LCA strategy for uncertainty in design phases

A Contribution to IEA EBC Annex 72

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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_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.

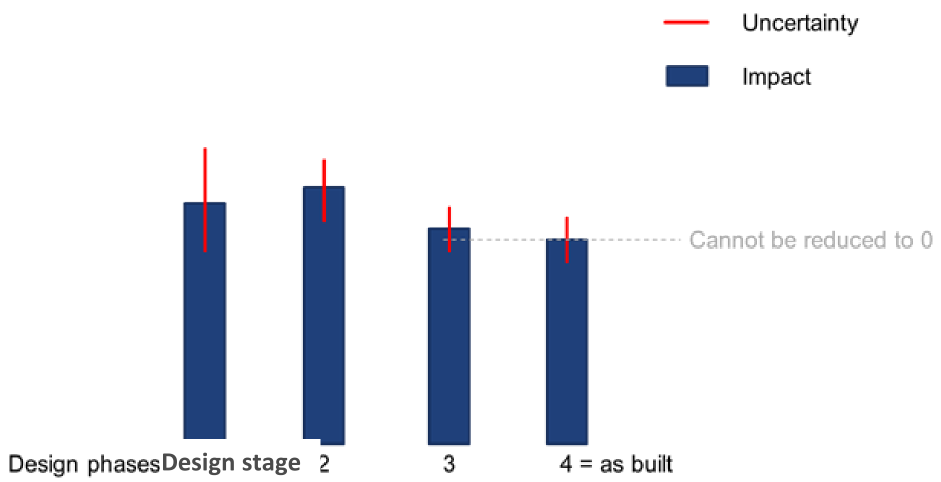


Figure 2: Qualitative representation of the development of the uncertainty during the design process form the early stage 1 to the final as-built stage 4.

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.

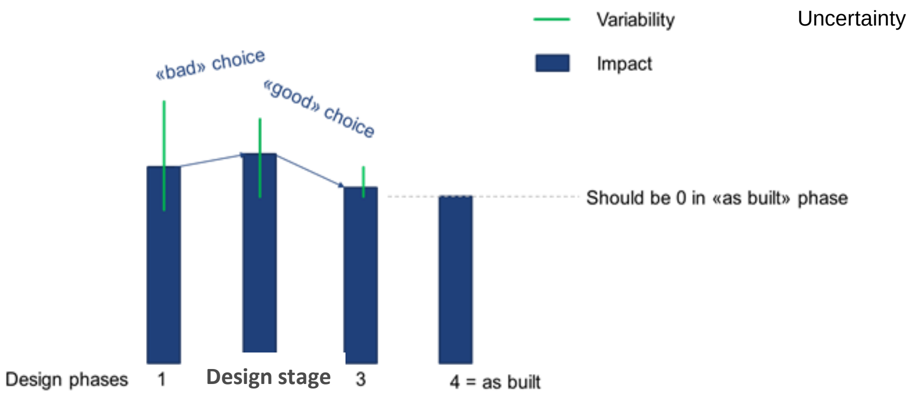


Figure 3: Qualitative representation of the development of environmental impacts and the variability during the design process form the early stage 1 to the final as-built stage 4.

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.

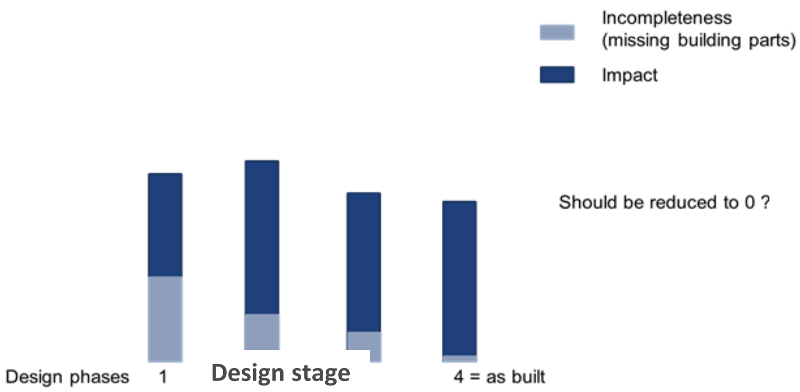


Figure 4: Qualitative representation of the development of environmental impacts and incomplete data (missing building parts) during the design process form the early stage 1 to the final as-built stage 4. In the LCA done as built there are still parts that are usually not considered as its expected 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.

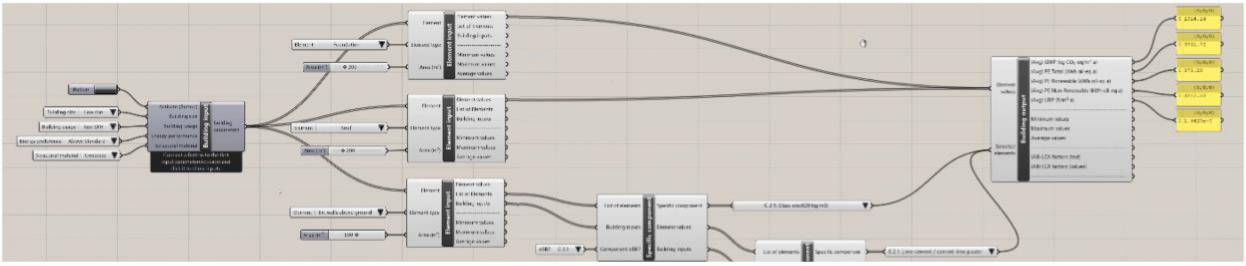


Figure 5: Example of the Rhino and Grasshopper based tool Bombyx. Source: internal archive.

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.

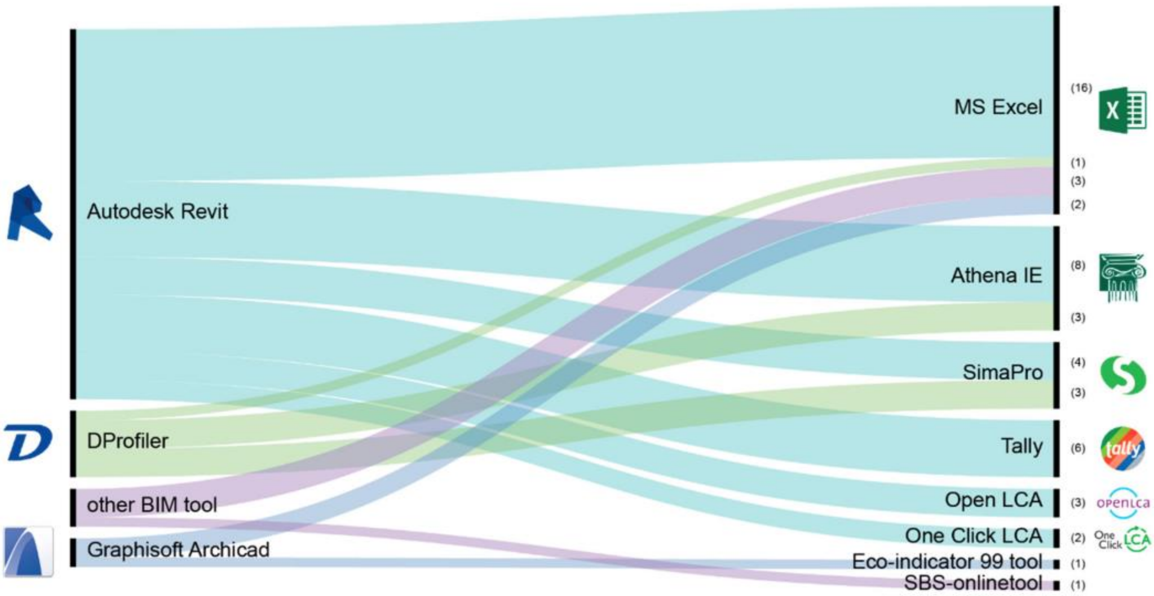


Figure 6: Software adoption in the selected cases studies; the coloured flow lines indicate the relationships between tools in data exporting from the BIM model to LCA analysis; on the left side, the chart gives evidence of the widespread adoption of Autodesk Revit (more than 80%) for BIM models; on 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.

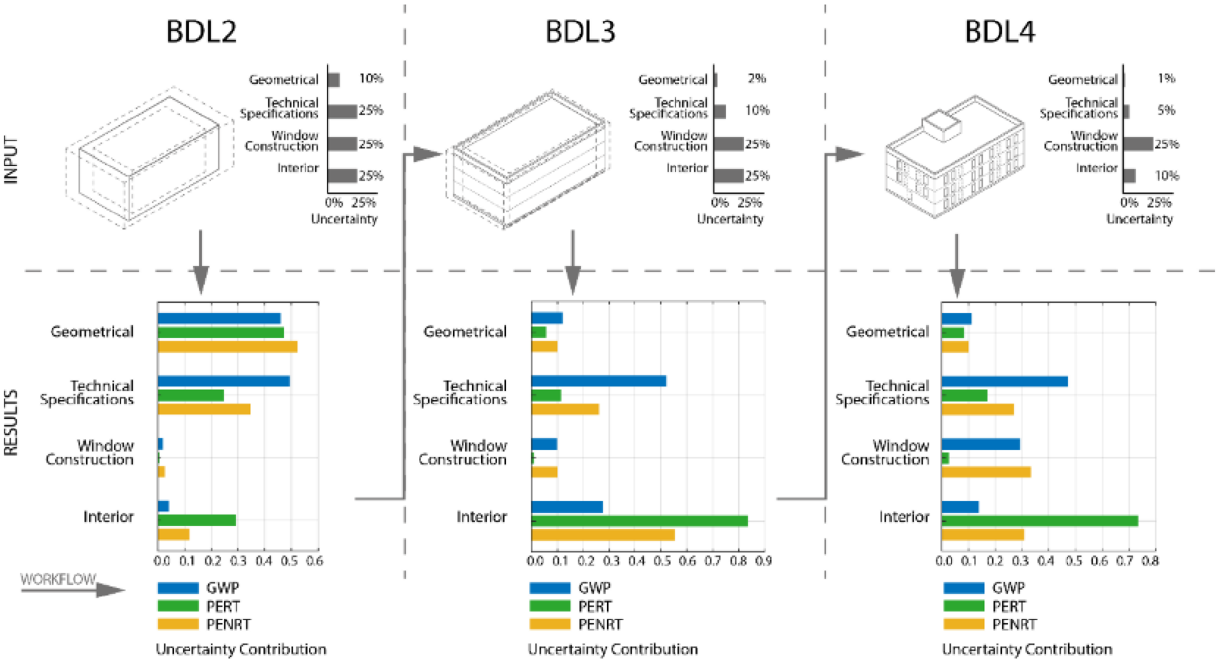


Figure 7: Overview of the used correction factors in a different phase. Source: (Schneider-Marin et al., 2020).

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%.

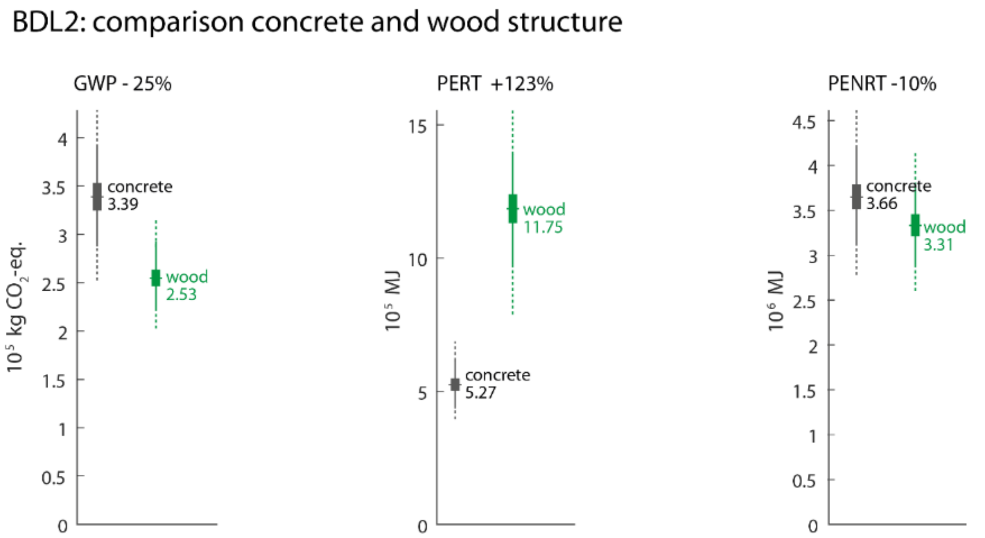


Figure 8: Contribution Analysis and comparison of concrete and timber structure. Source: (Schneider-Marin et al., 2020).

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 .

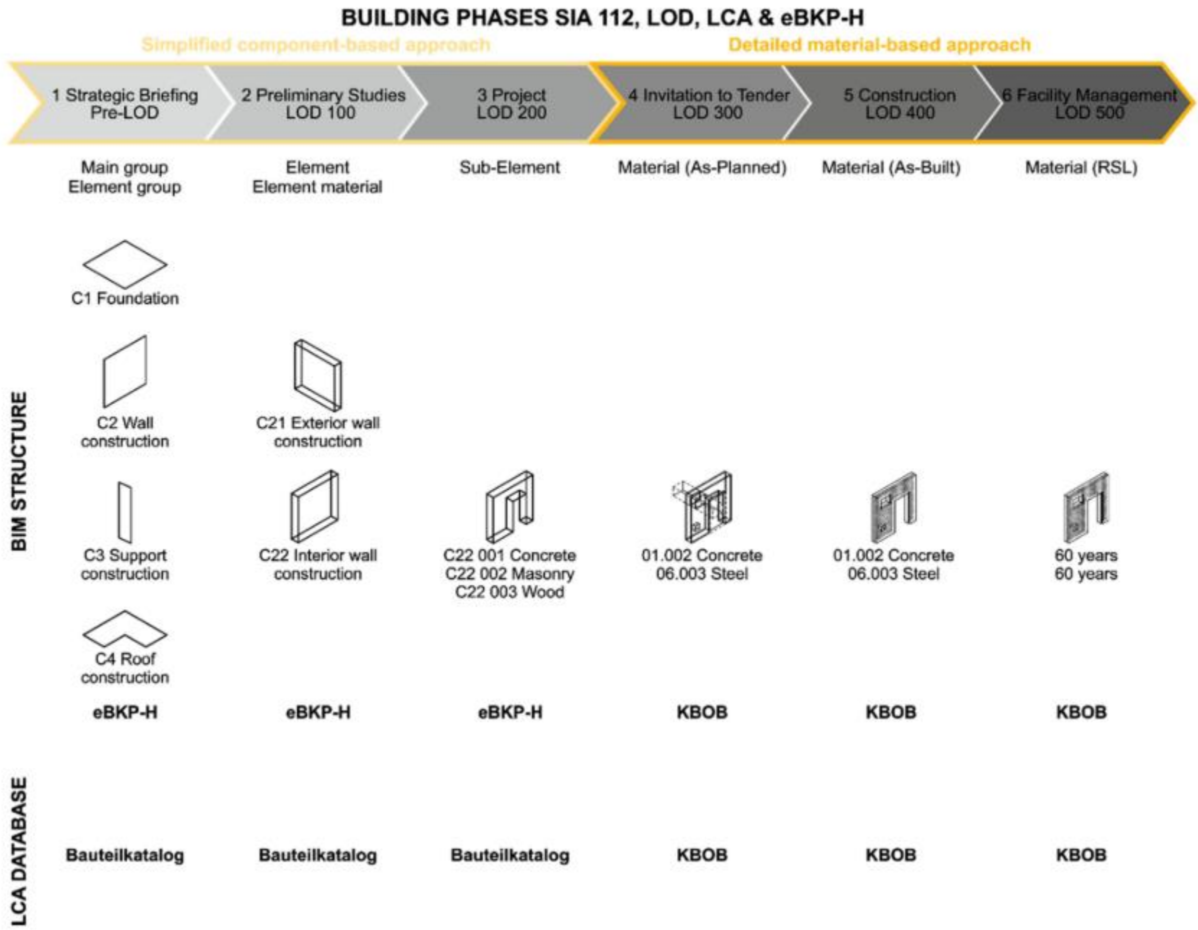


Figure 9: Overview of different BIM data structure and LCA database in a different project phase. Source: (Naneva et al., 2020).

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.

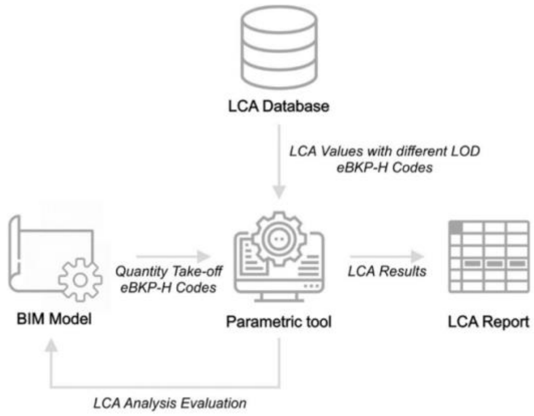


Figure 5: Proposed dynamic approach workflow. Source: (Naneva et al., 2020).

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.

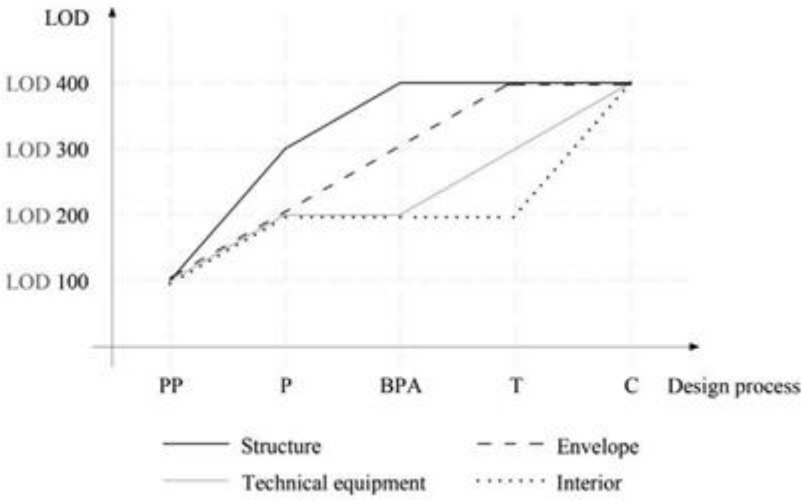


Figure 6: Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction. Source: (Cavalliere et al., 2019).

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.

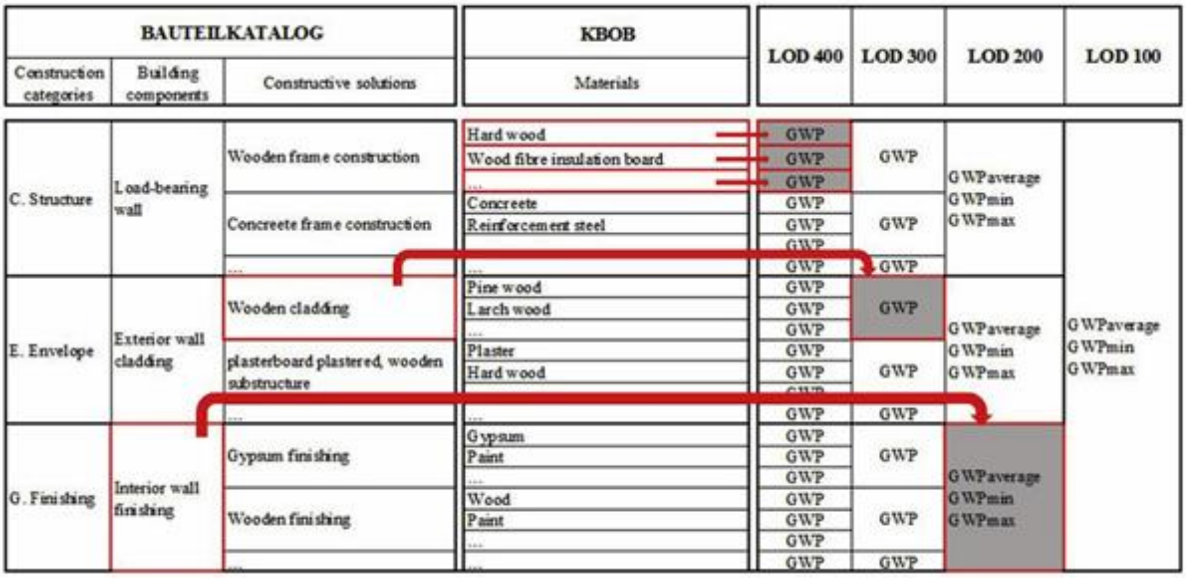


Figure 7: Example of the proposed method for the LCA of an exterior wall above ground at the Building Permit Application phase. Source: (Cavalliere et al., 2019).

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.

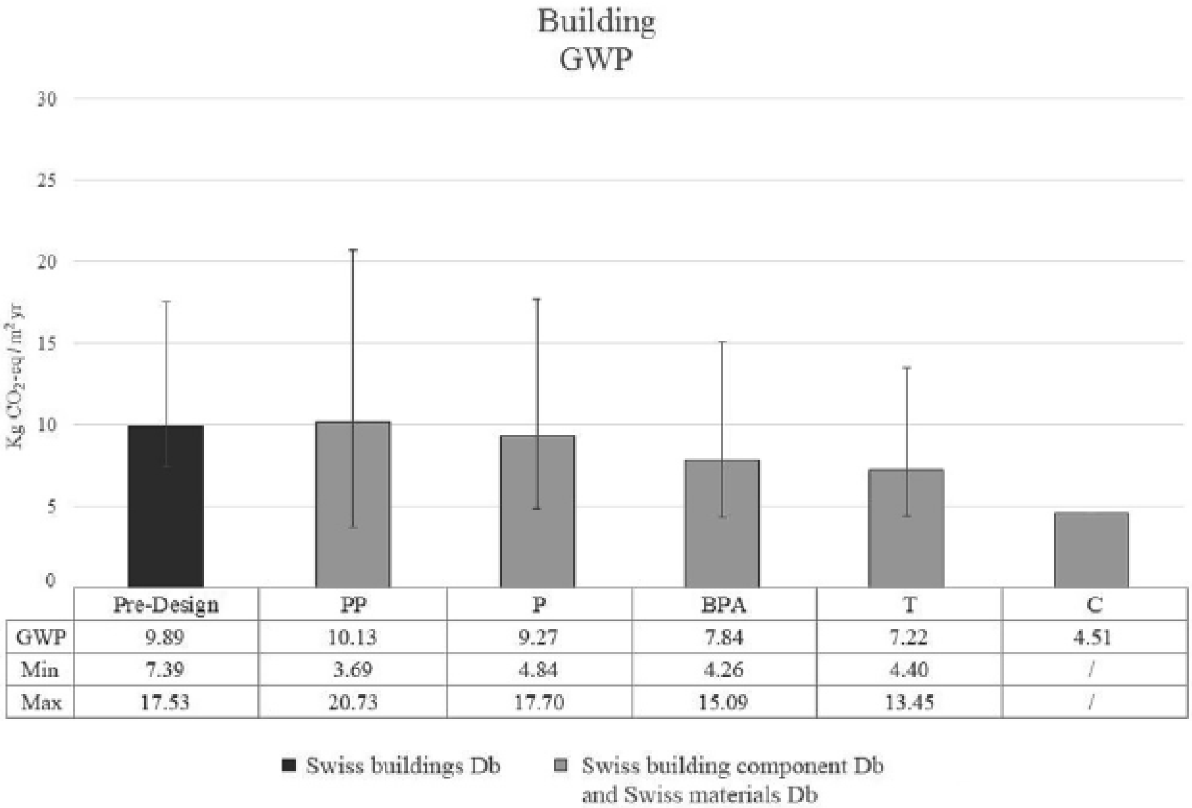


Figure 8: Evolution of calculated GWP of the building during the design process. Source: (Cavalliere et al., 2019).

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.

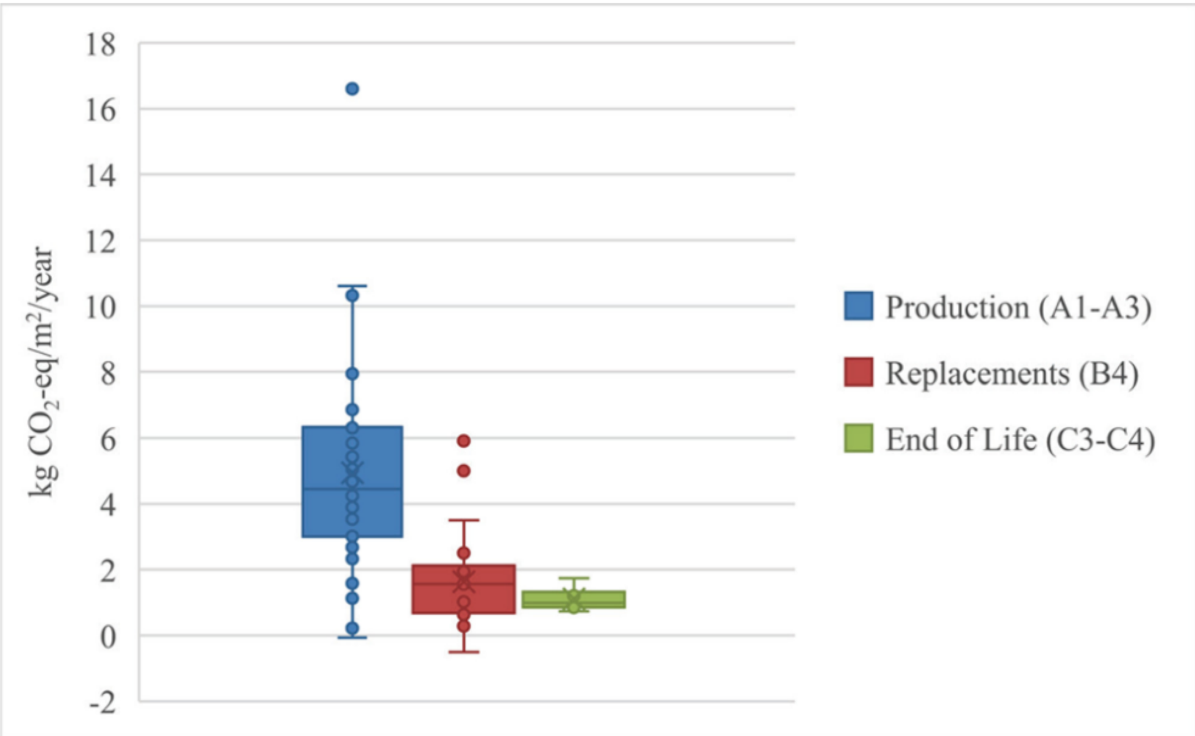


Figure 9: Variations in embodied greenhouse gases from different life-cycle stages representing product stage A1–A3 (56 cases), replacements B4 (42 cases) and end-of-life C3 and C4 (nine cases). Source: (Anderson & Moncaster, 2020).

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.

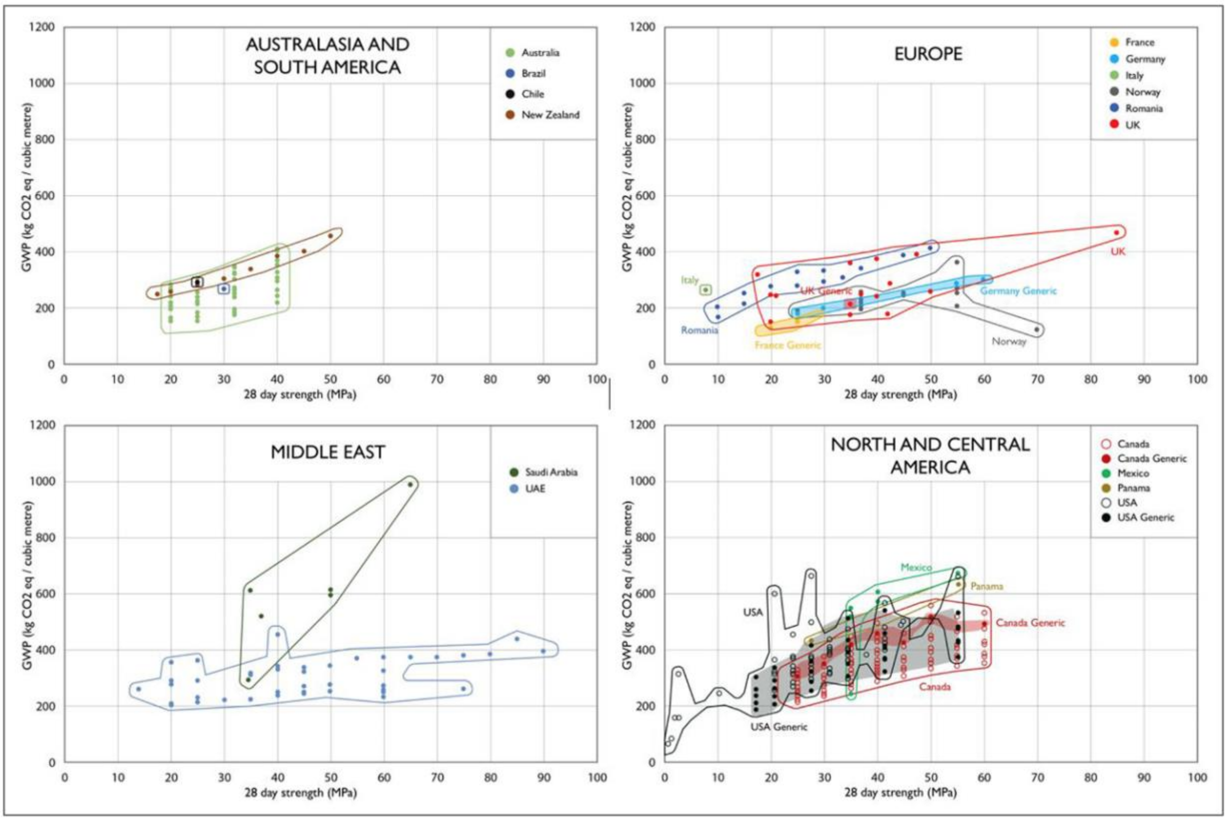


Figure 10: Relationship between GWP and compressive strengths of a concrete by regions. Source: (Anderson & Moncaster, 2020).

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.

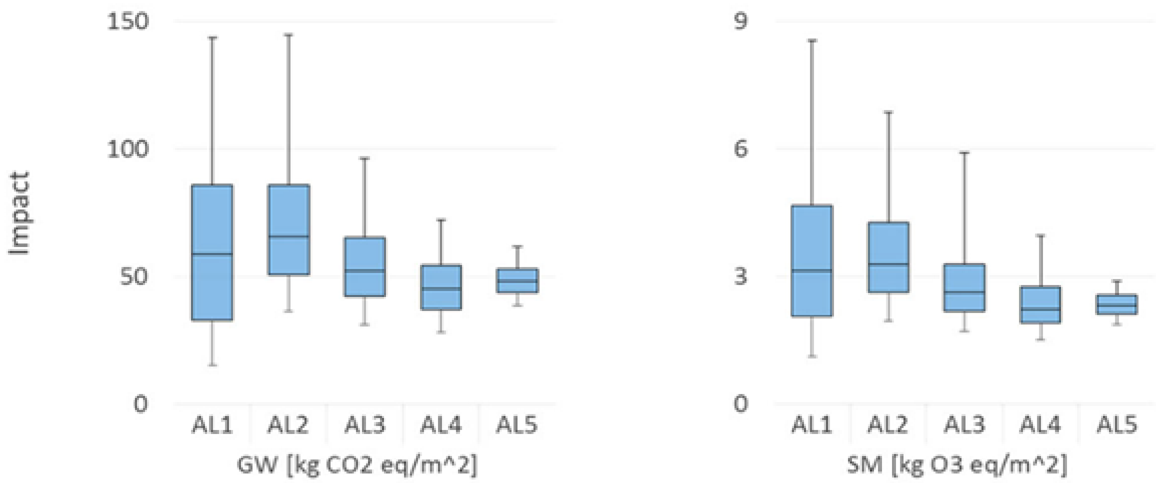


Figure 11: Probabilistic distributions of impact metrics (Global warming, Smog creation) for an ICF wall. AL1 to 5 = Assembly level 1 to 5. CV = Coefficient of variation. MAD-COV = median absolute coefficient of variation Source: (Tecchio et al., 2019).

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.

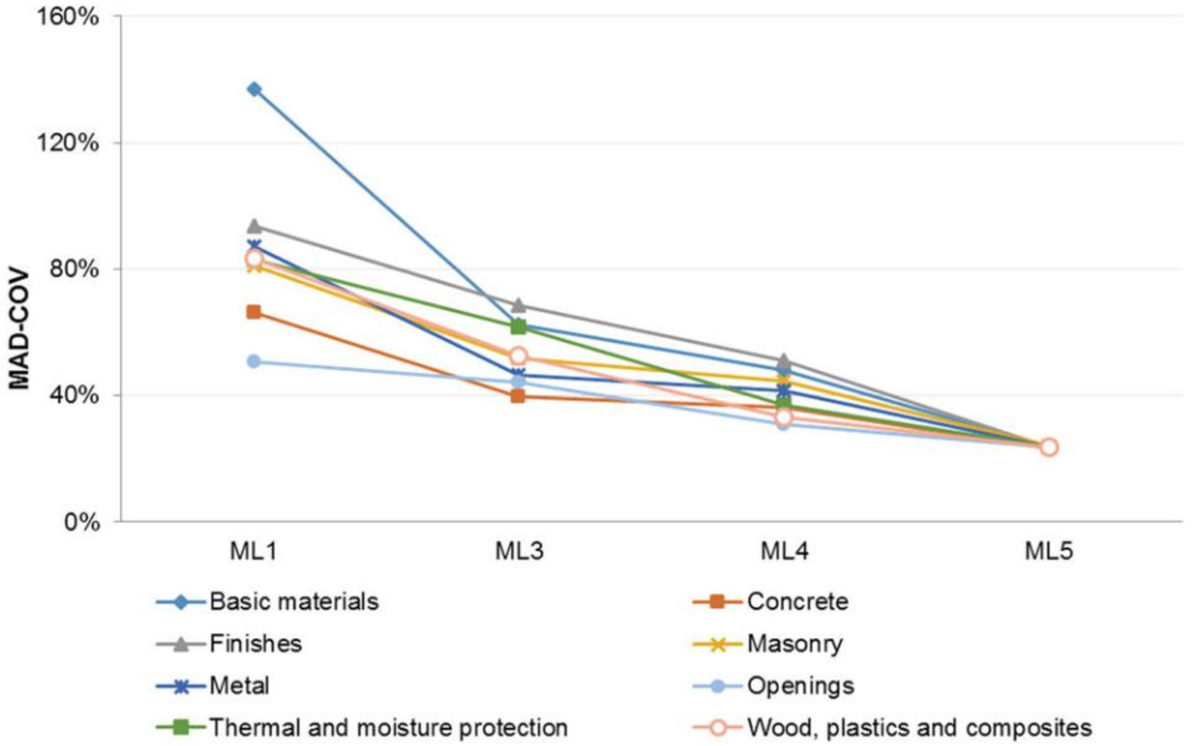


Figure 12: Average median absolute deviation coefficient of variation. Source: (Tecchio et al., 2019).

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.

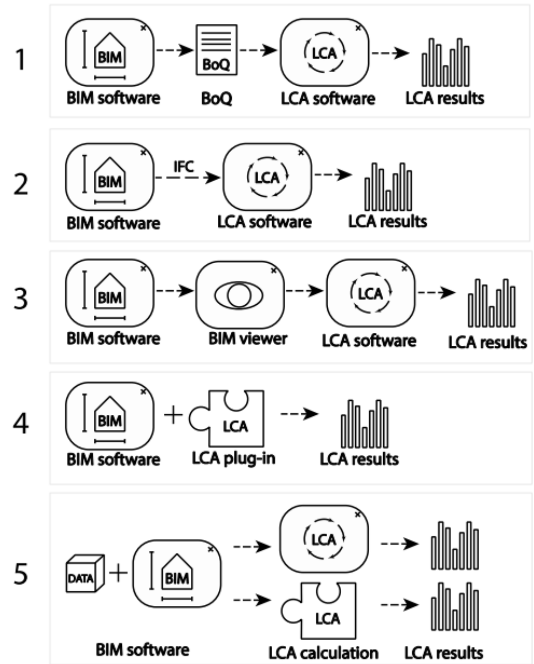


Figure 13: Different BIM-LCA approaches. Source: (Wastiels & Decuypere, 2019).

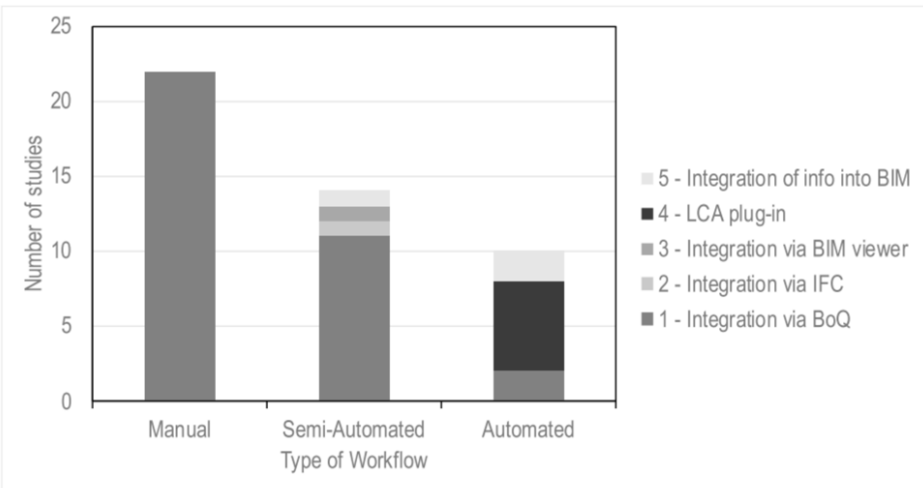


Figure 19: Level of automation in different case studies collected in the systematic literature review. Source: (Obrecht et al., 2020).

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.

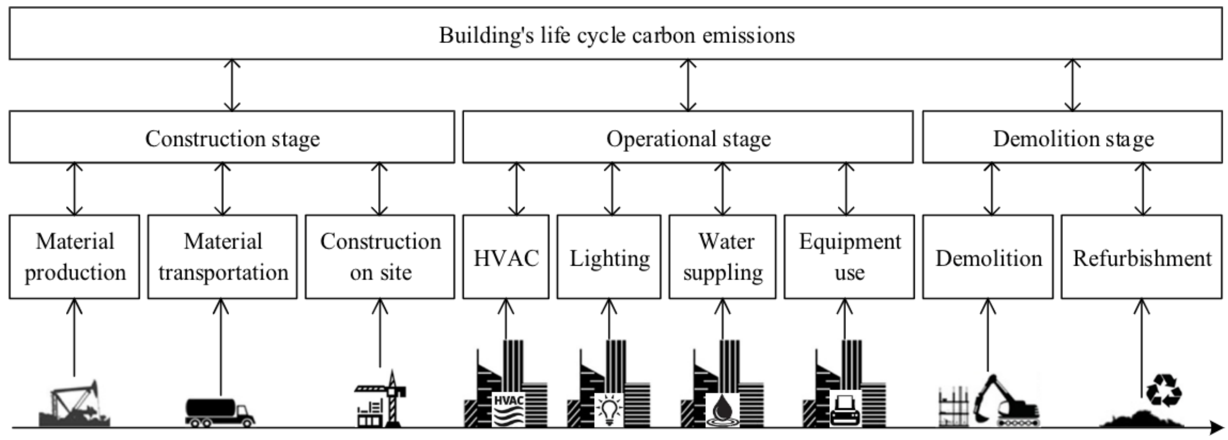


Figure 15: Schema of Boundary of Building`s Life Cycle Carbon Emissions (BLCCE) approach. Source: Lu, Kun et al.

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.

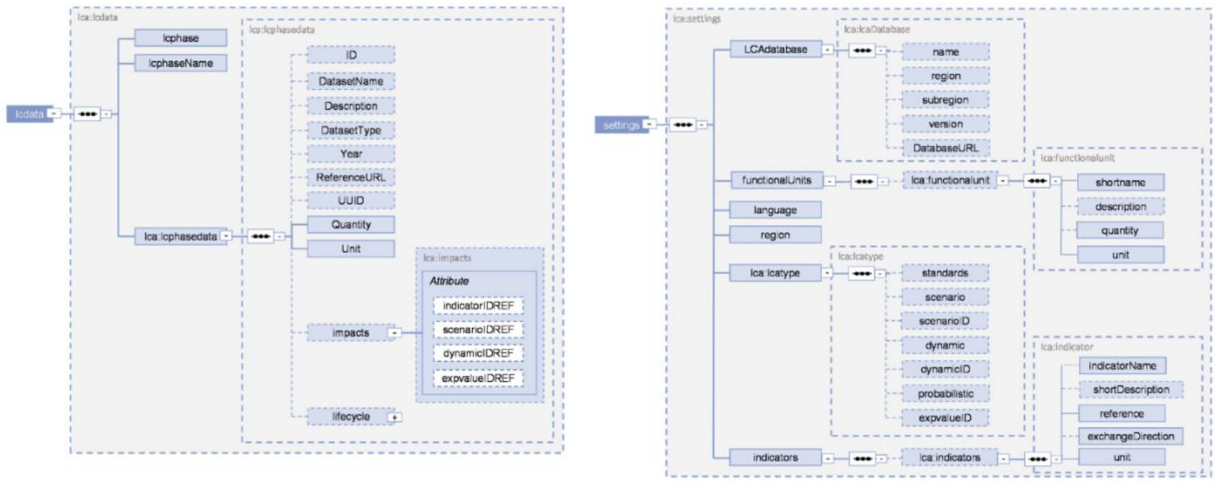
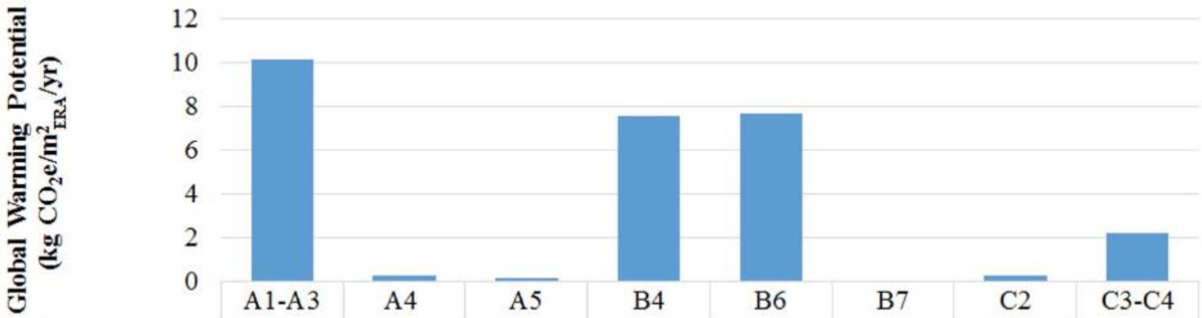


Figure 16: Using LCA in data structure with IFC. Source: (Horn et al., 2020).

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		0.20			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	0.16	0.44	7.66	0.05	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.

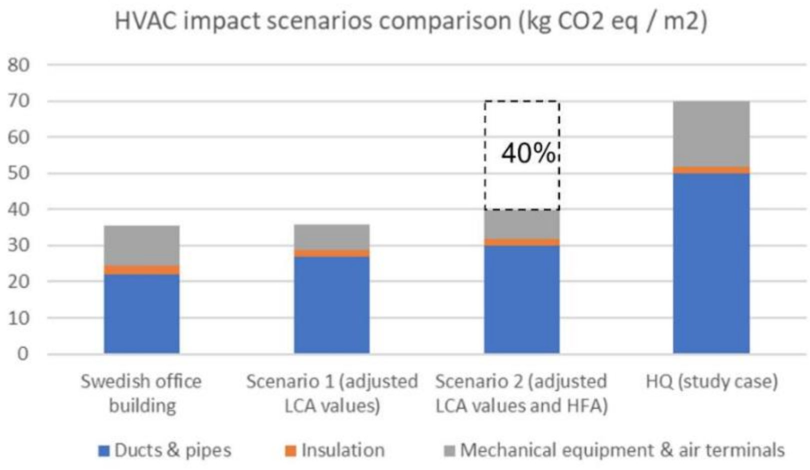


Figure 18: Comparison of different case studies. Environmental impact of HVAC system (per sqm) is significant. Source: (Kiamili et al., 2020).

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.

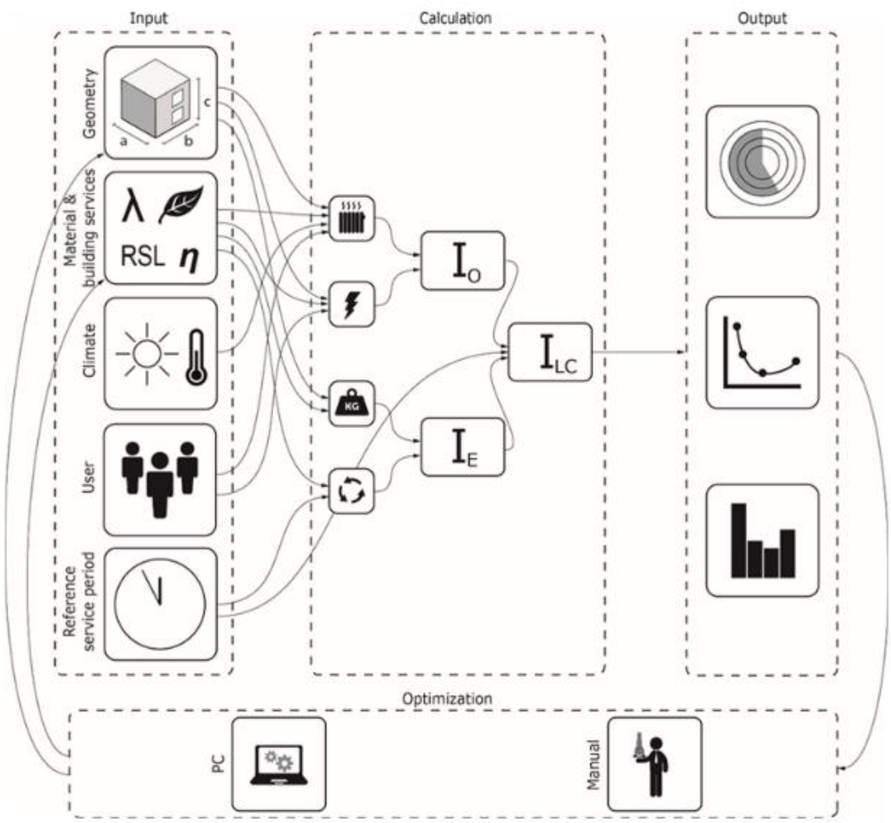


Figure 20: Concept of the parametric workflow. Source: (Hollberg & Ruth, 2016).

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).

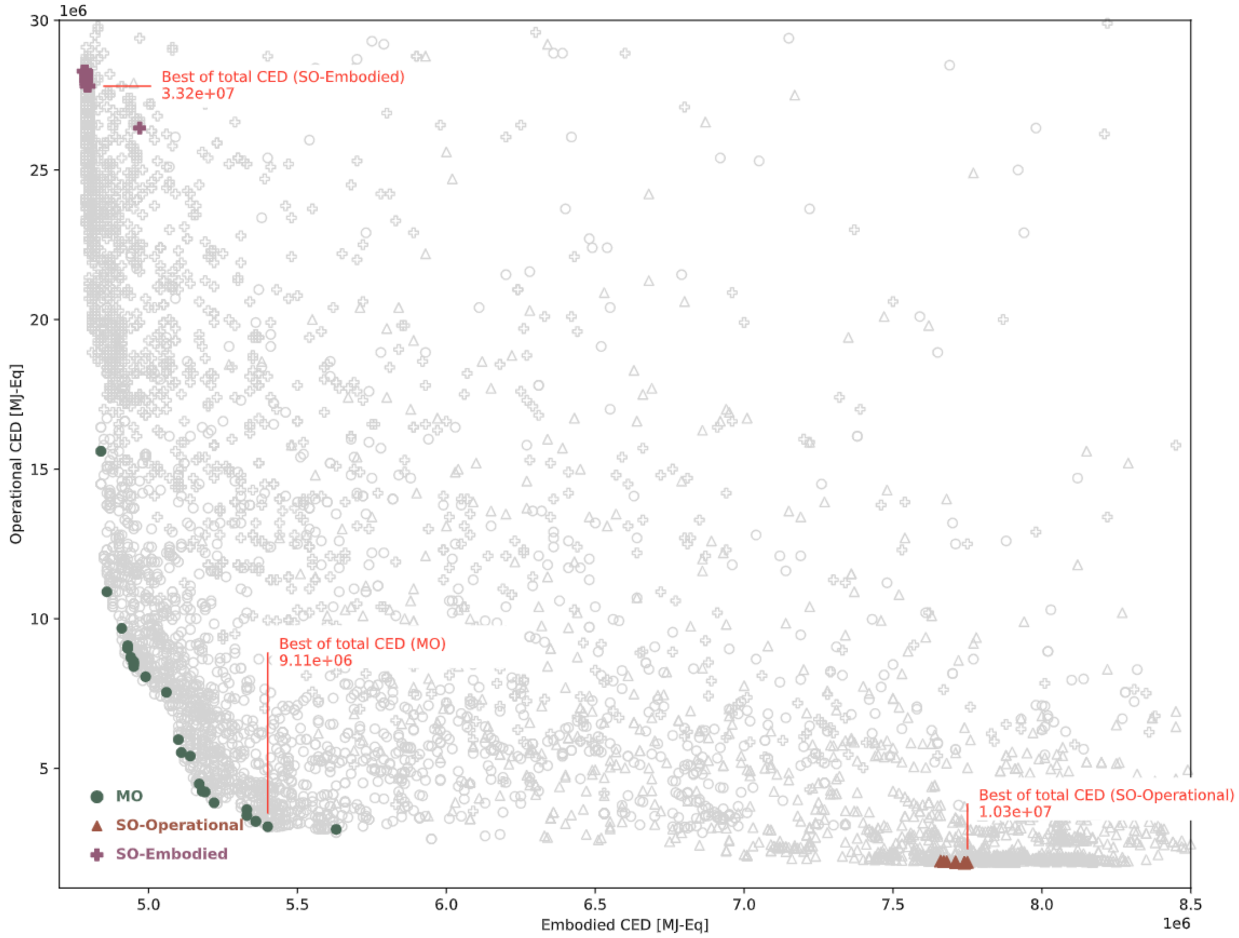


Figure 21: Results of the multi- (MO - green dot) and single-objective (SO-operational - red triangle, SO-operational - purple cross) optimizations on the objective space for cumulative energy demand (heating energy carrier: gas). Source: (Kiss & Szalay, 2020).

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.

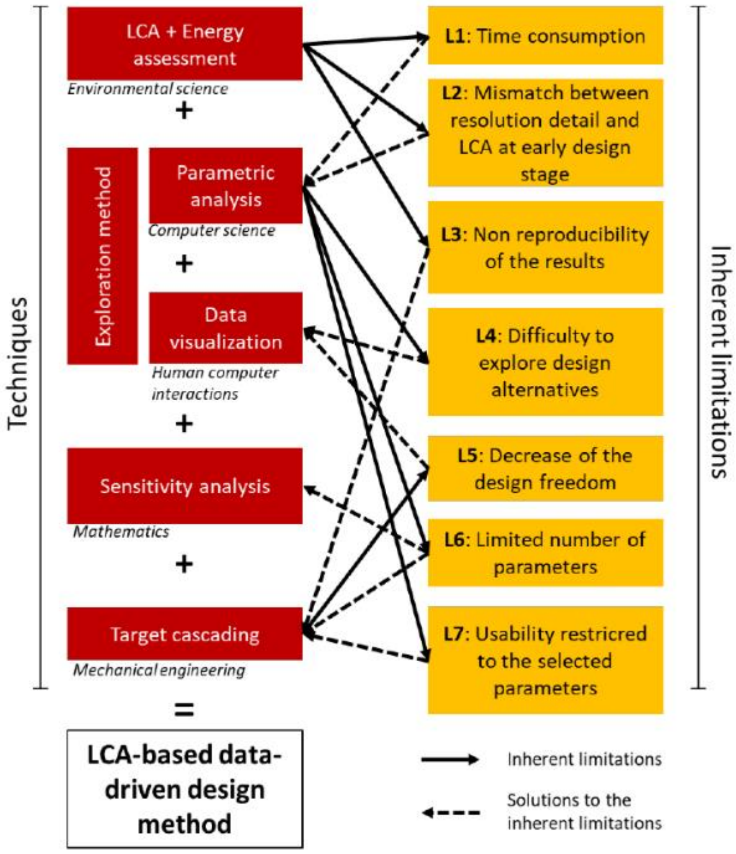


Figure 22: Techniques for increasing LCA usability at early design stages and their identified inherent limitations. Source: (Jusselme, 2020).

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.

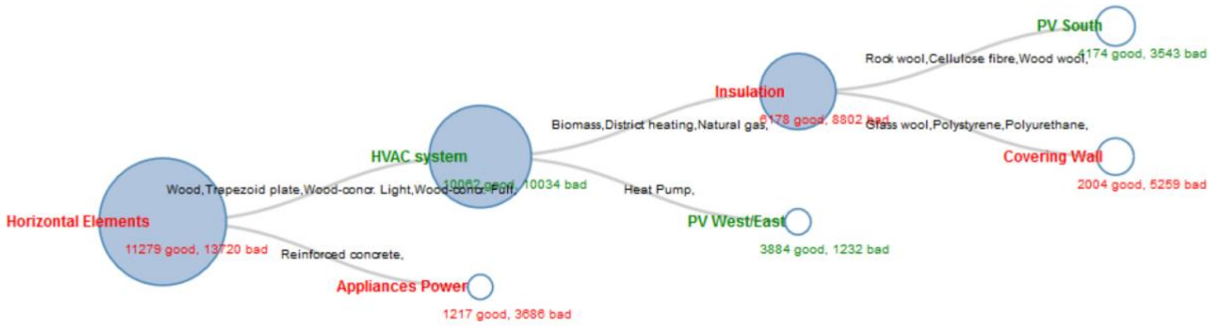


Figure 29: Visualization of the smart living building data set with a Decision Tree. Source: H-IST UNI-FR and (Jusselme et al., 2017)

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).

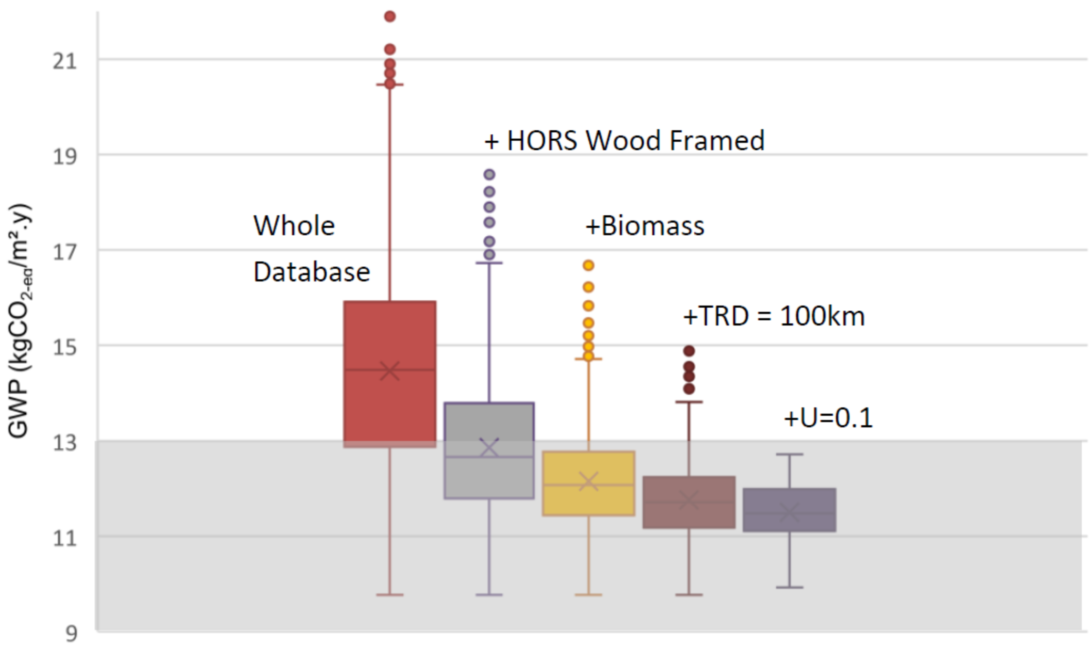


Figure 23: *Distribution of the GWP impacts of the full database (left), and other subpopulations with cumulative constraints by the sensitivity indices of the design parameters. The grey zone represents GWP impacts below the SIA2040 objective. GWP axis starts at 9 kg $CO2_{-eq}/m_2.y$.*

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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