Table 1). Only one uses a complete package that is capable of geometry modelling, energy calculation and LCA calculation in one environment (Pleiades – Equer). For geometry modelling, the mostly applied tools are commercial CAD softwares, such as Revit, Rhino and Archicad. LCA calculations are usually carried out in dedicated LCA softwares, plug-ins or self-developed Excel spreadsheets (see previous section). For energy calculation a number of dynamic building energy simulation tools are applied (e.g. EnergyPlus, DesignBuilder, IESVE). In addition, for developing own tools, data analysis tools and programming packages are applied. The popularity of Revit and Excel is clearly visible on Figure 5.

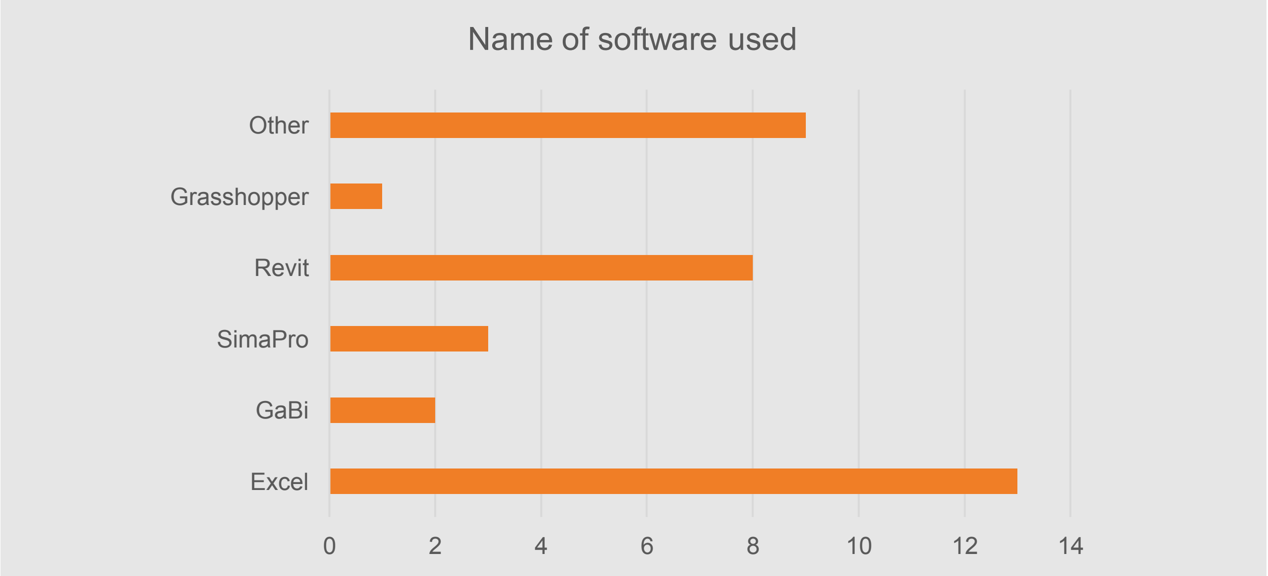


Figure 5: Answers to “Do you (your institution) develop your own LCA software (including Excel spreadsheet)?

Table 1: Name of software tools used by the survey participants in their assessment workflow

Software type	**Software name**
Geometry, BOM	Revit, Rhino, Archicad, Autocad, DESITE BIM
LCA calculation	GaBi, SimaPro, OpenLCA, Tally, Caala, Bombyx, eLCA, liNear, own Excel tool (SBToolPT, LCAQuick, US_LCA_Building Systems, KESZ_LCC_LCA)
LCA data	ecoinvent database, SBToolPT, EPDs
Energy calculation	IESVE, EnergyPlus, DesignBuilder, Trnsys, PhPP, EnEV, HULC
Map	Google maps
Data analysis	Presto
Programming	Excel, Python, Matlab, R, Grasshopper, Dynamo
Complete package	Pleiades - Equer

2.3 Calculation structure and workflow

Based on the responses, we created figures to represent the calculation structures and workflows applied by 13 of the partners (Figure 6-19). The calculation workflow includes the following steps in all cases: geometry definition, material definition, bill of materials, life cycle impact calculation and documentation. Four workflows include an optimization algorithm and one a manual Excel-based optimization. Energy calculation is not included in four cases.
The figures show the connections between the different modules of the calculation, with a blue arrow showing automatic and red arrow showing manual information exchange. It is clear that most of the workflows are not completely automatic and a lot of manual interventions are required from the user. As detailed in the previous sections, most partners use different tools for most purposes.

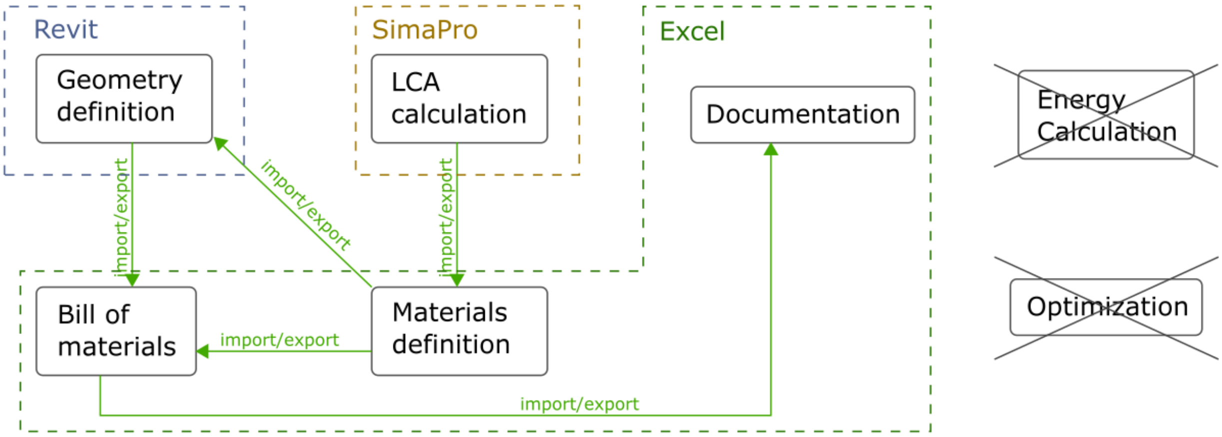


Figure 6: Calculation structure (Austria)

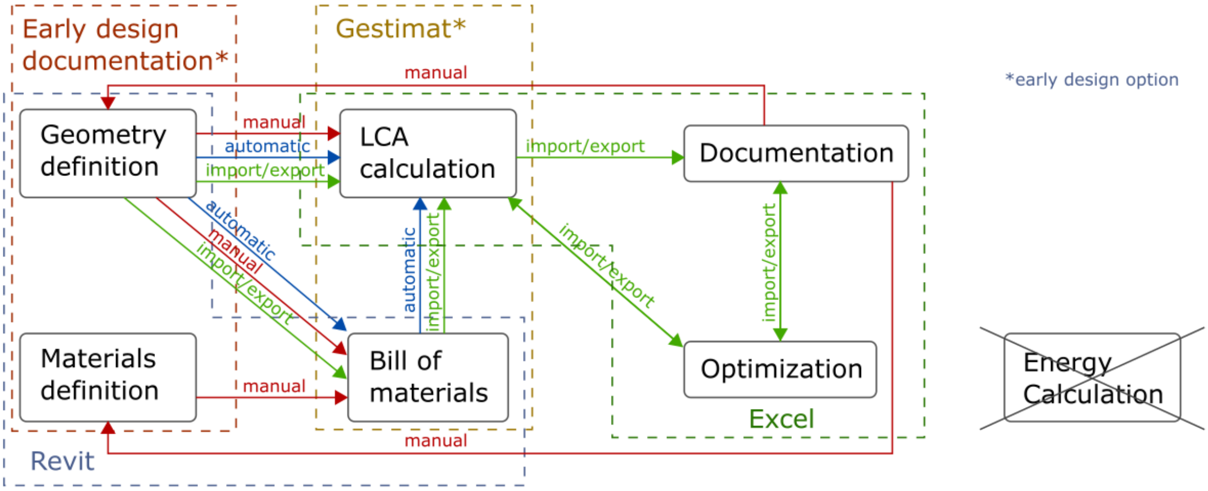


Figure 7: Calculation structure (Canada)

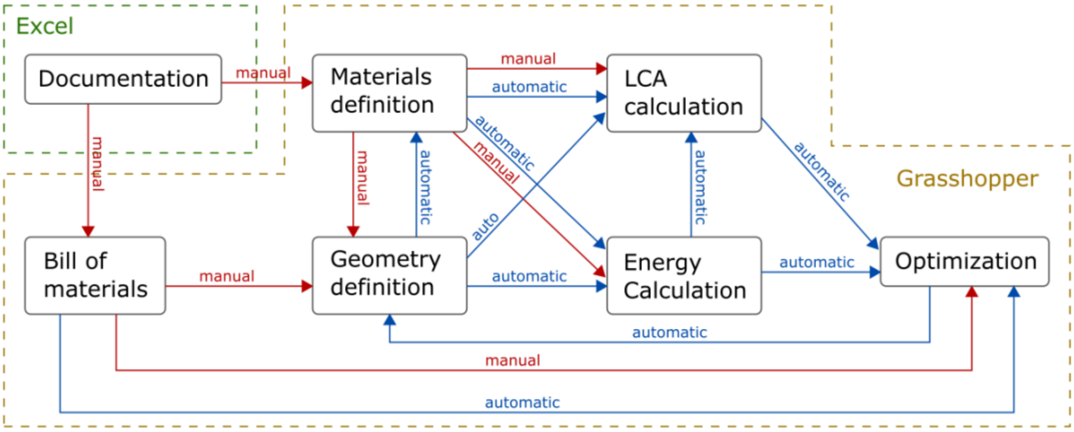


Figure 8: Calculation structure (China)

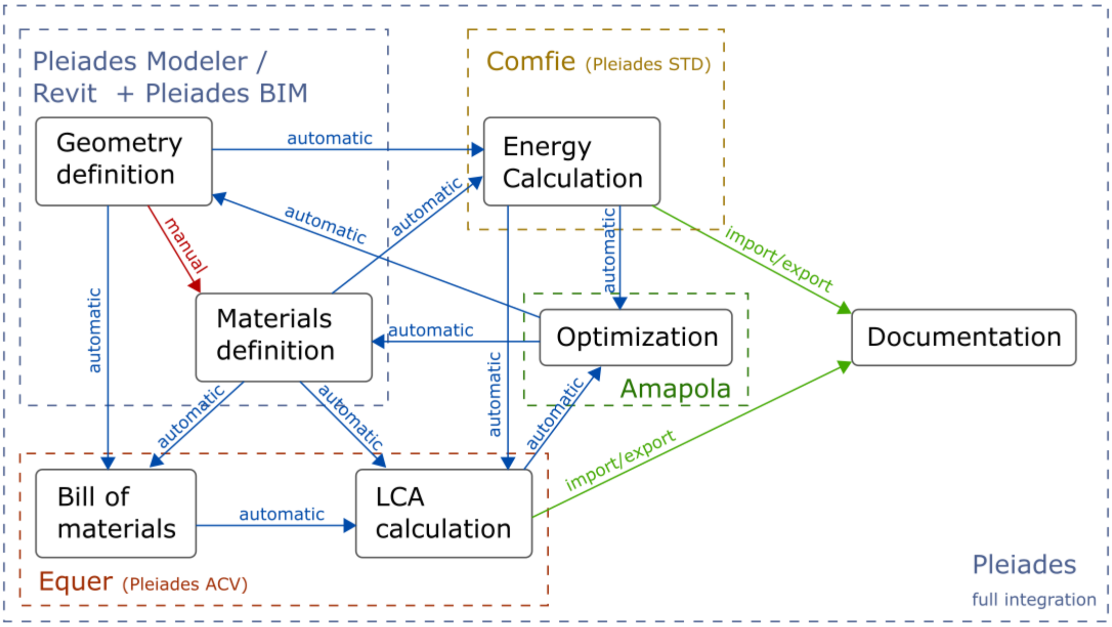


Figure 9: Calculation structure (France)

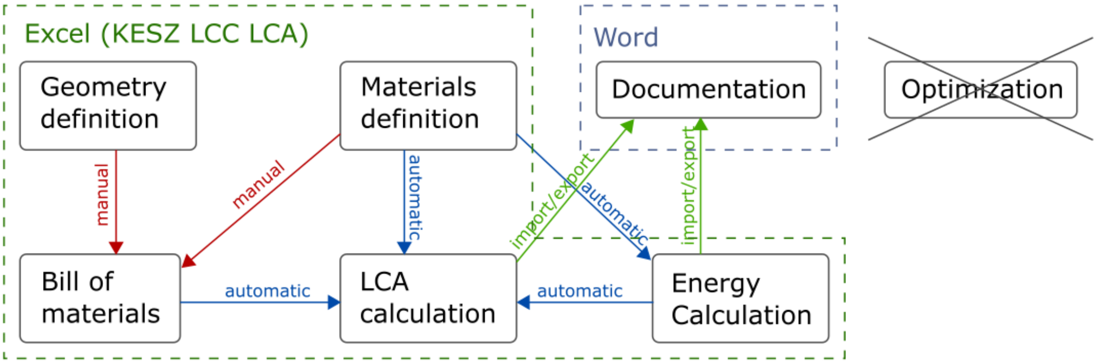


Figure 10: Calculation structure (Hungary1)

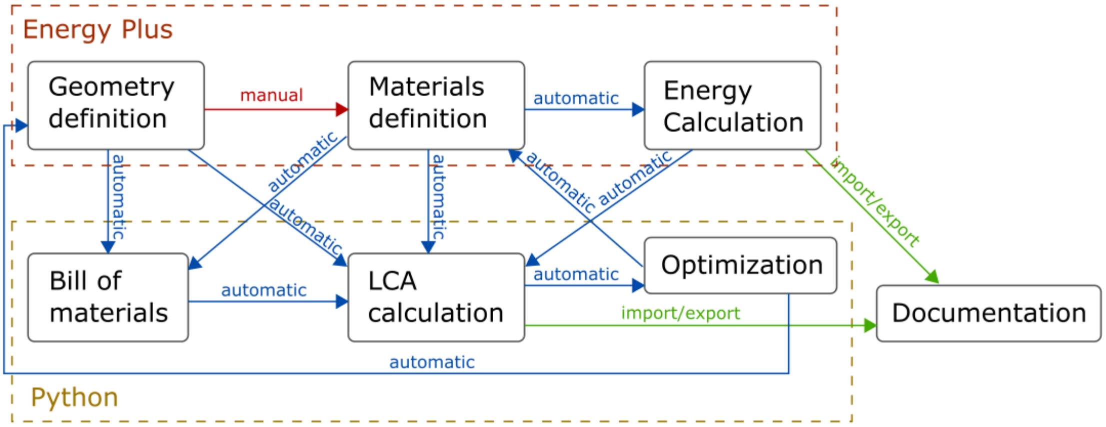


Figure 11: Calculation structure (Hungary2)

The workflow in Figure 11 has been applied in research projects primarily focusing on optimization (B. Kiss & Szalay, 2020; Szalay & Kiss, 2019). Therefore, the automatized data exchange as well as the integrated energy calculations have been prioritized during the development of the framework.

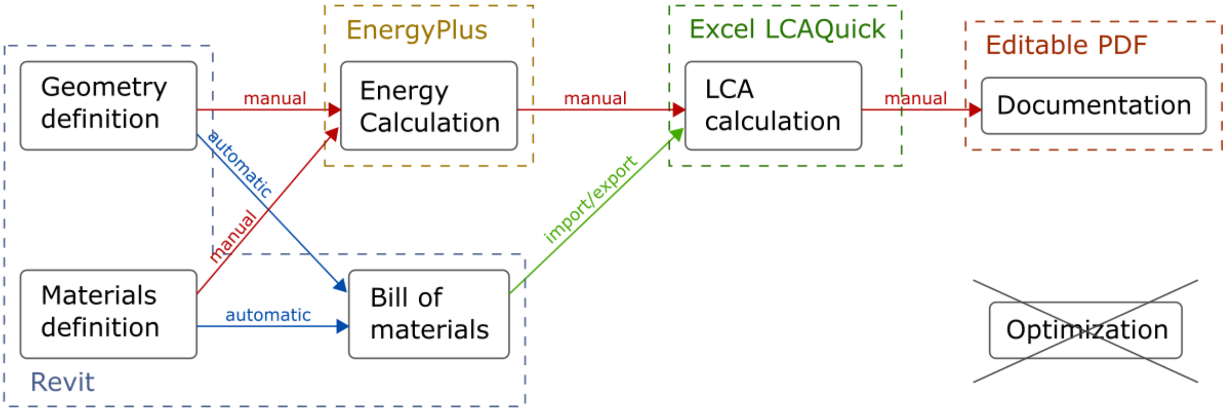


Figure 12: Calculation structure (New Zealand)

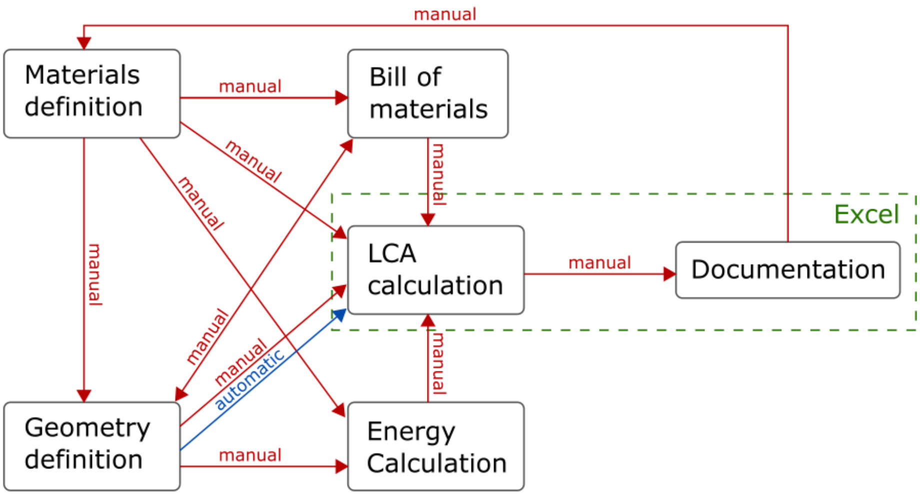


Figure 13: Calculation structure (Portugal 1)

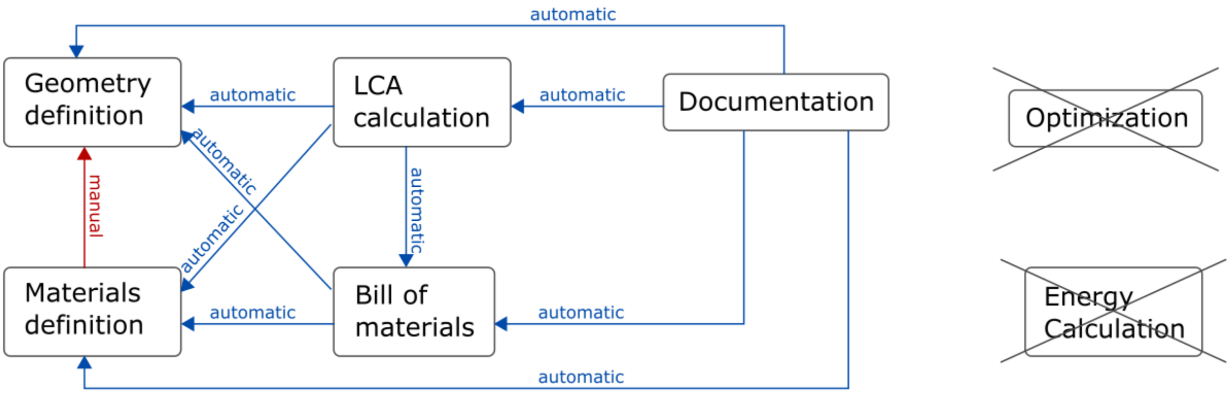


Figure 14: Calculation structure (Portugal 2)

Figure 14 shows a workflow with BIM integration in the primary focus (Santos, Aguiar Costa, Silvestre, & Pyl, 2020). Although optimization and energy calculation are not part of the workflow, a deep automatized connection between the other components are presented using the capabilities of BIM.

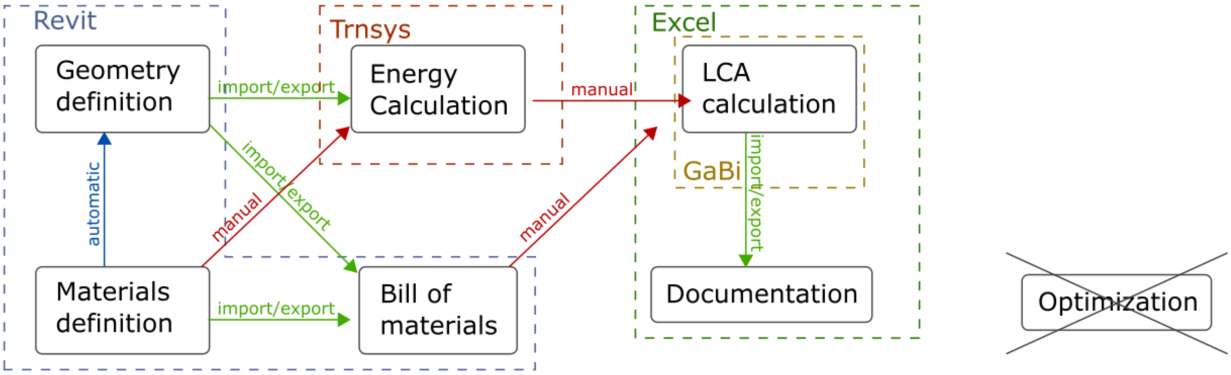


Figure 15: Calculation structure (Slovenia)

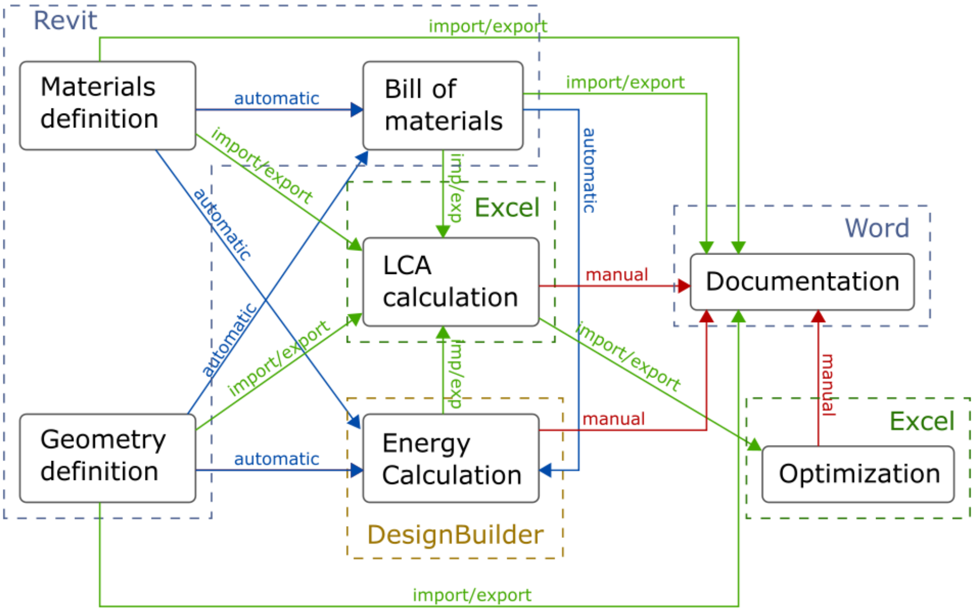


Figure 16: Calculation structure (Spain 1)

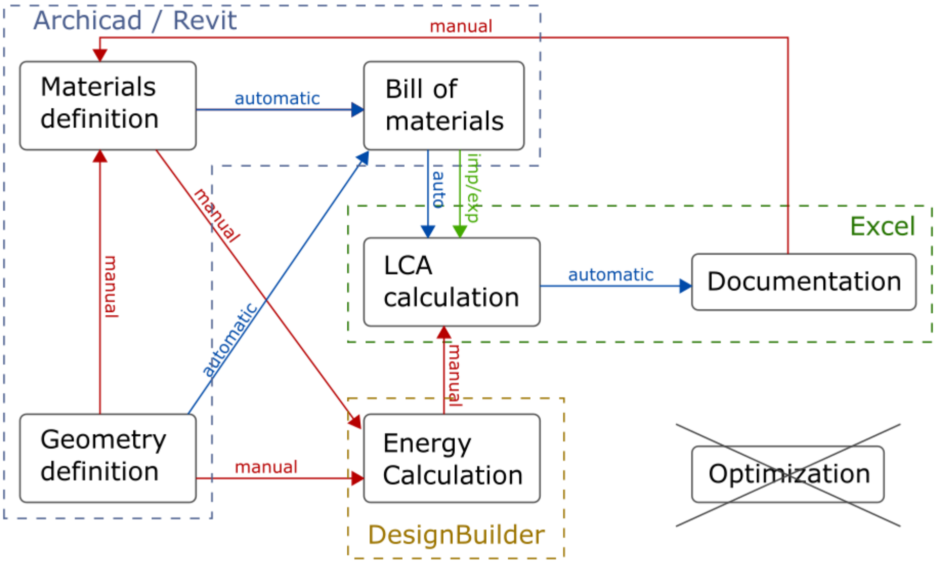


Figure 17: Calculation structure (Spain 2)

The workflow depicted in Figure 17 has been verified in the publications (Soust-verdaguer et al., 2018; B Soust-Verdaguer, Llatas, & Moya, 2020). Although, the optimization with algorithms is not performed, the comparison of different alternatives (solutions) is proposed. The different alternatives are modelled in different BIM files and link to an excel file where the LCA calculation is developed and the information about the compared alternatives is shown.

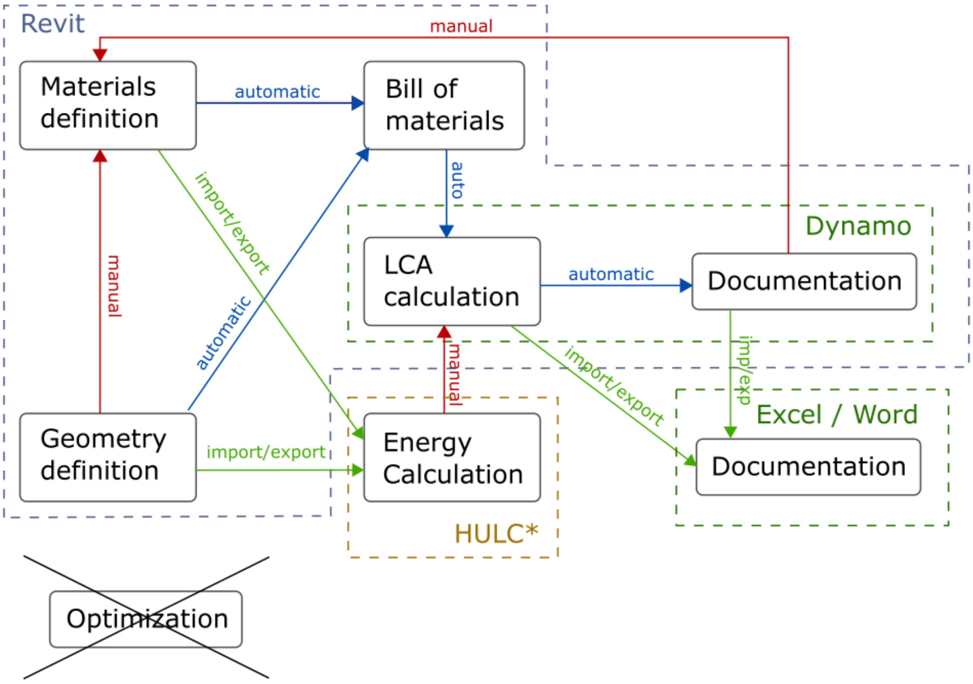


Figure 18: Calculation structure (Spain 3)

Figure 18 shows an additional proposed workflow that is under verification in an ongoing research project. It proposes an automatic solution that can help to obtain the LCA results inside the BIM environment (Revit).

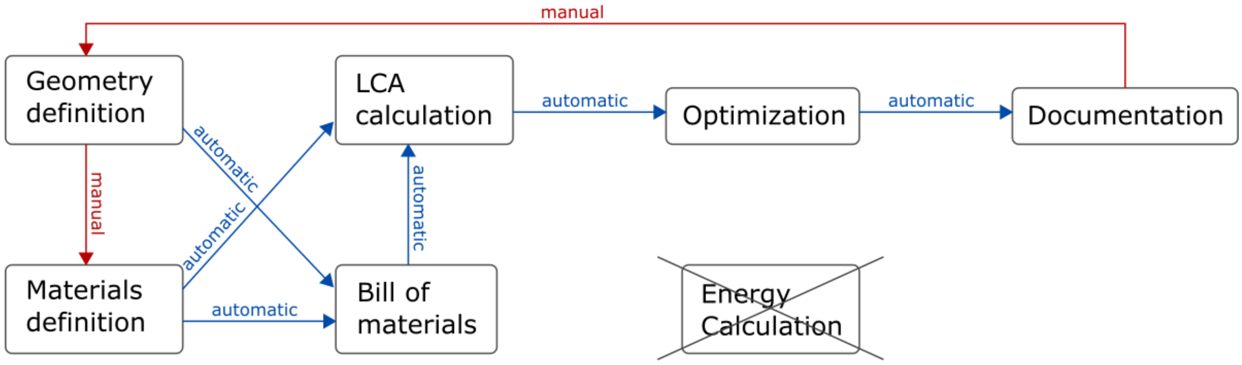


Figure 19: Calculation structure (United Kingdom)

The calculation structure is very specific for each country, but there are some similarities. A common solution integrates The *Geometry definition*, *Material definition* and *Bill of materials* in Revit (Spain, New Zealand, France, Canada, Austria, Slovenia). Most of the times, the *LCA calculation* is fulfilled in Excel, in some cases as a dedicated solution including some extra features (*Documentation, Optimization*). For *Energy calculation* a common solution is to apply EnergyPlus/DesignBuilder when simulation is used. In some cases, optimization is included, but not necessarily with a fully automated, integrated system. In general, all experts use multiple software to do building LCA calculations and there is only one country (France) that applies a full integrated software suite for all the modules.

Finally, the structures can be classified into four categories (Table 2) with decreasing integration/automation in the following order:

- *Specialized standalone software (with BIM integration)*: Externally or internally developed software solutions for multiple modules, including BIM integration (either with a plugin to existing BIM software or standalone BIM module). This is the most advanced solution, but it is usually the result of long-term software-development strategies, which is only feasible with industry participation.

- *Modules based on (visual) scripting*: The automated workflow is enabled through (high-level) visual scripting interfaces of existing software (e.g. Rhino Grasshopper or Revit Dynamo) or other scripting languages (e.g. python, Matlab). This option is more available for a wider community including engineers, designers, and researchers, and therefore it is becoming more and more popular.
- *BIM with further spreadsheet-based calculations:* The workflow is based on existing BIM solutions (e.g. Revit), where the required data can be extracted for further evaluation in a spreadsheet-based system. This option is the most flexible regarding external models since the required data export does not require any special rules to be applied to the model. Therefore, this method is often used with real design projects.
- *Manual (spreadsheet-based) calculation structure*: In this (legacy) case all input data need to be added manually to a spreadsheet, where all the necessary calculations are done. This requires time-consuming work, but the data is fully controlled and transparent in return.

Table 2: Classification of calculation structures

Type of calculation structure	**Participant**
Specialized standalone software (with BIM integration)	CA, FR
Modules based on (visual) scripting	CN, HU2, UK, ES
BIM with further spreadsheet-based calculations	NZ, ES, SI, AT, PT
Manual (spreadsheet-based) calculation structure	HU1, PT

2.4 Visualization options

The third part of the survey focused on the different output (visualization) options to evaluate the results of the LCA calculations. Figure 21 shows the available options regarding result granularity within the frameworks of the participants. Most of the frameworks apply all three impact decomposition options, but the most common is the “impact per building element”. Impact per life cycle stage is also available in 13 tools, and impact per individual materials is available in 11 tools.

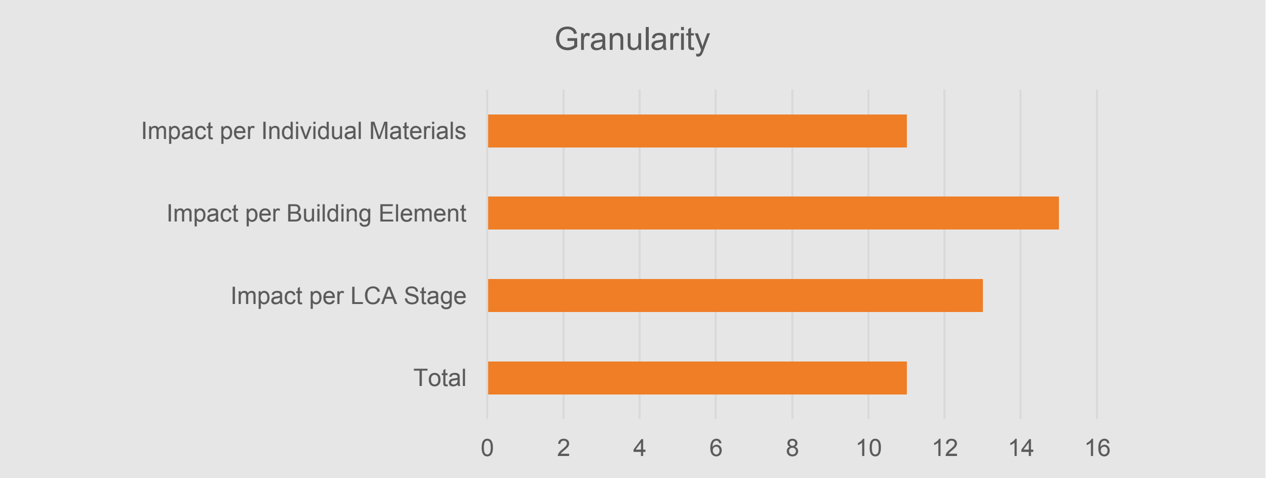


Figure 20: Available result granularity in the respondents’ frameworks

Depending on the framework type the result data might be exported as raw data, or reports are generated. Figure 21 summarizes the answers for the question “What kind of results can you retrieve from your software?” All respondents can retrieve charts and single numbers. Six of the participants have the ability to produce building-based visualizations, and seven can export the raw data for further evaluation.

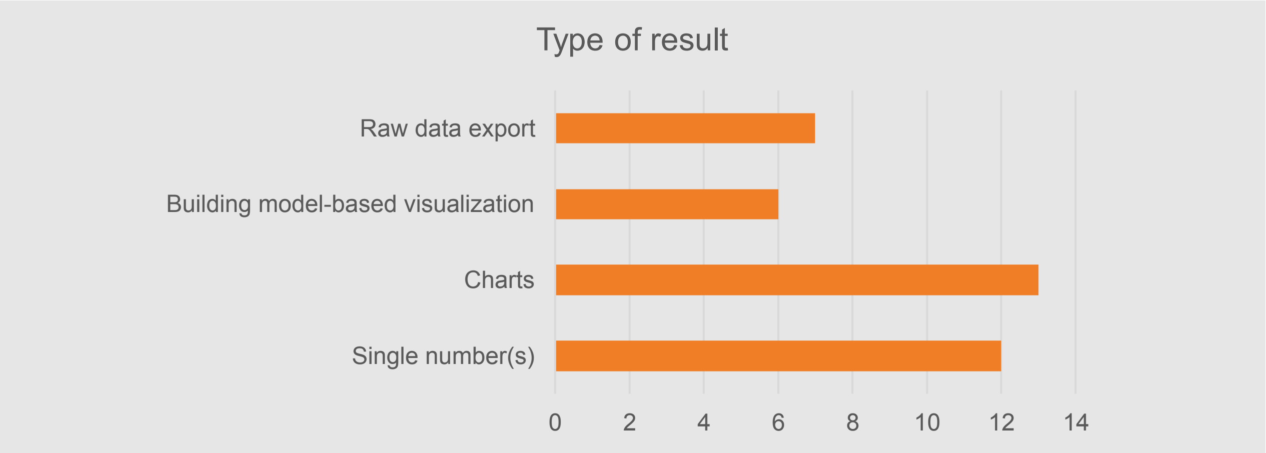


Figure 21: Available type of result in the respondents' frameworks

The next question targeted the focus of the visualization. Figure 22 shows that most of the times, visualization is used for "contribution analysis" or "comparison of design options" but "building optimization and "decision support" is also marked as one of the most frequent focus areas of visualizations. Only four respondents use the visualizations for certification.

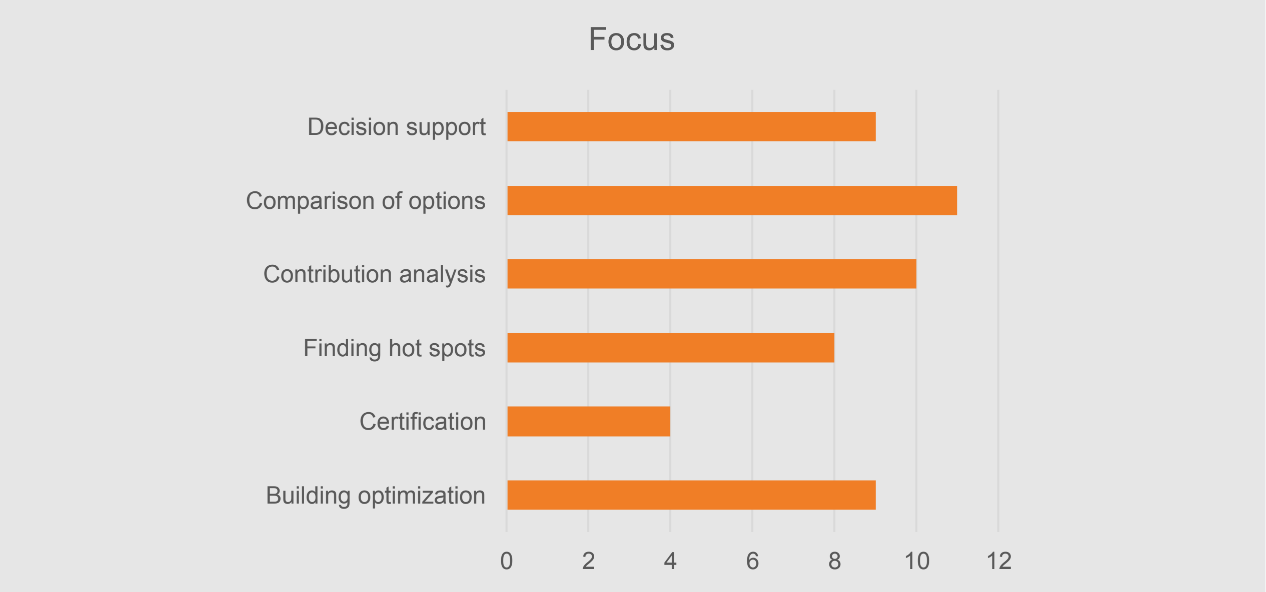


Figure 22: Responds to the question: "What is the focus of the result communication?"

Finally, the different available visualization types were collected. For each type three options ("available in my software", "I'm interested in", and "I'm using") were possible.

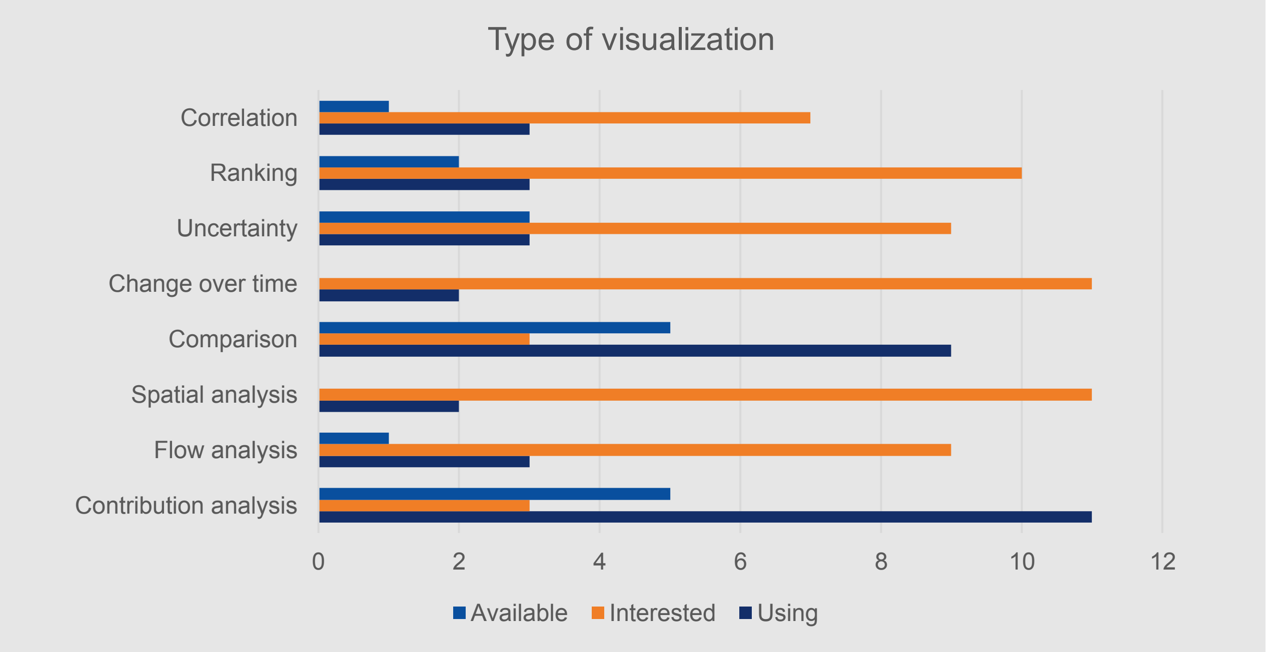


Figure 23: Responds to the question: “Which type of visualization are you using in practice, and which would be interesting for you?”

On Figure 23, it is visible that there is high interest about various types of visualizations, especially with focus on “change over time” and “spatial analysis”. A more detailed description of the characteristics of different visualisation types can be found in the paper published by Hollberg et al. (2021).

Despite of the high interest, these two types are used by only 1-1 of the respondents. The most used and most available options are the “contribution analysis” as well as the “comparison”.

More details about the different visualisation types and the

3. Annex 72 assessment LCA- BIM exercise

3.1 Aim of the LCA-BIM exercise

The objective of this exercise was to investigate how BoQ exported from BIM can influence the outcomes of LCA and how these environmental impacts can be mitigated. The process of extracting BoQ out of the model has potential for causing a problem, therefore identification of possible sources of errors is also included in this study.

3.2 The workflow of the LCA-BIM exercise

The whole work was divided in following parts: (1) survey among participants from various countries; (2) collection and comparison various workflows and BoQ results; (3) identification and summarization potential sources of errors in used workflows; (4) summarization key suggestions for developing BIM models.

Eight partner countries took part in this experiment: Austria, Canada, Czech Republic, France, Germany, New Zealand, Slovenia, Spain and Switzerland.

In the first part an online survey was developed to collect the information about the workflows and the software programs used to perform this exercise. It follows the logical framework in the study of Kiss at al, which was used to collect the typical workflows used in in separate countries. The goal of the survey was to improve the understanding of the calculation procedures and environmental assessment workflows applied in the exercise.

The answers of the survey were analyzed and based on them harmonized flowcharts were created to represent the workflows of each country in a uniform way. An example of the survey is shown below:

AUSTRIAN WORKFLOW: The Austrian Workflow is so far completely manual, which offers detailed insight into the generated Bill of Quantities and will therefore act as a reference workflow in this study.
The list of materials, sorted by building family and type, is exported directly from the Revit model and is further processed with a python script to fit into the workflow template provided. As the BIM-model did not have information on the exchange rates for different building parts, those were added manually according to DIN 276. The excel sheet is then used to summarize the amounts per material/transportation distances per vehicle type for the supported modules.
The workflow allows the calculation of the emissions of the production and construction phase, the use phase except for B5 and the End-of-Life.

The full Life Cycle Inventory is then entered into SimaPro using the respective processes. The results can easily be exported to excel and further analyzed with various tools.

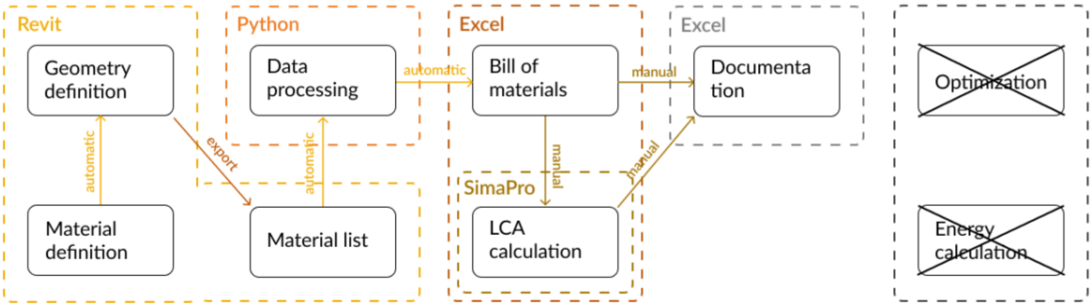


Figure 24: Austrian workflow in the LCA BIM exercise

In the second step the case study was distributed among the participants and the Bill of Quantities were collected. The case study represents the university building Inffeldgasse 13, PZ02 (Fig 25). PZ02 is part of the "Produktionstechnikzentrum", a complex consisting of several buildings, used as laboratories and administrative purposes of the TU Graz (Innenfeldgasse 13, 2021).

Figure 25: Austrian workflow in the LCA BIM exercise

Each of the study participants used a different type of workflow which is typical in their country. Participants of this study were requested to deliver: (1) edited model with all the data needed for BoQ exported from the model (e.g., classification system); (2) BoQ in the spreadsheet format; (3) form describing used workflow.

In the third step the identification and summarization potential sources of errors in used workflows was performed. The materials, the volumes and the errors were identified.

Material analysis

Since a detailed BoQ was not available for all submissions, only submissions from the following participants could be compared: CZ, DE, ES, NZ, SL. From these submissions, 55 missing materials were identified. The missing materials were investigated, and the following reasons were found. For two materials the source could not be identified. List of all errors is shown in Table 3.

1. Material ignored (n=14). The single material was deliberately not considered for the calculation.

2. Material not decomposed (n=39). The composite material which includes the single material was not decomposed. The single material was not considered explicitly.
3. “0” thickness (n=10). Some layers in the model have a thickness of 0. In some cases, this meant that the material was not included in the calculations.
4. Not identifiable (n=2). The reason for the missing single material could not be identifiable.
5. Included in a similar material (n=1). The quantity of the material was joined together with a similar single material.

Table 3: List of all errors

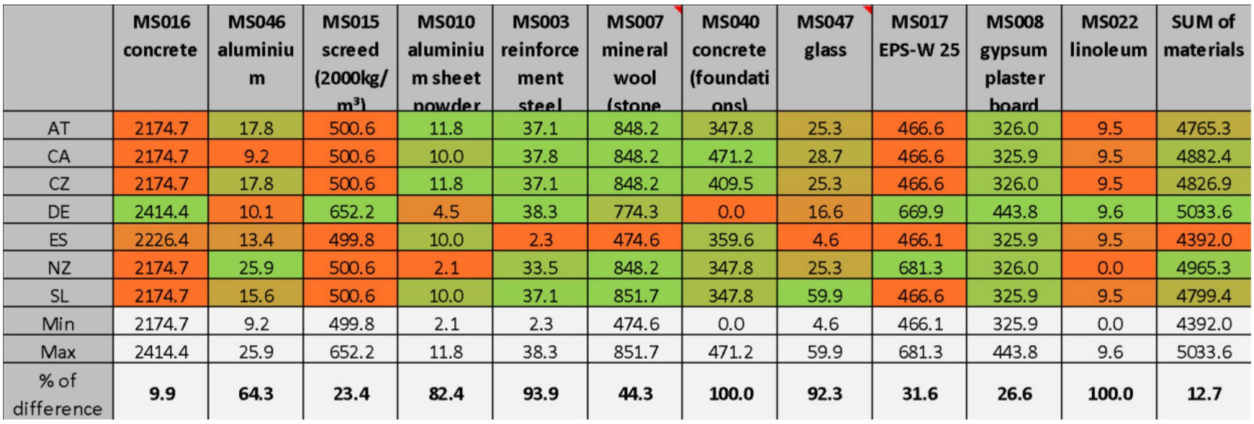
Material	AT	CZ	ES	NZ	SL	Material	AT	CZ	ES	NZ	SL
MS001 mineral wool (glas wool) WF (50 kg/m³)	✓	✓	✓	✓	✓	MS002 concrete (outer walls)	✓	✓	∑	✓	✓
MS004 gypsum plaster (1300 kg/m³)	✓	✓	✓	-	✓	MS003 reinforcement steel	✓	✓	∑	✓	✓
MS005 plastic-modified bitumen coating	✓	✓	✓	✓	✓	MS006 concrete (roofs)	✓	✓	∑	✓	✓
MS008 gypsum plaster board (700kg/m³)	✓	✓	✓	✓	✓	MS007 mineral wool (stone wool) WD	✓	✓	✓	✓	✓
MS009 waterproofing membrane PE root-proof	✓	✓	✓	✓	✓	MS011 concrete (inner walls)	✓	✓	✓	✓	✓
MS010 aluminium sheet powder coated	✓	✓	✓	✓	✓	MS016 concrete (floors)	✓	✓	∑	✓	✓
MS012 vapour retarder PE	Ø	✓	✓	✓	Ø	MS033 steel sheet	✓	-	∑	?	?
MS013 XPS-G (80-100mm (43kg/³m))	✓	✓	✓	✓	✓	MS036 mineral wool (stone wool) WF (40kg/m³)	✓	=	∑	✓	✓
MS014 bound split fill	✓	✓	✓	✓	✓	MS040 precast concrete	✓	✓	∑	✓	✓
MS015 screed (2000kg/m³)	✓	✓	✓	✓	✓	MS045 concrete (columns)	✓	✓	∑	✓	✓
MS017 EPS-W 25	✓	✓	✓	✓	✓	MS046 aluminium	✓	✓	✓	✓	✓
MS018 EPS-T 650	✓	✓	✓	✓	✓	MS047 glas	✓	✓	∑	✓	∑
MS019 parquet	✓	✓	✓	✓	✓	MS048 argon	✓	✓	∑	✓	∑
MS020 EPS-T 1000	✓	✓	✓	✓	✓	MS049 air	✓	-	∑	-	∑
MS021 polyisobutylene rubber (930 kg/m³)	✓	✓	✓	-	✓	MS050 cement	✓	✓	∑	∑	✓
MS022 linoleum	✓	✓	✓	✓	✓	MS051 water	✓	✓	∑	∑	✓
MS023 terrazzo	✓	✓	✓	-	✓	MS052 water based paint	✓	✓	∑	∑	✓
MS024 tilework (2300 kg/m³)	✓	✓	✓	✓	✓	MS053 glass wool	✓	✓	∑	∑	✓
MS025 liquid foil (protective coating)	Ø	✓	✓	-	Ø	MS054 glass tissue	✓	✓	∑	∑	✓
MS031 rubber granulate mat	Ø	✓	✓	✓	Ø	MS055 water based glue	✓	✓	∑	∑	✓
MS032 timber (525 kg/m³)	✓	✓	✓	✓	✓	MS056 cement bound wood wool	✓	✓	∑	-	✓
MS037 PE liner	Ø	✓	✓	✓	Ø	MS057 epdm	✓	✓	∑	-	∑
MS038 bitumen coating	✓	✓	✓	✓	✓	MS060 polyamide	✓	✓	∑	∑	∑
MS039 PE membrane LD (920kg/m³)	Ø	✓	✓	✓	Ø	MS061 stainless steel	✓	✓	∑	∑	∑
MS041 vapour barrier aluminium	✓	✓	✓	✓	✓	MS062 brass	✓	✓	∑	∑	∑
MS042 extensive roof greening	✓	-	✓	-	-	MS040 concrete (foundations)	✓	✓	✓	✓	✓
MS058 solid chipboard	✓	✓	✓	-	✓	MS049 steel	✓	✓	∑	-	✓
MS059 steel	✓	✓	✓	✓	✓						

✓ single material present - material ignored ∑ material not decomposed Ø 0 thickness = included in a similar material ? not identifiable

Volume analysis

The volumes of the following materials were examined: MS016 concrete (floors), MS046 aluminum, MS015 screed (2000kg/m³), MS010 aluminum sheet powder coated, MS040 concrete (foundations), MS003 reinforcement steel, MS007 mineral wool (stone wool) WD, MS047 glass, MS017 EPS-W 25, MS008 gypsum plaster board (700kg/m³), MS022 linoleum. The results are summarized in the Table 4

Table 3: Volume comparison



	MS016 concrete	MS046 aluminium	MS015 screed (2000kg/ m³)	MS010 aluminium sheet powder	MS003 reinforcement steel	MS007 mineral wool (stone	MS040 concrete (foundations)	MS047 glass	MS017 EPS-W 25	MS008 gypsum plaster board	MS022 linoleum	SUM of materials
AT	2174.7	17.8	500.6	11.8	37.1	848.2	347.8	25.3	466.6	326.0	9.5	4765.3
CA	2174.7	9.2	500.6	10.0	37.8	848.2	471.2	28.7	466.6	325.9	9.5	4882.4
CZ	2174.7	17.8	500.6	11.8	37.1	848.2	409.5	25.3	466.6	326.0	9.5	4826.9
DE	2414.4	10.1	652.2	4.5	38.3	774.3	0.0	16.6	669.9	443.8	9.6	5033.6
ES	2226.4	13.4	499.8	10.0	2.3	474.6	359.6	4.6	466.1	325.9	9.5	4392.0
NZ	2174.7	25.9	500.6	2.1	33.5	848.2	347.8	25.3	681.3	326.0	0.0	4965.3
SL	2174.7	15.6	500.6	10.0	37.1	851.7	347.8	59.9	466.6	325.9	9.5	4799.4
Min	2174.7	9.2	499.8	2.1	2.3	474.6	0.0	4.6	466.1	325.9	0.0	4392.0
Max	2414.4	25.9	652.2	11.8	38.3	851.7	471.2	59.9	681.3	443.8	9.6	5033.6
% of difference	**9.9**	**64.3**	**23.4**	**82.4**	**93.9**	**44.3**	**100.0**	**92.3**	**31.6**	**26.6**	**100.0**	**12.7**

In the further step a detailed analysis of the potential sources of errors is developed. The most common sources of errors are the following:

- Composite material decomposition incorrect/partial (n=4)
- Combination of similar materials (n=3)
- Rounding error (n=3)
- Wrong application of factor for decomposition (n=2)
- Generic factor for decomposition (n=2)
- Wrong factor for area to volume (n=2)
- Transposed digits (n=1)

3.3 The recommendations of the LCA- BIM exercise

Based on the analysis a decision making process was developed that should help the practitioners to chose the right process for obtaining the BoQ. The positive (PROs) and negative (CONs) aspects of each decision are highlighted in the Fig 26.

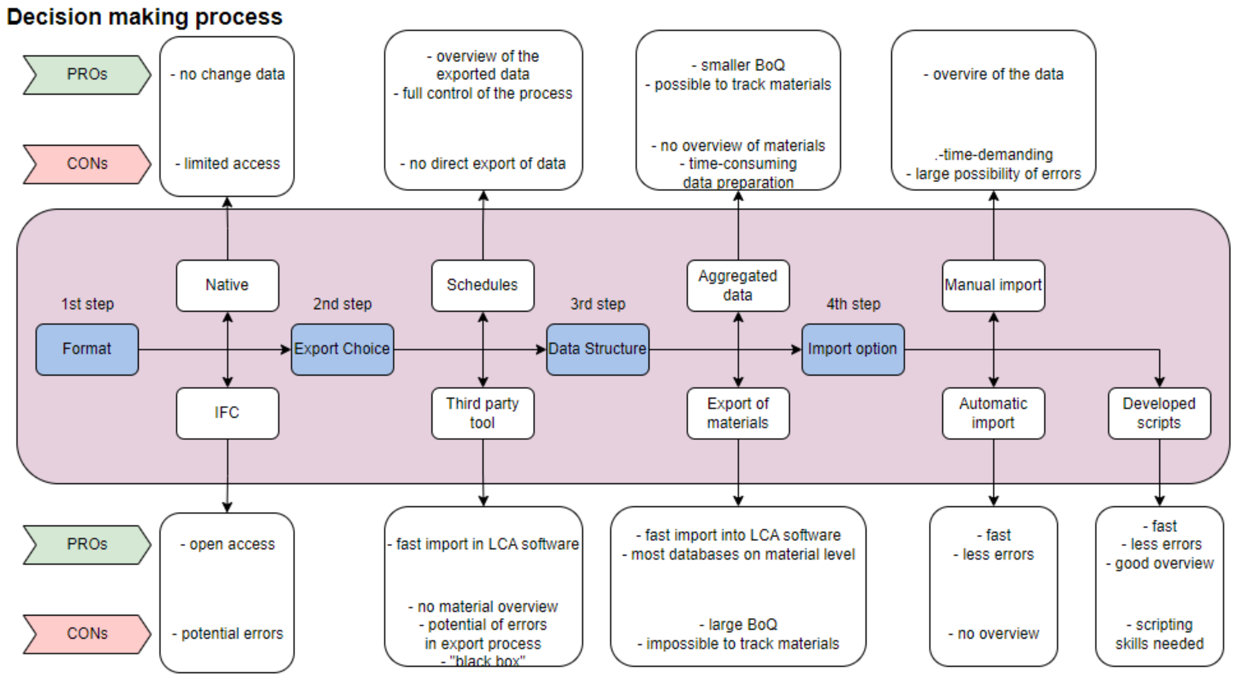


Figure 26: Austrian workflow in the LCA BIM exercise

Additional to the selection of the right process, it is especially important:

- the composed materials are handled with additional care (right materials and right amount of them is taken into the analysis),
- that we do not make any errors when we transforming the units,
- that similar materials are not combined,
- that we are careful to not make rounding errors, transpose the digits.

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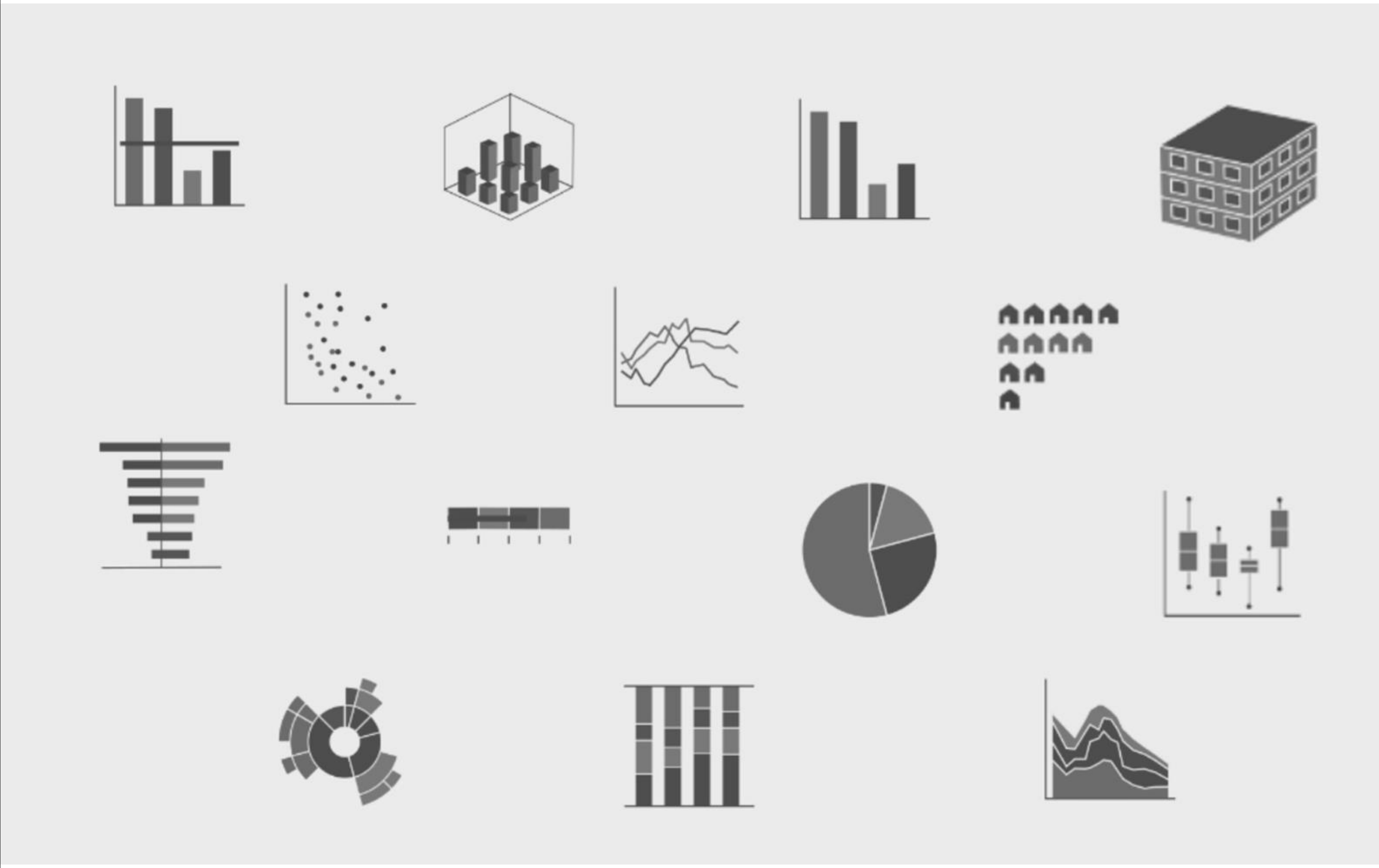
Visualising LCA results in the design process

A Contribution to IEA EBC Annex 72

April 2023



International Energy Agency

Visualising LCA results in the design process

A Contribution to IEA EBC Annex 72

April 2023

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Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_2eq	CO_2 equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House

ST1	Annex 72 Subtask 1: Harmonised methodology guidelines
ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financer, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes

Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process
Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Life Cycle Assessment (LCA) is increasingly used for decision-making in the design process of buildings and neighbourhoods. Therefore, visualisation of LCA results to support interpretation and decision-making becomes more important. The number of building LCA tools and the published literature has increased substantially in recent years. Most of them include some type of visualisation. However, there are currently no clear guidelines and no harmonised way of presenting LCA results. In this report, we review the current state of the art in visualising LCA results to provide a structured overview. Furthermore, we discuss recent and potential future developments. The review results show a great variety in visualisation options. By matching them with common applications of LCA we provide a structured basis for future developments. Case studies combining different kinds of visualisations within the design environment, interactive dashboards, and immersive technologies, such as virtual reality, show a big potential for facilitating the interpretation of LCA results and collaborative design processes. The overview and recommendations presented in this report provide a basis for future development of intuitive and design-integrated visualisation of LCA results to support decision-making.

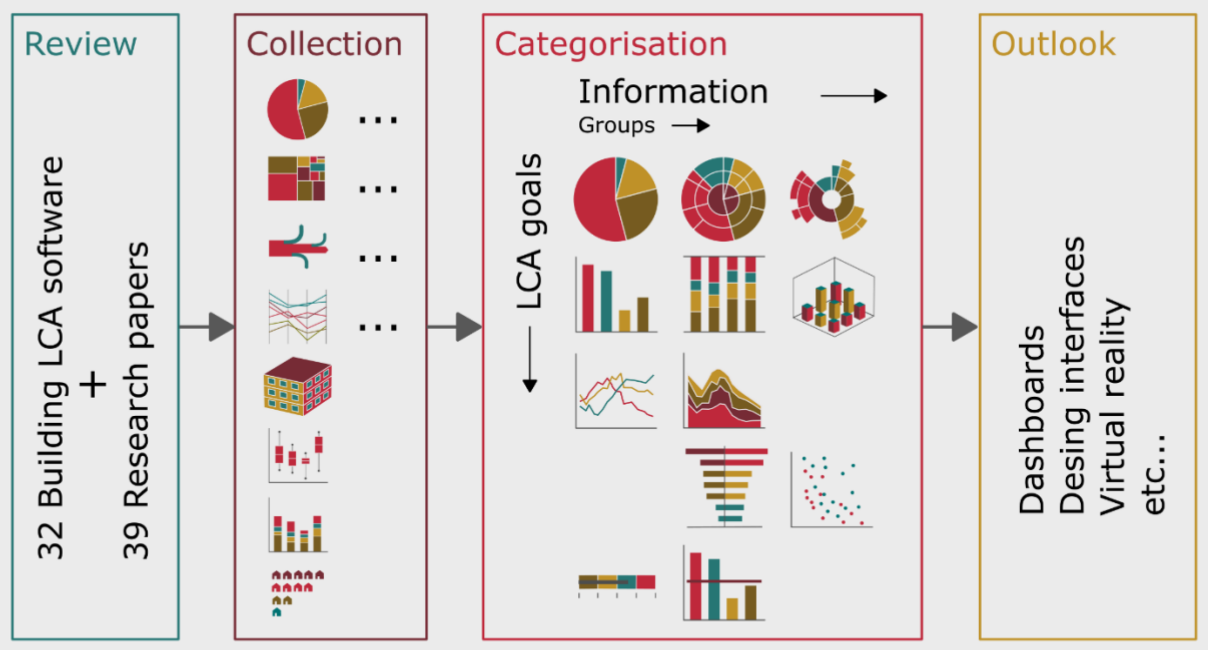


Figure 1: Graphical abstract

A publication was created at the same time as this background report. The publication can now be found under: Alexander Hollberg, Benedek Kiss, Martin Röck, Bernardette Soust-Verdaguer, Aoife Houlihan Wiberg, Sebastien Lasvaux, Alina Galimshina, Guillaume Habert. 2021. "Review of visualising LCA results in the design process of buildings" *Building and Environment*, 190, 107530, https://doi.org/10.1016/j.buildenv.2020.107530

Introduction

Need for visualisation of LCA results

Many aspects of the goal and scope phase of Life Cycle Assessment (LCA), such as functional unit or reference study period are defined in the national standards or the guidelines for Green Building Certification Systems. Furthermore, it is defined which environmental indicators should be provided as results, e.g., Sweden will only make Global Warming Potential (GWP) mandatory, while Switzerland looks at GWP, the Primary Energy Non-Renewable Total (PENRT) and a single-score indicator called *Umweltbelastungspunkte* (UBP). This indicator is specifically calculated for Switzerland based on the method of ecological scarcity (Frischknecht & Knöpfel, 2013). The DGNB system uses five environmental output indicators, and PENRT and the Primary Energy Renewable Total (PERT) in addition.

However, the form in which the LCA results should be communicated is not clearly defined. The EeBGuide (Wittstock et al., 2012) includes guidelines and templates for reporting of the results, but they aim at LCA experts. Furthermore, the European Joint Research Centre published a guideline for the interpretation of results for LCA experts (Zampori et al., 2016).The American Institute of Architects issued an extensive guide for building LCA, but only mention a benchmark comparison as support for interpretation (Joshi et al., 2010). There are no guidelines for interpretation of LCA results addressing a wider range of stakeholders involved in the building design.

As a result, the interpretation phase of LCA is still considered complex (Malmqvist et al., 2011; Zanghelini et al., 2018). Previous studies in this field (Cerdas et al., 2017; Frankl & Rubik, 2018) provide evidence that one of the obstacles to the broader use of LCA is the difficulties in the understanding and communication of results. Often the LCA results are not comprehensible for stakeholders such as policy and decision makers, although previous research demonstrates that the integration of life cycle aspects in the design process can improve decision-making involving non-experts (Baldassarri et al., 2016). In current practice, LCA results of buildings are used for certification and documentation, but barely to improve the building design or fundamental decisions related to the intended project (J. Basbagill et al., 2013; Wittstock et al., 2009). To use LCA results as basis for decision-making in the design process, the results have to be interpretable. At the same time, the interaction and cooperation between the different stakeholders and the exchange of relevant data and information between them should be promoted (Baldassarri et al., 2016).

Here, a particular emphasis on suitable visualisations can provide the necessary information and decision support. The importance of visualisation of LCA results has been widely discussed in the literature (Cerdas et al., 2017; Otto et al., 2003a; Sala & Andreasson, 2018). Visualisation techniques are usually used to communicate and analyse data and information for a different purpose. For example, they can make information easy to explore and more usable when the volume of information grows (Shneiderman, 1996). The field of visualisation is closely related to the visual analytic field, which intends to reduce complex cognitive work and is "required to process large data sets towards enabling an informed decision-making" (Cerdas et al., 2017). The application of visualisation techniques has been expanded to different disciplines and domains, especially to those that involve an extensive use of data such as LCA. Hence, regarding the potential of the visual analytics to improve the understanding of LCA results, visualisation can facilitate efficient human cognitive capabilities by amplifying cognitive sensors, reducing search/lost, enhancing the pattern recognition and supporting easy reasoning, among others (Rio et al., 2019). Considering the different application areas of LCA (e.g. EPDs, design optimisation, or legislative decisions taken by policymakers), each application focuses on different stakeholders, and each one has its information requirement (Cerdas et al., 2017). As such, visualisation is key for decision support (Sala & Andreasson, 2018), but also optimisation of the design during the design process (Attia et al., 2013).

In 1996, Shneiderman defined a type by task taxonomy based on the common visual information seeking mantra “overview, zoom and filter, details on demand” (Shneiderman, 1996). If provide at the right time and in the right form, visualisations can support the information seeking. If designers cannot intuitively match the results with the architectural design then there is a tendency that the analyses performed will not affect the actual design decisions (Jensen et al., 2018). In contrast, if the visualisations are meaningful to designers, significant improvement of the environmental impact can be achieved (John Basbagill et al., 2017) and collaboration in interdisciplinary design teams is improved (Landgren et al., 2019).

While the need for visualisation is evident and often stated in the literature, few researchers have focussed on developing visualisations for building LCA results. These few studies such as (John Basbagill et al., 2017; Houlihan Wiberg, Lovhaug, et al., 2019; Kiss & Szalay, 2019; Otto et al., 2003b; Martin Röck et al., 2018b) propose novel types of visualisation often dedicated to one type of stakeholder involved in the design process of a building. These studies compare a few visualisation types, but a comprehensive review of visualisation of building LCA results is currently not available. Although the number of building LCA tools has been growing recently, they provide limited visualisation options. Currently, there is no harmonisation between the ways of visualising building related LCA results neither in practice nor in academia. This makes it especially difficult for practitioners and non-LCA expert to make use of the LCA results.

Objectives

This report provides a review the current state of the art in visualising LCA results for buildings. Visualisations used in current building specific LCA software tools and the scientific literature are collected and clustered to provide an overview. This overview should provide a starting point for improved visualisation of LCA results and harmonisation. Furthermore, the potential of using the visualisation of LCA results in design interfaces that support decision-making in the design phase of buildings are discussed.

1. Method

The method consists of three parts. In the first part, typical applications for LCA in the design process are defined. In the second part, visualisation options from both building LCA software tool and the scientific literature in the field are collected and analysed. The building LCA tools are used to cover the state of the art in practice while the literature is analysed to review the current research. In the third part, categories to classify the different visualisation options found in the review are defined.

1.1 Definition of applications for LCA in the design process

Six typical applications for LCA are defined with relation to visualisations.

1. Identification of hotspots
   Many LCA studies are conducted to identify so-called hotspots that are responsible for a large share of the environmental impact. This hotspot analysis can be conducted at different levels of

detail. In the case of buildings, the aim is often to identify building elements (walls, roof, etc.), individual materials, or life cycle phases with a large environmental impact.

2. Comparison of options for design improvement

   If the aim is to use the LCA results to improve the design or decide between several design alternatives, a comparison becomes crucial. The comparison can be carried out on different levels of detail, for example comparing different buildings, different building elements or building materials.

3. Correlation, uncertainty, and sensitivity analysis

   The analysis of the correlation of parameters or indicators becomes important when the aim is to optimise a design towards different criteria, see for example (Kiss & Szalay, 2020). The correlation analysis is often applied to support design guidance to make appropriate choices based on a large set of options instead of only a few. Uncertainty analysis often refers to the uncertainty inherent to the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty, and data variability (ISO 14044, 2006). Furthermore, sensitivity analysis is often carried out in the interpretation phase to test the influence of modelling choices, such as system boundaries, allocation approaches or the choice of specific datasets (Guo & Murphy, 2012), on the overall assessment results.

4. Benchmarking

   Especially with regards to fulfilling thresholds defined in national building regulations or GBCS, benchmarking becomes very important. Additional benchmarks could include national averages, previous projects or the average within a building portfolio. Furthermore, global targets, such as the 2 degree target or global frameworks, such as the planetary boundaries (Rockström et al., 2009) or 2000 Watt society (Jochem et al., 2004) can be used as benchmarks.

5. Spatial distribution

   This aspect relates to the aim of identifying where environmental impacts are caused. Therefore, maps are often used to highlight the spatial distribution of the impact, e.g. (Houlihan Wiberg, Wiik, et al., 2019).

6. Temporal distribution

   To identify when environmental impacts are caused, often charts plotting the development of the impact over time are used, e.g. over the lifetime of the building (Eberhardt et al., 2019).

1.2 Analysis of existing visualisation options

The main research question for the review is "Which types of visualisation of LCA results are used when and for which stakeholders during the design process of buildings?" To answer this main research question, three sub-research questions are used for the review of both the building LCA software and the scientific literature.

1) Which design stage is targeted?
2) Which are the intended stakeholders?
3) Which visualisation types are used?

The currently most commonly used LCA software tools for buildings are reviewed. The list of tools is based on previous reviews (Cavalliere, 2018; Alexander Hollberg, 2016). The list was updated and extended based on input from the IEA EBC Annex 72 researchers. The final list includes 39 LCA software tools dedicated explicitly to buildings or building components. The majority of tools have been developed for whole building LCA, but most of them also allow for the assessment of individual components. It cannot be guaranteed that all building LCA tools are included, but we are sure to have covered the most common ones based on the expert feedback. We therefore assume the analysed tools to be sufficient to provide an overview of the field. The information about the tools was collected based on free demo versions, experts' feedback using the tools and freely available online material such as tutorials, demo videos, and handbooks. Tools that were not published or where there was no information accessible were excluded from the review. Seven of these tools were excluded from the analysis due to lack of information leading to 32 analysed tools.

To identify different visualisation approaches presented in scientific literature, we conducted a systematic literature review, based on the protocol for Systematic Literature Review (SLR) and including additional studies via the 'snowball' approach (Higgins & Green, 2008; Wohlin, 2014). As the aim is to identify studies addressing the visualisation of LCA aspects related to buildings and construction, we conducted the systematic search using the keyword string: "(LCA OR life cycle assessment OR life cycle analysis) AND (building OR construction) AND (visualization OR visualisation)". The search was performed via 'ScienceDirect', searching the selected terms in the papers' “abstract, title or author-specified keywords”. Documents identified through the SLR protocol were screened based on their title and abstract and excluded if out of scope (e.g. if they were not addressing buildings or construction). The database search was conducted in April 2020. The addition of snowball studies continued until submission of the manuscript.

The SLR provided 32 papers. 16 papers were removed from the review as the main focus was not LCA of buildings. 23 papers were added following the snowball approach and using expert knowledge. Primarily, literature focusing on visualisation methods and development of new LCA methods or tools was added. Secondly, case studies were added that provide novel or unique types of visualisations. As there are a large number of building LCA case studies using at least one type of visualisation, it is impossible to include all. Therefore, the snowball approach was stopped when no new types of visualisations could be found. Finally, 39 papers were included. Although we selected literature on visualisation method or tool development first, most of the analysed papers present case studies. Eleven papers aim at providing visualisation methods or examples for building LCA. The majority of analysed papers are scientific journal papers followed by peer-reviewed papers in conference proceedings. One book was added as grey literature, because this type of visualisation could not be found in the peer-reviewed literature.

1.3 Definitions for classification

Definition of design stages

Design stages in the planning process of buildings are usually defined differently by different stakeholders and in different national contexts. Furthermore, no common definition is used in the analysed literature to further specify the intended design stages. Therefore, we only differentiate between an early and a detailed design phase and use the joint model proposed in Figure 2: . We define the early design phases as including the strategic definition, preliminary studies and the concept design phase, typically including sketches and the competition design (phases 0 to 2). Often there is a break in the tools and sometimes the design team after this phase. The detailed design phase describes the development of the design until the completion of the building, including the building permit application, tendering, construction drawings and the construction itself (phases 3 to 6). The operational and end-of-life phase are significant considering the life cycle. However, the user influence in the operational phase is very big and often unpredictable. Monitoring completed buildings would allow stakeholders typically involved only in early design phases to learn from previous decisions. Nevertheless, stages 7 and 8 are excluded here.

Design stages definition	Strategic definition 0	Preliminary studies 1	Concept Design 2	Developed Design 3	Technical Design 4	Manufacturing and Construction 5	Handover and close out 6	Operation and management 7	End of use, re-cycling 8
Core Objectives	Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, Construction and supervision	As-built documentation, hand over, comissioning and testing	Facilities Management and Asset Management, Evaluation and improvement of building performance	Decommissioning of the building, deconstruction, reuse and recycling

Figure 2: Proposal for a joint model of building design and project phases

Definition of stakeholder groups

Three groups of stakeholders, which can be expected to have an increasing level of expert knowledge regarding LCA are defined based on their role in the design process.

1) *Decision-makers* are defined as the group responsible for the final decision. Often these stakeholders are responsible for the budget or the ones paying for the building. The group includes private and public clients, individual building owners, but also investors, project developers, housing associations, portfolio managers, policymakers, etc. In the case of participatory design processes, citizens can also be included in this group.

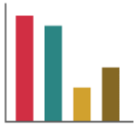
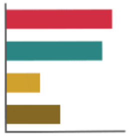
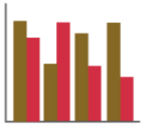
2) *Building design professionals* is used as a term to summarise all building experts without specific LCA training. The group mainly consists of architects and engineers involved in the design process.

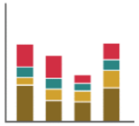
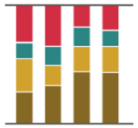
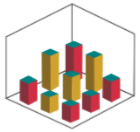
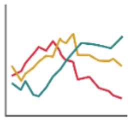
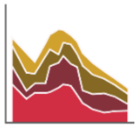
3) *LCA experts* are a group typically consisting of sustainability consultants, auditors for GBCS, and researchers.

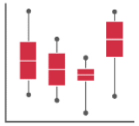
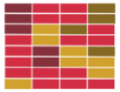
Definition of visualisation types

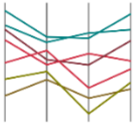
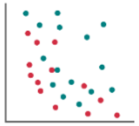
The different types of visualisation found in the review are sorted and structured. Charts with similar names but referring to the same visualisation type such as radial chart and spider chart are combined. **Error! Not a valid bookmark self-reference.** provides an overview with icons of the 27 visualisation types their advantages and disadvantages and examples for application from the literature.

Table 1: Visualisation types found in the review with examples of application, advantages, and disadvantages

#	Name	Icon	Description	Examples of application	Advantages	Disadvantages
1	Pie chart / donut chart		A circle divided into sectors which are proportional to the share of the category they represent. The sectors can be labelled with additional textual information.	Share of impact between building elements (Alexander Hollberg et al., 2016) or life cycle stages (Paulsen & Sposto, 2013).	Quick overview, often used, and easy to understand	Only one variable can be displayed at once
2	Multi-level Pie Chart		Same as the pie chart, but each sector can be further divided into subsectors that represent categories within that sector.	Share of impact between materials (first level) and life cycle stages (second level) (Kiss & Szalay, 2019); Share of emissions between building types in a neighbourhood (level 1-2), and life-cycle-stage (level 3) (Resch et al., 2020).	Multi level hierarchy can be displayed, can be enriched and enlarged by integrating interactive elements.	Hierarchy needs to provide same depth for each main category. Same angle (and represented value) in different levels will appear as different plotted area, which can be misleading.
3	Sunburst		Same as the multi-level pie chart with subsectors that do not necessarily fill the parent sector. Usually 2-5 levels are possible to display. Can be increased in interactive plots.	Share of impact within the LCA stages, building components down to materials (Kiss & Szalay, 2020).	Multi level hierarchy can be displayed. With interactive elements, many leaves are possible.	Same angle (and represented value) in different levels will appear as different plotted area, which can be misleading.
4	Vertical bar chart		Rectangular bars in a vertical chart with proportional height/length to the values represented. Expresses relation of categorical value against a numerical on the same scale.	Comparison of building façade composition alternatives for impact (Bernardette Soust-Verdaguer et al., 2018); Comparison of impact in different locations (Oyarzo & Peuportier, 2014).	Quick overview, often used, and easy to understand	One value per variable is possible, and if a large number of bars is included can be more difficult to read the labels/tag of the values in a horizontal position.
5	Horizontal bar chart		Same as the bar chart but horizontal.	Comparison of different materials' performance (Kiss & Szalay, 2020) or embodied impacts (Resch et al., 2020; B Soust-Verdaguer et al., 2020).	Quick overview, often used, and easy to understand, also allows to include a large number of bars.	One value per variable is possible.
6	Grouped bar chart		Same as the bar chart but includes more than one series to horizontally compare different categories.	Comparison of life cycle impacts of different design alternatives (B Soust-Verdaguer et al., 2020); Comparison of life cycle impacts of different materials (thickness, heating system, isolation material and type of glazing) (Alexander	Quick comparison of different series of values. Series can be even plotted with different units by applying a secondary y axis on the right side.	One value per variable and series is possible. The comparison between values with different units is difficult.

				Hollberg & Ruth, 2016; Kiss & Szalay, 2020).		
7	Stacked bar chart		Same as the bar chart but includes more than one series to vertically compare different categories.	This option allows to compare different categories (as the grouped bar chart) but also the grouped total, for example the comparison of the embodied emissions produced by different materials and the contribution of the different building parts (Lobaccaro et al., 2018).	Possible to compare the relative weight of different series of values.	Only absolute values can be displayed
8	Normalised bar chart		Similar to the stacked bar chart but includes more than one series to vertically compare different categories.	Comparison of the environmental impacts in percentages of different design alternatives, for example, the contribution of life cycle stages' of environmental impacts over the building lifespan (Eberhardt et al., 2019).	Quick comparison of different series of values. Also allows to compare the sum of them (partial and total values per series and bar).	One value per variable and series is possible
9	Multiple series 3D bar charts		Similar to the grouped bar chart but provides three axes to compare different series of values.	Comparison of the environmental impacts of different design alternatives on two axes, for example heating systems and insulation material for renovation measures (Alexander Hollberg & Ruth, 2013).	Extends dimensionality compared to 2D bar charts.	Difficult to overview, the visibility depends on view angle
10	Line chart		Display information as a series of (ordered) data points connected by straight line segments. Can show one or several lines. An error band could be included to visualise the distribution of results similar to the box plot, but continuous.	Change of cumulated emission over years (Eberhardt et al., 2019); Cumulated embodied and operational impact change over years (M. Röck et al., 2020); Monthly energy demand within a year (Tronchin et al., 2019).	Can show how values change over a continuous variable (e.g. time).	Can cause misunderstanding if the cut of y axis is improperly done
11	Stacked area chart		Similar to a line chart but the area below the line is filled. Multiple series of data are plotted on top of each other, resulting the filled area to express the sum of the data. The values could also be normalised to provide a normalised stacked area chart	Change and share of emission factors of grid-electricity over time and within neighbouring countries (Vuarnoz & Jusselme, 2018).	Can shows how different group/series of values change over a continuous variable (e.g. time)	Can cause misunderstanding if the cut of y axis is improperly done

12	Sankey /Alluvial Diagram		Flow diagram where the width of the arrows is proportional to the flow quantity they are representing.	Representation of flows, energy distribution(Jusselme et al., 2018); representation of financial and environmental costs during the building life cycle (Miyamoto et al., 2019).	Specific type of flow diagram	Can cause confusion if the organization of the nodes and the connections is not carefully considered
13	Box plot		A representation of groups of numerical data by their quartiles. One box refers to a series of numerical data (usually >1000)	Deviation of the hourly impact of grid electricity within a year (Kiss et al., 2020); Distribution of expected environmental impact within alternative designs (A Hollberg et al., 2019); Distribution of impact within case studies (Martin Röck et al., 2018b).	Possible to compare distributions instead of single values	Statistical sampling may bias the results
14	Tree map		Tree maps display hierarchical (tree-structured) data as a set of nested rectangles. The area of a rectangle is proportional to the data.	Share of energy and associated emissions of grid electricity originating from different countries (Vuarnoz & Jusselme, 2018).	Express the relative weight with different size shapes.	Limited information provided
15	Heat map		Individual data contained in a matrix form is coloured by the third dimension.	Percentage of impact savings within building elements and impact categories (Eberhardt et al., 2019); Variation of the impact of hourly grid electricity within days of a year and hours of day (Kiss et al., 2020; Vuarnoz & Jusselme, 2018).	Useful to categorize or organise a set of variables in a hierarchy.	When a large number of values is included, it can be difficult to understand and identify (rank or visualize) the categories.
16	Radial chart / spider chart / polar chart		Type of diagram that allows to show more than one series of values and related them to multiple categories.	Comparison of different alternatives and environmental impact categories (Oyarzo & Peuportier, 2014).	Possible to visualize multiple indicators.	The order, origin, and scale of the axes heavily influence the appearance and the interpretation of results (Odds, 2011), which can easily lead to bias.
17	Tornado chart		Special type of horizontal bar chart, where the categories are ordered so that the largest is on the top.	Expression of design parameter influence (positive or negative) on performance (John Basbagill et al., 2017).	Quick comparison of a sets of data series where different variables can be displayed	Can display only two sets of data series.

18	Parallel coordinates		Allows to represent the relations between multiple features with even different scale. Each vertical bar represents one variable and each line is one observation /individual/case.	Display the different design variants that form the supporting points for the meta-model (Jusselme et al., 2017). Used in multi-objective optimization to show the evolution of the parameters (Kiss & Szalay, 2020).	Useful to visualize many variables and many observations	The appearance depends on the order of variables.
19	Pictorial unit chart		Allows to represent and compare the relation (in magnitude) between different elements by using icons to represent them.	Not an example directly related to building LCA, but could be adapted: Comparison of different dietary patterns related to meat consumption (Goossens et al., 2018).	Useful to graphically express a comparison between more than two values. The use of icons can help to express a message for non-expert audience (such as designers, policy makers, clients)	Limited information about values, only generic comparison of variables.
20	Pictorial fraction chart		Similar to the pictorial unit chart but use one icon to represent and compare the relation (in magnitude) of different aspects of the element (icon).	Visualisation of the environmental impact per resident of a building (Alexander Hollberg & Klüber, 2014).	Useful to graphically express a comparison between two values. The use of icons can help to provide a clear and simple message to non-expert audience	Limited to the comparison of two values.
21	Scatter plot		Numerical two-dimensional data in Cartesian coordinates, where each dot represents a dataset	Solutions in the objective space of a bi-objective optimization (embodied, operational impact) (Kiss & Szalay, 2020) or GWP and investment costs (Klüber et al., 2014).	Multiple categorical dimensions can be expressed with using colour, size, shape, etc.	When a large number of dimensions are displayed it may be difficult to read. Also, there is risk of overplotting.
22	Cluster		Similar to the scatter plot but groups values into clusters.	Comparison and grouping into clusters of values. Clusters representing the energy performance classes (M. Röck et al., 2020).	Multiple categorical variables can be showed and grouped with using colour, size, shape, etc.	When a large number of dimensions are displayed it may be difficult to read. Also, there is risk of overplotting.
23	3D Scatter plot		Numerical three-dimensional data in Cartesian coordinates, where each dot represents a dataset.	Solutions in the objective space of a three-objective optimization (Klüber et al., 2014); Correlation of energy demand to two building parameters(Jusselme et al., 2018).	Multiple categorical variables can be expressed with using colour, size, shape, etc.	When too many dimensions are included, it may be difficult to understand. Also, the angle may be an issue regarding visibility.
24	3D Colour code		Parts of the represented item is coloured according to the associated numeric data.	The building can be used to intuitively identify the elements with the highest impact as part of a hot spot analysis, for example: Improvement potential of building elements (Martin Röck et al., 2018b); Share of impact/energy	Useful to visualize the distribution and magnitude (colour code scale) of the variables in the usual design environment (CAD/BIM). This can help to get a closer relation to the object.	The visibility angle may be an issue.

				loss of surfaces within the building life cycle (Kiss & Szalay, 2019); Emission factors of building elements projected in VR (Houlihan Wiberg, Lovhaug, et al., 2019)		
25	Bubble map		Combines a map visualisation (2D image) with the bubble chart. The sizes of the bubbles are proportional to the magnitude they represent.	Used for display the location of the manufacturing points of different products (Houlihan Wiberg, Wiik, et al., 2019).	Useful to visualize the variation of a variable in a region (map support).	The scale and visibility may be an issue.
26	Colour map		Combines a map visualisation (2D image) and its correlation with other variables and/or magnitudes.	Combines the map visualization with a colour scale in order to assist into intuitive understanding of environment (Samsel et al., 2019).	Useful to georeference the values' distribution, and a size reference of the values magnitude.	The scale and visibility (overlapping) may be an issue.
27	Scale		Represents the visualisation of a bar graph indicating the correlation with a benchmark, reference or target value.	Common in different building LCA tools (e.g. Lesosai, CAALA, Bombyx), to show the performance of the building to benchmarks.	Useful to focus on a single variable	Limited information can be shown.

In the analysed literature, the general goal of the visualizations is to show the relation between design variables or design alternatives and the environmental impact. In most cases, there are multiple options to visualise the relation. Therefore, we introduce several categories. Four aspects are used to categorize the collection of visualizations specifically for the use in a building LCA study:

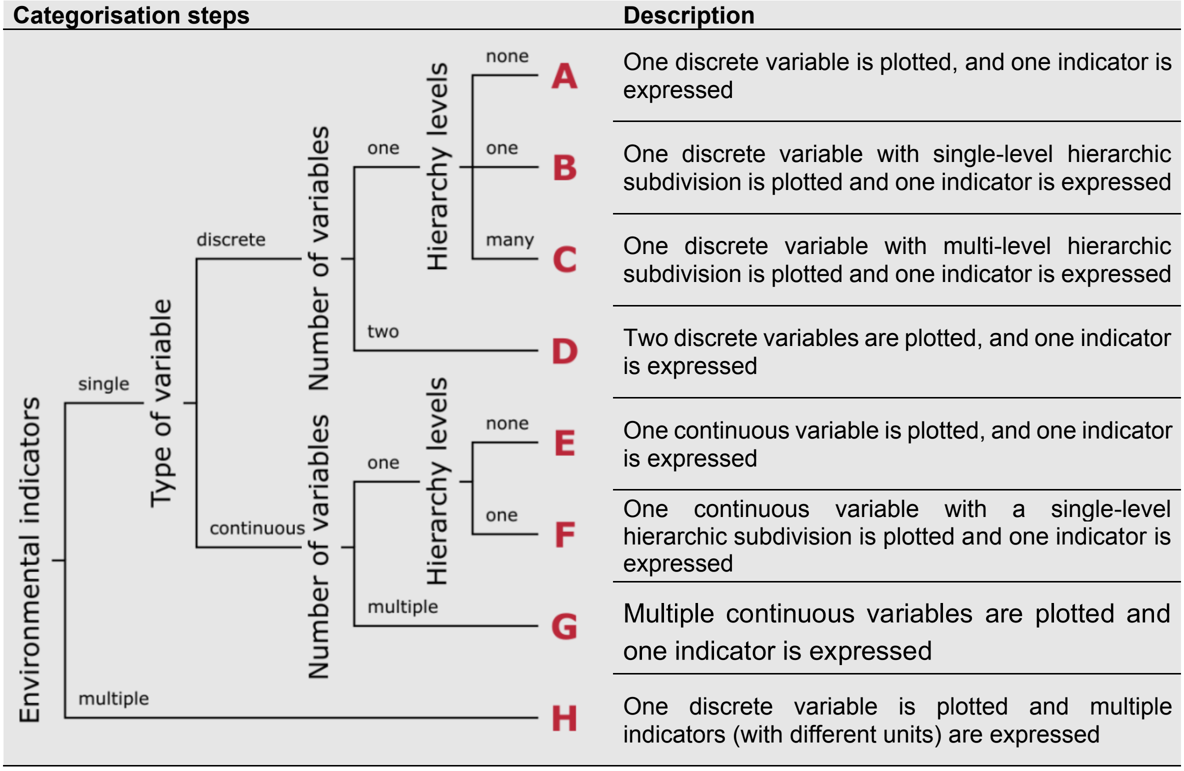
1. Number of environmental indicators
   The representation of the environmental impact as a single-score value or multiple values is often discussed by LCA experts (Kägi et al., 2016). Therefore, the capability of visualising single or multiple indicators with different units in one graph (without aggregation) is used as one differentiation. If the aggregation into a global indicator is possible, it is seen as one indicator from the perspective of visualization, because the values have the same unit and can be plotted on the same axis.

2. Type of variables
   Visualised variables can be either discrete (e.g. construction material options or design alternatives) or continuous (e.g. fenestration ratio or insulation thickness), which is a key aspect in choosing the visualization type. Each variable is plotted on a separate axis.

3. Number of variables
   The number of evaluated variables can range from one (e.g. comparing a few fixed design alternatives will result in one categorical axis) to many (in a complex optimization problem) and the possible number of visualised variables are limited by the dimensionality of the plot. Furthermore, it is important to mention that a colour scale or colour code can be seen as expressing another dimension of information. In general, the sum of indicators and variables gives the dimensionality of the graph.

4. Hierarchy levels
   The hierarchic decomposition of the results plays a key role in finding hotspots. The hierarchy may refer to lifecycle stages, the decomposition of the object (e.g. building components) or even to environmental aspects in case of an aggregated indicator. Different visualisations can be used to express hierarchic data, but the level is limited by the type of visualisation. We differentiate between non-hierarchic charts, visualisations with one level of hierarchy (parent-child), and multiple (deep) levels of hierarchy.

Using these aspects for categorisation, eight groups of visualisation types are identified within the collected visualisations. The categorisation process is shown in Figure 3.



Categorisation steps	Description
A	One discrete variable is plotted, and one indicator is expressed
B	One discrete variable with single-level hierarchic subdivision is plotted and one indicator is expressed
C	One discrete variable with multi-level hierarchic subdivision is plotted and one indicator is expressed
D	Two discrete variables are plotted, and one indicator is expressed
E	One continuous variable is plotted, and one indicator is expressed
F	One continuous variable with a single-level hierarchic subdivision is plotted and one indicator is expressed
G	Multiple continuous variables are plotted and one indicator is expressed
H	One discrete variable is plotted and multiple indicators (with different units) are expressed

Figure 3: Categorisation steps to define groups of visualisation types and description of the groups

2. Results

2.1 General analysis of building LCA tools and the literature

The full table of the review of the building LCA tools and the scientific literature can be found in **Table 2** and **Table 3**.

Table 2: Results of review of building LCA tools (If the analysed tool completely matches one of the boxes, it is marked with x, while (x) is used, if it matches partially.)

#	Country of origin	Name	Goal		Design stage		Stakeholders			Visualisation type																											Number of visualisations	Website
			Whole building LCA	Building component LCA	Early	Detailed	Decision makers	Building design professionals	LCA experts	Pie chart / donut chart	Multi-level pie chart	Sun burst	Vertical bar chart	Horizontal bar chart	Grouped bar chart	Stacked bar chart	Normalised bar chart	Multiple series 3D bar chart	Line chart	Stacked ordered area chart	Sankey	Box plot	Tree map	Heat map	Radial / spider / polar chart	Tornado chart	Parallel coordinates	Pictorial unit chart	Pictorial fraction chart	Scatter plot / Pareto front	Cluster	3D Scatter plot	3D Colour code	Colour map	Bubble map	Scale		
			27	5	7	25	0	28	13	13	0	3	11	4	14	18	5	0	4	1	4	1	2	0	2	0	2	0	0	1	0	0	2	1	0	5		
1	AT	eco2soft		x		x		x	(x)																											x	1	https://www.baubook.info/eco2soft/?SW=27&lng=2
2	AU	eTool LCD	x	(x)		x		x						x										(x)													1	https://etoolglobal.com/
3	BE	Totem	x			x		x		x						x	x																			x	4	https://www.totem-building.be/
4	CDN	Athena Impact Estimator	x		x			x		x				x	x	x																					4	http://www.athenasmi.org/our-software-data/impact-estimator/
5	CDN	Athena EcoCalculator		x	x			x		x				x	x	x																					4	http://www.athenasmi.org/our-software-data/ecocalculator/
6	CH	Bombyx	x		x			x																									x			x	2	https://www.food4rhino.com/app/bombyx
7	CH	Lesosai	x	(x)		x		x	(x)	x			x		x	x									x												5	http://www.lesosai.com/en/
8	CH	Eco-Sai	x	(x)		x		x	(x)	x			x		x	x																					4	http://www.eco-sai.com
9	DE	CAALA	x	(x)	x	(x)		x		x			x																							x	3	https://caala.de/
10	DE	Legep	x			x		(x)	x	x			x			x			x		x																5	https://legep.de/?lang=en
11	DE	Generis	x	(x)		x		(x)	x						x																						1	www.generis.live
12	DE	eLCA	x	(x)		x			x				x			x	x																				3	https://www.bauteileditor.de/
13	DK	LCAbyg	x			x		x	(x)				x		x		x		x																		4	https://www.lcabyg.dk/
14	ES	TCQM-GMA	x	(x)		x		x	x						x				x	x	x														x				5	https://itec.es/programas/tcqi/gestion-ambiental/
15	ES	NECADA	x	(x)		x		x	x				x		x										x					x			x				5	http://project.necada.com/
16	FI	OneClick LCA	x	(x)	x			x		x			x	x	x	x			x		x		x														8	https://www.oneclicklca.com/
17	FR	ClimaWin	x	(x)		x	(x)	x	x				x		x	x																					3	www.bbs-logiciels.com/clima-win/
18	FR	ELODIE	x	(x)	(x)	x	(x)	x	x			x	x		x	x																					4	www.elodie-cstb.fr

19	FR	Pleiades ACV	x	(x)	(x)	x	(x)	x	x				x		x	x	x																				4	www.izuba.fr
20	FR	ThermACV	x	(x)		x	(x)	x	x	x						x																				x	3	www.logicielsperrenoud.com
21	FR	ArchiWIZARD	x	(x)		x	(x)	x	x			x															x										3	fr.graitec.com/archiwizard/
22	FR	Vizcab	x	(x)		x	(x)	x	x			x															x										2	vizcab.io
23	FR	COCON-BIM	x	(x)		x	(x)	x	x				x		x	x																					3	www.cocon-bim.com
24	NL	MRPI MPG - software	x			x		x		x																											1	http://www.mrpi-mpg.nl/Home/Home
25	NO	ZEB Tool	x	(x)	(x)	x		x	x				x																								1	Internal use only
26	SE	BM2	x			x																															0	https://www.ivl.se/sidor/vara-omraden/miljodata/ byggsektorns-miljoberakningsverktyg.html
27	SE	Klimatkalkyl		x		x		x		x			x			x																					3	https://www.trafikverket.se/tjanster/system-och-verktyg/Prognos--och-analysverktyg/Klimatkalkyl/
28	UK	BRE Lina		x		x		x		x																											1	https://www.bre.co.uk/lina
29	US	EC3 tool	x			x		x								x					x	x															3	https://buildingtransparency.org/dashboard
30	US	Tally	x		x			x		x					x	x	x																				4	https://choosetally.com/
31	US	Bees		x		x		x								x																					1	https://www.nist.gov/services-resources/software/bees
32	UK	H\B:ERT	x		x			x								x							x														2	https://www.hawkinsbrown.com/services/hbert

Table 3: Literature review (If the analysed paper completely matches one of the boxes, it is marked with x, while (x) is used, if it matches partially.)

#	Reference	Type			Aim			Stake holders			Visualisation type																										
		Journal	Conference	Grey	Visualisation	Method/tool	Case study	Decision makers	Building design professionals	LCA experts	Pie chart / donut chart	Multi-level Pie Chart	Sun burst	Vertical bar chart	Horizontal bar chart	Grouped bar chart	Stacked bar chart	Normalised bar chart	Multiple Series 3D Bar Charts	Line chart	Stacked ordered area chart	Sankey	Box plot	Tree map	Heat map	Radial / spider / polar chart	Tornado chart	Parallel coordinates	Pictorial unit chart	Pictorial fraction chart	Scatter plot / Pareto front	Cluster	3D Scatter plot	3D Colour code on building	Colour map	Bubble map	Scale
		24	14	1	11	12	16	6	28	17	2	2	1	11	4	10	10	2	1	7	1	2	8	1	5	2	2	4	1	1	12	2	2	6	1	1	1
1	(John Basbagill et al., 2017)	x			x				x					x									x				x				x						
2	(Cerdas et al., 2017)		x		x					x															x												
3	(Duprez et al., 2019)	x				x			x	x				x		x																					
4	(Eberhardt et al., 2019)	x					x			x						(x)	x	x		x					x												
5	(Gilles et al., 2017)	x				x			x																						x						
6	(Goossens et al., 2018)	x				x		x		x				x		x	x								x				x								
7	(Hester et al., 2018)	x				x			x																		x				x						
8	(Alexander Hollberg et al., 2016)		x				x		x		x					x																					
9	(Alexander Hollberg et al., 2019)		x				x		x														x														
10	(Alexander Hollberg & Ruth, 2016)		x				x		x							x			x																		
11	(Alexander Hollberg & Ruth, 2013)	x				x			x	x						x																					
12	(Alexander Hollberg & Klüber, 2014)			x			x		x								x													x							
13	(Jusselme et al., 2017)		x		x				x	x																		x									
14	(Jusselme et al., 2018)	x					x			x												x						x					x				
15	(Kiss & Szalay, 2019)		x		x				x			x																						x			
16	(Kiss & Szalay, 2020)	x					x		x	x			x	x	x	x												x			x						
17	(Kiss et al., 2020)	x					x	x		x				x			x	x		x			x		x												
18	(Klüber et al., 2014)		x				x		x	x																					x		x				
19	(Le et al., 2018)	x					x		x	x						x										x											
20	(Lobaccaro et al., 2018)	x					x									x	x			x											x						
21	(Miyamoto et al., 2019)		x		x				x	x												x						x									

22	(Mousa et al., 2016)		x		x		(x)	x																										x			
23	(Otto et al., 2003a)	x		x					x																						x					
24	(Oyarzo & Peuportier, 2014)	x				x		x	x				x											x												
25	(Paulsen & Sposto, 2013)	x				x		x		x						x																				
26	(Resch & Andresen, 2018)	x			x				x		x		x	x								x								x						
27	(Resch et al., 2020)	x			x			x					x	x	x	x			x											x						
28	(M. Röck et al., 2020)	x			x		x	x								x			x			x								x	x					
29	(Martin Röck et al., 2018b)	x		x				x														x											x			
30	(Martin Röck et al., 2018a)		x	x				x														x											x			
31	(Samsel et al., 2019)	x		x					x																									x		
32	(Scherz et al., 2018)		x		x			x																												x
33	(Bernardette Soust-Verdaguer et al., 2018)	x				x		x					x			x																				
34	(B Soust-Verdaguer et al., 2020)	x				x		x					x	x																						
35	(Tronchin et al., 2019)		x		x		x												x			x								x						
36	(Houlihan Wiberg, Lovhaug, et al., 2019)		x	x			x	x																									x			
37	(Houlihan Wiberg, Wiik, et al., 2019)		x	x				x	(x)				x																				x		x	
38	(Vuarnoz & Jusselme, 2018)	x				x			x						x				x	x			x	x						x						
39	(Zea Escamilla & Habert, 2015)	x			x		x	x					x			x														x						

The analysis showed that most building LCA tools focus on the detailed design stages (see **Figure 4**) while there are slightly more scientific papers addressing the early design stages. Most tools address several design stages but have a focus either on the early or detailed design stages. If this differentiation was not provided by the tool developers, expert judgement was used for classification.

The results furthermore show that most building LCA tools intend to address building design professionals. No tool tries to specifically address decision-makers. As most tools claim to address several stakeholders, expert judgement was used to classify the tools to simplify the classification and provide clear results. Similar to the building LCA tools, the majority of the visualisations presented in the literature address building design professionals. About one third focusses on LCA experts, while only 12% address decision-makers.

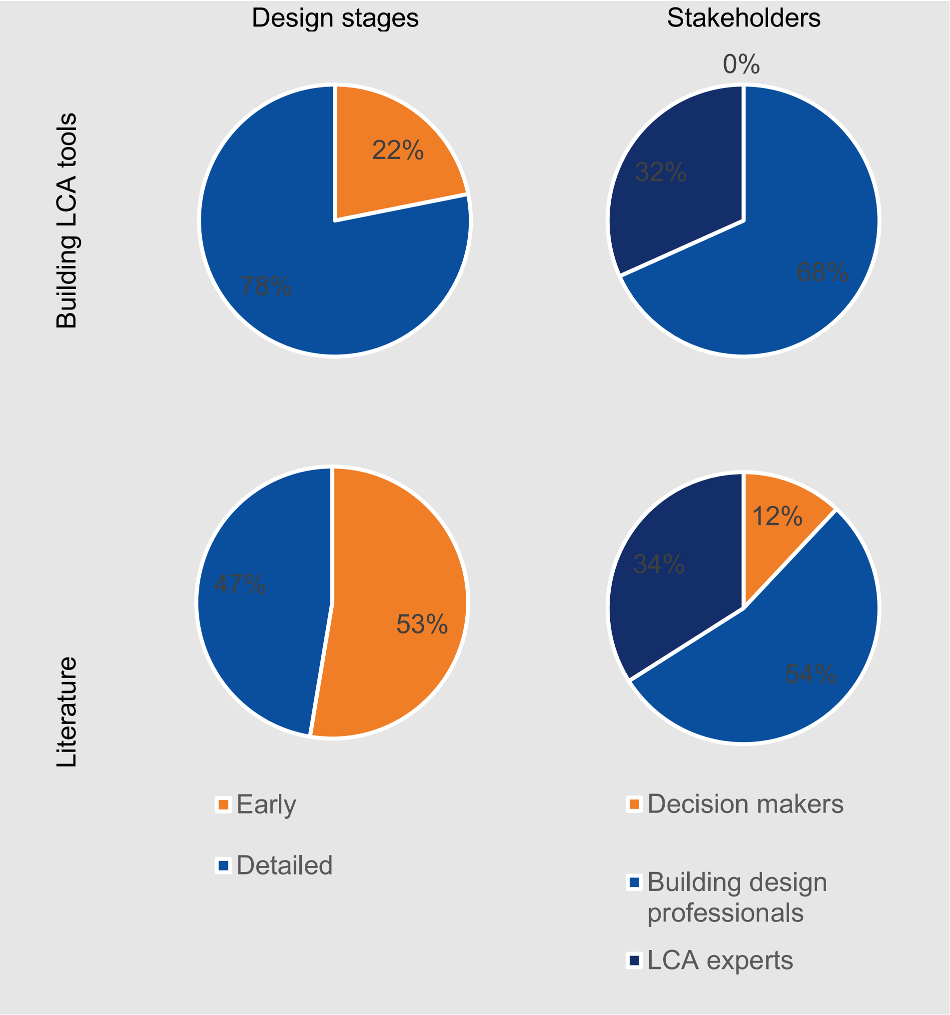


Figure 4: Design stages and stakeholders mainly addressed by building LCA tools and the literature

2.2 Types of visualisations used

Counting the number of visualisations used by the building LCA tools reveals that most tools use more than one, but only a few types of visualisation, e.g., pie chart and bar chart. Only one of the analysed tools does not provide any visualisation. On average, three types of visualisations are used per tool, while the tool with most different types of visualisations uses eight types.

Bar charts and variations of it such as grouped or stacked bar charts are the clear majority, followed by pie charts (see Figure 3). Those kinds are used by more than ten tools and can therefore be seen as common visualisations. Furthermore, the use of 'complex' visualisations with a large amount of information, such as scatter plots or parallel coordinate plots is very limited. The only tools that make use of a 3D colour code visualisation are developed by researchers. Currently, no commercial tool uses this kind of visualisation.

Like the building LCA tools, most published literature use bar charts and variations of it. A major difference to the results of the tools is the increased use of complex visualisations. Scatterplots sometimes including a Pareto front are used 12 times. Six publications use a representation on a 3D model. Five of them represent the colour code within the 3D design environment, while one uses Virtual Reality (VR) to show the results on the 3D model.

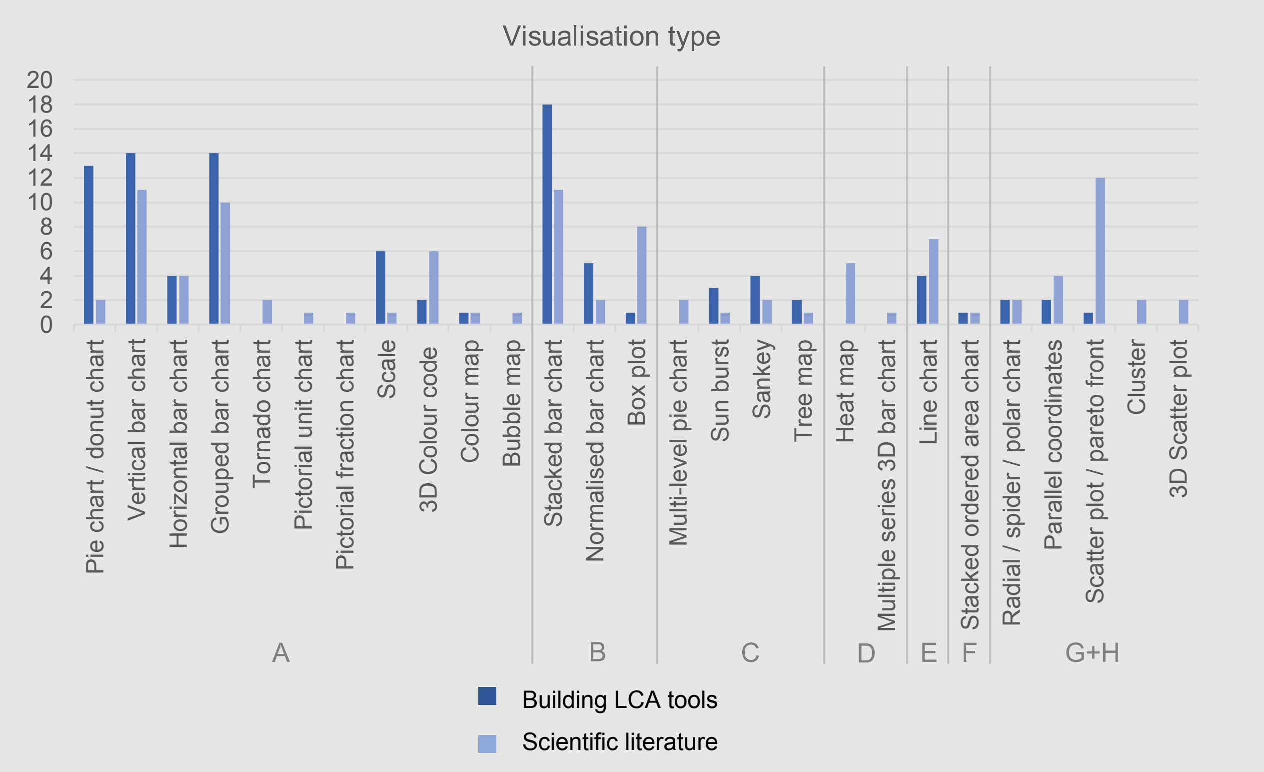


Figure 5: Number of visualisation types found in the review of building LCA tools and the literature

Analysing the hotspots regarding the use of visualisation options by building LCA tools for different stakeholders (see Table 2) shows that common visualisations (e.g. bar charts) are used as well as more complex visualisation options (e.g. scatter plots) for both LCA experts and building design professionals. For decisions-makers, we find that a small variety of visualisations is presented. The literature with a focus on visualisation provides more variety including options such as clusters or maps. The literature presenting case studies have a clear majority of common visualisations such as bar charts and variations of it. Scatter plots and Pareto fronts seem to be the only complex visualisations that are used by all types of papers. Although many authors in analysed literature specifically focus on early design stages, no clear differences of the use of visualisations can be seen with regards to the design stages.

Table 4: Number of visualisation types per stakeholder and design phase

		A											B			C				D		E	F	G+H				
		Pie chart / donut chart	Vertical bar chart	Horizontal bar chart	Grouped bar chart	Tornado chart	Pictorial unit chart	Pictorial fraction chart	Scale	3D Colour code	Colour map	Bubble map	Stacked bar chart	Normalised bar chart	Box plot	Multi-level pie chart	Sun burst	Sankey	Tree map	Heat map	Multiple series 3D bar	Line chart	Stacked ordered area	Radial / spider / polar chart	Parallel coordinates	Scatter plot / pareto front	Cluster	3D Scatter plot
LCA tools	Decision makers	1	4	0	4	0	0	0	1	0	0	0	5	1	0	0	3	0	0	0	0	0	0	0	2	0	0	0
	Building design prof.	13	13	4	14	0	0	0	6	2	1	0	17	4	1	0	3	4	2	1	0	4	1	2	2	1	0	0
	LCA experts	4	11	0	10	0	0	0	3	1	1	0	9	3	0	0	3	2	0	0	0	3	1	2	2	1	0	0
	Early	5	5	3	6	0	0	0	2	1	0	0	7	2	0	0	1	1	2	0	0	1	0	0	0	0	0	0
	Detailed	9	13	1	10	0	0	0	5	1	1	0	13	4	1	0	3	3	0	1	0	3	1	2	2	1	0	0
Literature	Decision makers	0	3	0	1	0	1	0	0	2	0	0	4	1	3	0	0	0	0	2	0	3	0	0	0	3	1	0
	Building design prof.	2	3	0	7	2	0	1	1	6	0	1	7	0	5	1	1	1	0	0	1	2	0	2	3	8	1	1
	LCA experts	0	7	2	6	0	1	0	0	1	1	1	4	2	2	1	1	2	1	5	0	3	1	2	4	4	1	2
	Early	1	7	3	5	2	0	1	1	5	0	1	4	0	5	1	1	2	0	0	1	1	0	0	4	5	0	1
	Detailed	2	4	1	7	0	1	0	0	1	1	0	8	2	3	1	0	0	1	5	0	7	1	2	0	8	2	1

2.3 Synthesis of visualisation types and applications for LCA

The results of the analysis of visualisation types are synthesised based on the typical application of LCA and the category of visualisation type in Figure 6. Several visualisation options exist for all the LCA applications. Therefore, they are ordered from left to right with the increasing amount of information transferred in the visualisation. In addition, the number of objects for the assessment proved to be relevant. From the visualization aspect, each design alternative corresponds to a data point. One data point may consists of the hierarchically structured results, but the different data points cannot be aggregated. Therefore, a differentiation between one, few and many (>100) objects of assessments is introduced and indicated by the type of border around the icons in Figure 6.

For the purpose of temporal distribution, spatial distribution, and benchmarking only two or three options each could be found in the literature. All these options are only suited to communicate one environmental indicator and one design variable. In the case of bar charts with a benchmark threshold, it is possible to show several environmental indicators next to each other, but this requires either normalisation or adding an individual axis for each bar, which would correspond to showing several single bar charts next to each other. The visualisation options that are part of group A and E have no hierarchy levels, while the stacked ordered area chart as part of group F has one hierarchy level that could be used to plot the evolution of the environmental impact of individual building elements and the sum for the whole building over time, for example.

Identification of hot spots and comparison of design options are the most common LCA applications in the reviewed literature and they show the highest variety of visualisation options. For identification of hot spots, only discrete variables are used. The options in group A, B, and C, all visualise one variable with increasing hierarchy levels, for example the embodied impact of building elements. The options in group D allow to visualise two variables, for example heating systems and insulation materials for renovation (Alexander Hollberg & Ruth, 2013).

The comparison of design options can be visualised with a limited amount of information, such as a bar chart. If the number of options for comparison reaches a certain point, the type of visualisation becomes limited. Then mostly scatter plots are used to identify clusters or a Pareto front (group G). There is a lower limit for the number of objects for these types of charts to become meaningful. Parallel coordinate plots are often used to visualise several parameters and their interdependencies. If few design options are compared regarding multiple indicators, visualisation options of group H, such as spider charts, are used.

Uncertainty analysis is often an important part of LCA. A common way to visualise uncertainty is an error bar in bar chart or a box plot providing additional information by showing quantiles. A simple but rarely used approach in the analysed literature, is to show and rank the sensitivity of design parameter using a tornado chart (John Basbagill et al., 2017). The most common way to show correlation is the use of scatter plots and variations of them in 2D and 3D, but also parallel coordinate plots are used, for example (Miyamoto et al., 2019). Scatter plots are also used to show uncertainties.

While several visualisation options exist for all LCA applications, certain types of visualisations are only used for one specific LCA application in the analysed literature, e.g., a pie chart is only used for a part-to-whole comparison to identify hotspots, and a scale is only used to show the result in relation to a benchmark.

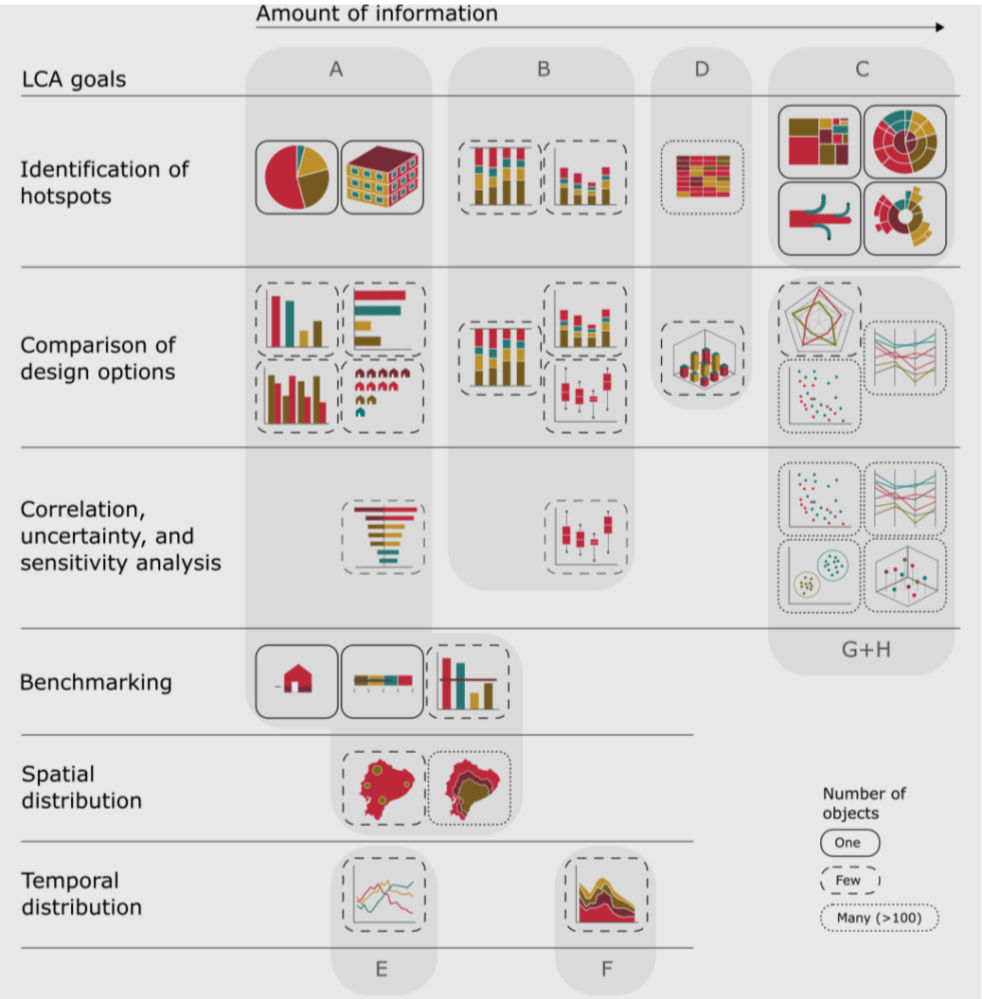


Figure 6: Synthesis of the LCA applications, the group of visualisation types, and the amount of information displayed in the visualisation

3. Discussion

3.1 Use of visualisations in the design and decision-making process

Information requirements

In contrast to most industrial design products, most buildings are individual designs. Therefore, each design task is approached differently in a different constellation of stakeholders, leading to different required information for decision-making. Nevertheless, tasks within the design process are repeated, and visual information can support when provided in the right way. It is important to define the visualisation strategy considering which are the decisions that should be taken during the design stages.

In terms of LCA, the *overview* part of the information seeking mantra (Shneiderman, 1996) is often related to identifying hot spots on a low level of detail (e.g. operational vs. embodied impact) or the relation to a threshold in a scale to answer the questions whether a national limit value can be met, for example. The overview could also include the comparison of total results of different building variants (Asdrubali et al., 2013; Pombo et al., 2016).

The *zoom and filter* phase often refers to a hot spot analysis on a more detailed level (e.g. building elements or life cycle phases). This can be implemented using visualisations with a higher level of hierarchy, such as sun burst diagrams (Kiss & Szalay, 2019) or heat maps (Cerdas et al., 2017), amongst others.

The *details on demand* phase can include a very detailed hot spot analysis, e.g. on individual materials or a temporal analysis to identify when impacts are caused. Such information could be confusing in the first interpretation of the LCA results, but very valuable for understanding the background and providing an explanation for results, see (M. Röck et al., 2020) for example.

Dynamic visualisations

When implemented in a building LCA tool, in theory, all visualisation options can allow for dynamic and interactive elements. The introduction of interactivity by using dynamic visualisations further enhances the possibilities of how information can be extracted from the charts. We identified three types of possible interactivities. *Subselection or filtering of data* allows to elaborate the further information on one or a set of results and can support the zoom and filter phase. *Expanding deep hierarchy levels* that cannot be displayed at the same time, is possible for the visualisation options in group C and can provide the details on demand. Furthermore, *ordering* of the data is possible in different kinds of visualisation, e.g. dynamic bar charts or tornado charts.

Multi-criteria assessment

Design and decision processes are complex and usually integrate many criteria. These can be multiple indicators for LCA as shown in group H, but also a combination of LCA results with other performance indicators, such as costs (Klüber et al., 2014) or daylight (Carlucci et al., 2015). The most typical example for visualisation of multiple criteria found in the literature are 2D (or 3D) scatterplots. They show a correlation between two (or three) indicators and allow to identify clusters, trade-offs and Pareto fronts of optima, e.g. (Kiss & Szalay, 2020; Płoszaj-Mazurek, 2020). If more than three indicators should be compared spider/radial/polar charts are used, e.g. (Oyarzo & Peuportier, 2014). However, they only work for a few objects of assessment and introduce potential bias when interpreting the results (see Table A1 in the Supplementary Information for the advantages and disadvantages). If many design parameters should be visualised at the same time, a common solution consists of parallel coordinates, e.g. (Kiss & Szalay, 2020; Miyamoto et al., 2019).

3.2 From visualisations to design interfaces

Dashboards as decision support tools

An alternative for multi-criteria assessment is a combination of different graphs in dashboards. Dashboards provide the opportunity to visualise different kinds of visualisation types to present information on many criteria at the same time. Furthermore, they allow using different types of visualisations at different levels of details, either for different stakeholders or to follow the information seeking mantra (Shneiderman, 1996). Adding dynamic visualisations allows for direct interaction and using the visualisations as design tool.

An early example of using a dashboard to visualise LCA results of buildings for decision making is provided by Basbagill et al. (John Basbagill et al., 2017). More recently, Houlihan Wiberg et al. (Houlihan Wiberg, Wiik, et al., 2019) and Cho and Houlihan Wiberg (Cho, 2019) developed dashboards for parametric net zero GHG emission neighbourhood (ZEN) developments. The ZEN key performance indicators (KPIs) as defined in the ZEN Definition report (Wiik et al., 2018), such as embodied GHG emissions and transport-related GHG emissions, are visualised amongst other parameters. Testing such an interactive tool was carried out on one of the proposed ZEN pilot case studies for a new and retrofit school design in Trondheim, Norway and showed how selected ZEN KPIs and interrelationships between different design parameters can be dynamically visualised to support the decision-making process (Cho, 2019).

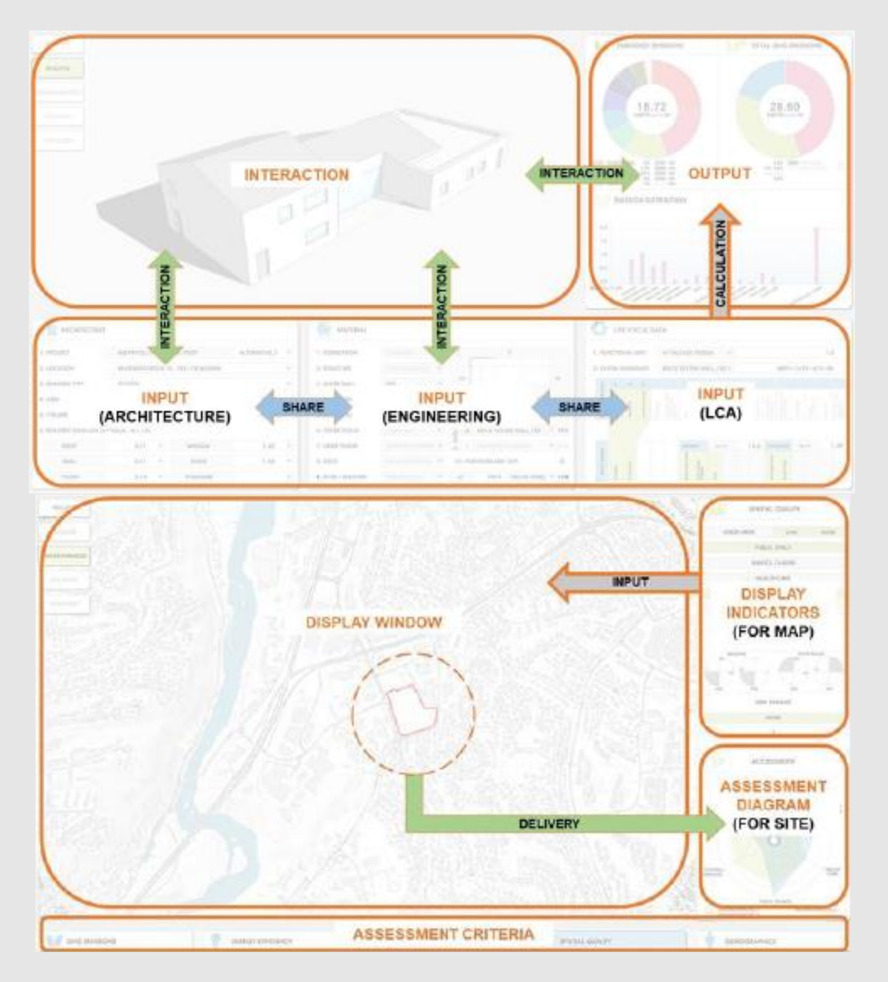
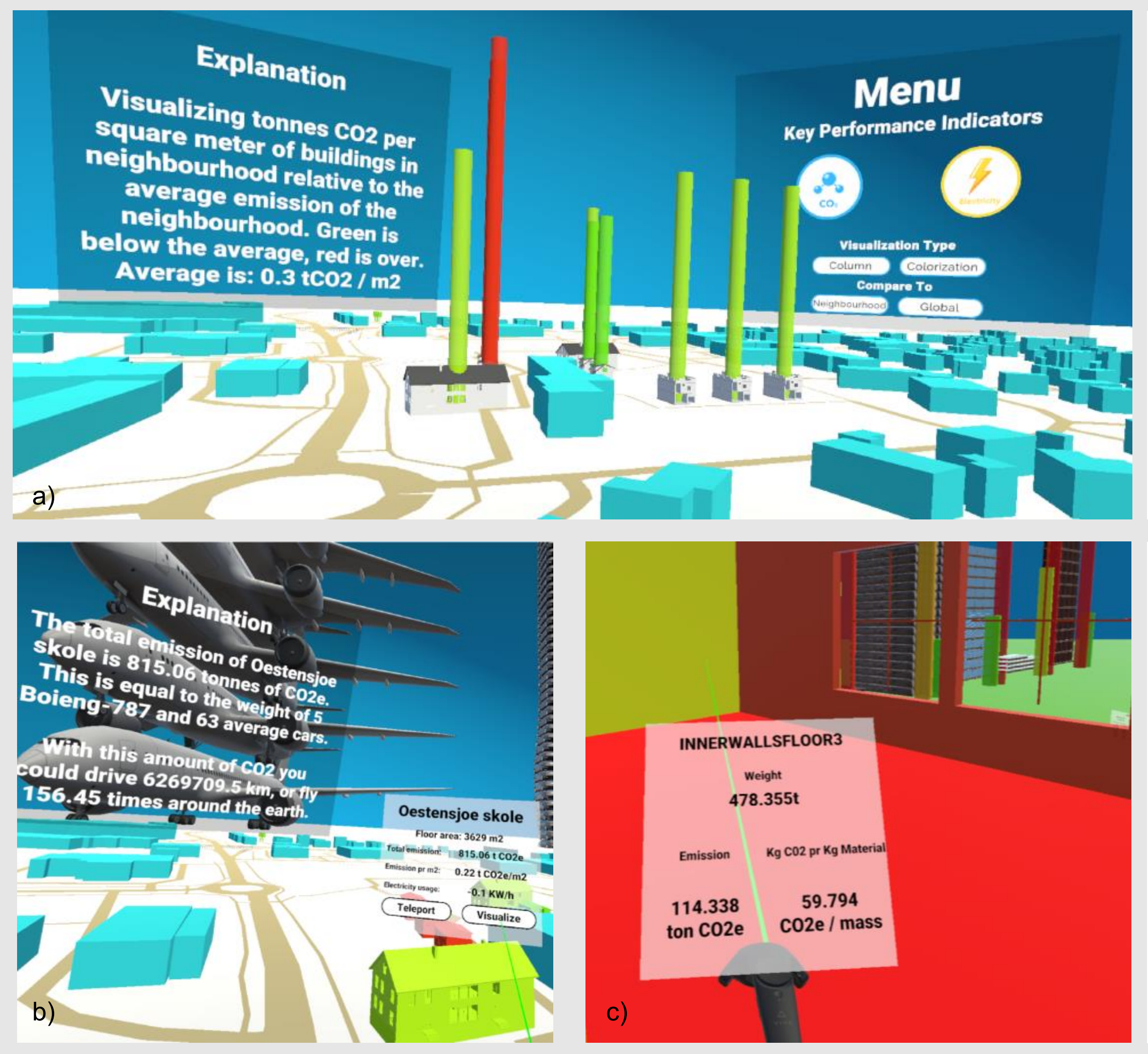


Figure 7: Dashboard showing the main structure of small-neighbourhood platform (Cho, 2019)

Virtual reality to support integrated design processes

Integrated design processes have been proposed to enable the design and implementation of sustainable buildings in practice, supporting communication and the exchange of relevant information amongst the various stakeholders (Leoto & Lizarralde, 2019). This is true for all kinds of building projects, but especially important for the development of net zero emission buildings and neighbourhoods. The complexity rises as ever more stakeholders are involved in handling both ‘top down’ neighbourhood level data as well as ‘bottom up’ building and material level information. Considering aspects such as GHG emissions as KPIs is still new and challenging for many policy makers and building design professionals, not to mention citizens, who also need to be included early in participatory, integrated design processes (Baer, 2018). A more recent approach to support these processes is the use of immersive technologies, such as virtual reality (VR). The potential of using VR to enable users to explore and interact with real design projects was investigated by Houlihan Wiberg et al. (Houlihan Wiberg, Lovhaug, et al., 2019). Figure 8 shows examples of visualisations applied in the virtual environment for presenting information such as a) performance in relation to benchmarks, b) airplane icons as a type of pictorial unit chart, and c) a colour code to visualise the impact of building elements. As such, these visualisation types do not differentiate from the visualisations used on screens or paper. According to Houlihan Wiberg et al. (Houlihan Wiberg, Lovhaug, et al., 2019), VR offers a more intuitive means to interpret the performance of a building or neighbourhood design and is an invaluable tool to engage users with no prior scientific knowledge. Furthermore, VR provides a means to overcome traditional interdisciplinary barriers by improving communication. These results are in line with Juraschek et al. (Juraschek et al., 2018) who emphasize the potential of VR in communicating LCA results and bridging the gap between LCA experts and non-experts.


Explanation

Visualizing tonnes CO2 per square meter of buildings in neighbourhood relative to the average emission of the neighbourhood. Green is below the average, red is over. Average is: 0.3 tCO2 / m2

Explanation

The total emission of Oestensjoe skole is 815.06 tonnes of CO2e. This is equal to the weight of 5 Boieng-787 and 63 average cars.

With this amount of CO2 you could drive 6269709.5 km, or fly 156.45 times around the earth.

Oestensjoe skole

Floor area: 3629 m2

Total emission: 815.06 t CO2e

Emission pr m2: 0.22 t CO2e/m2

Electricity usage: -0.1 KW/h

INNERWALLSFLOOR3

Weight 478.355t

Emission 114.338 ton CO2e

Kg C02 pr Kg Material 59.794 CO2e / mass

Figure 8: Snapshots using VR to visualise GHG emissions of buildings (Mathisen & Løvhaug, 2019) using a) red and green columns to show being below or above a treshhold, b) airplane icons to relate GHG emissions of a building to flying, c) a colour code to visualise the impact of building elements

3.3 Implications and recommendations

The review of the literature emphasised the need for visualisation of LCA results for LCA experts, but especially for stakeholders involved in the design process without detailed LCA knowledge. This need becomes even stronger due to the increased use of LCA results as KPIs in participatory design processes not only on building but also on neighbourhood level.

The analysis of the current building LCA tools showed that most tools use common visualisations such as pie charts or bar charts and variations of them. The review of the literature revealed a variety of more advanced visualisation types. Advanced visualisation types and design interfaces can enable the communication of complex information for LCA experts and building design professionals as well as decision makers concerned with assessing and improving the environmental performance of buildings and neighbourhoods. In general, there is still much room of exploring different visualisation options for presenting LCA-related information and for investigating their suitability for different stakeholder groups. Especially, the use of dynamic visualisations for interactive exploration of the results can support the information seeking during the design process. We would like to propose the synthesis of Figure 6 as starting point for building LCA tool developers to adapt more visualisation types for different purposes and stakeholders.

In relation to the preferences for different visualisations of stakeholders, the review presented here, is limited. We structured the visualisation types according to the LCA applications, the amount of information shown in the visualisation, and the number of objects. It can be assumed that with the increasing level of LCA knowledge stakeholders have an increasing demand for detailed information. However, this assumption should be verified in studies with stakeholders. We therefore recommend to use the results presented here for stakeholder surveys and interviews in the future. In addition, more case studies and application tests are needed to evaluate the support the visualisations provide in the design process for the final objective of planning more sustainable buildings and neighbourhoods.

4. Conclusions

The need for visualisations has been widely discussed in the literature. The importance of making LCA results understandable for decision-makers is growing as LCA is increasingly used in the design process The need for visualisations has been widely discussed in the literature. The importance of making LCA results understandable for decision-makers is growing as LCA is increasingly used in the design process as a basis for environmental performance assessment of buildings and neighbourhoods. This report presents a review of the most common building LCA tools, which showed that the majority uses common visualisation options, such as pie charts or bar charts. In addition, we systematically reviewed the scientific literature and found a greater variety of visualisations and more complex visualisation options. Most of the complex visualisation with a larger amount of information communicated in the visualisations are used for correlation analysis, multi-criteria optimisation, or uncertainty quantification. Furthermore, a trend towards visualising the results in a 3D design environment is observed.

The discussion highlighted the importance of providing visualisations adapted to the goal and scope of the LCA study, as well as to provide the right amount of information during the design phase to support the information seeking mantra of overview, zoom and filter, and details on demand. Furthermore, we provided examples of how dynamic visualisations can support this process and showed that there is a big potential of combining different visualisations into dashboards which allow an overview to be provided and answers to several design questions and applications of LCA at the same time. In this report, we provide a synthesis of LCA visualisation options, which, in combination with the common information seeking mantra, can provide a good starting point for building LCA tool developers and researchers to develop stakeholder-specific dashboards and provide relevant information on the environmental performance of buildings and neighbourhoods. There is a big potential to be addressed in the near future by the LCA and building performance community to make the most of the large variety of visualisation options available.

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