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BIM-based LCA of Buildings: The Influence of LOD

Master Thesis

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Files Used

For this thesis the following files were used. They can be found on the USB drive attached to the thesis.

- Building Information Model as an Autodesk Revit file
- Multiple Microsoft Excel files for the calculation of the LCI and LCA
- Mendeley library file
- The master thesis as PDF-file

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I hope that you will enjoy reading this thesis.

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Abstract

The construction and operation of buildings has been identified as a major factor in reducing global carbon emissions mitigating climate change effects. In recent years, the Life Cycle Assessment (LCA) methodology has been connected to Building Information Modelling (BIM) to assess a variety of environmental impacts of buildings. The assessment of buildings' environmental performance in early design stages supports design improvement. However, the challenge remains to provide reasonably accurate and time-efficient assessments in early design stages. As BIM models are constantly evolved throughout the design process, the results of an LCA based on a BIM model in different stages can vary significantly. The purpose of this research is to investigate the difference in LCA results from differences of BIM model's Level of Development (LOD). This is achieved by comparing two LCA studies: One based on the quantities extractable from a BIM model with LOD 300 and a second assessment based on an LOD 100 model, which is usually applied in early design. The results show that the environmental impacts reported through LCA increase along with the LOD and that this correlation allows projections and the establishment of correction factors.

Kurzfassung

Der Bau und Betrieb von Gebäuden beeinflusst den globalen CO2-Ausstoßes wesentlich, und damit auch die Auswirkungen der Klimakrise. In den letzten Jahren wurde die Methode des Life Cycle Assessment (LCA) mit Building Information Modelling (BIM) verbunden um eine Vielzahl von gebäudespezifischen Umwelteinflüssen zu beurteilen. Die Beurteilung in frühen Planungsstadien erleichtert die Berücksichtigung von Umweltkriterien in der Planung. Aber genau in den frühen Planungsstadien stellt eine ausreichend genaue und gleichzeitig zeit-effiziente Ökobilanz ein Problem dar. Denn BIM-Modelle verändern sich im Laufes des Planungsprozesses und so können auch die Ergebnisse der BIM-basierten Ökobilanzen signifikant variieren, abhängig vom aktuellen Planungsstand. Diese Masterarbeit untersucht den Einfluss, den der Level of Development (LOD) auf die Ergebnisse der Ökobilanz hat. Das geschieht durch den Vergleich zweier Ökobilanzen: Eine Ökobilanz wird auf Basis der Mengen und Information durchgeführt, die sich aus einem LOD 300 Model entnehmen lassen. Die andere basiert auf einem LOD 100 Model, welches einem frühen Planungsstand entspricht. Die Resultate zeigen, dass der Umwelteinfluss des untersuchten Gebäudes gemeinsam mit dem LOD des BIM Modells steigt und, dass diese Korrelation für Projektionen von frühen auf spätere Planungsstadien über Korrektorfaktoren genutzt werden kann.

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1 Introduction

On the next few pages the essence of the thesis is explained. First the motivation and the goal of this thesis is stated as a basis for the development of the hypotheses. Then the approach to the testing of the hypotheses and the structure of the report is described.

1.1 Motivation and Goal

It is paramount that humankind cares for their environment and takes responsibility for its well-being. In order to ensure that following generations can draw from the same natural resources as we do and are able to live their lives in comparable prosperity, it is essential that we get used to thinking in longer terms. When considering multiple years or decades, even small influences on the environment can add up and pose significant threats to earth's ecosystem. Progress in science and technology has given us the ability to actually influence the entire ecosystem in a significant way. And with some delay, it has also provided us with the methods to measure our footprint on earth's ecosystem. It is crucial to use these tools to re-evaluate current practices as well as in the planning of new actions. Life-cycle assessment (LCA) is one of these methods. It quantifies the environmental impacts of a product over its entire life-cycle, starting from the sourcing of raw materials to the final disposal or recycling. LCA is defined in Standard ISO 14040 [1] as a generic approach that can be adapted to take into account a specific product's characteristics. Trying to widen the field of application of this approach, research projects e.g. IEA EBC Annex72 tackle the task to adapt LCA to buildings. However, buildings comprise of numerous products and are vastly more complex to assess.

Obtaining information on materials that were used in the building proves to be a very time-consuming process. But Building Information Modelling (BIM), a fast-growing trend in the construction industry that makes use of recent developments in information technology promises to solve this problem. By managing all information of a construction project in a digital 3-dimensional model, it allows the extraction of the required information from the model. This way, an LCA can be conducted much faster.

It seemed to be evident, that an LCA is performed when the design is complete and the information in the model is comprehensive and accurate. However, at such a design stage, major design choices have already been made or are greatly limited. But what if there is a correlation between the LCA conducted on the basis of a very detailed digital model and one that uses a model in an early design stage? If there is a correlation that proves to be significant, BIM-based LCA would be a time-efficient and meaningful instrument in the early design stages of a building project. It would pave the way for environmental considerations to be a more important part of any building design process.

The goal of this thesis is to investigate whether such a correlation exists, and if so, how it can be used to conduct a more complete LCA in an early design stage than would be possible with the information available then.

1.2 Hypothesis

The research behind this report was built on the following hypothesis:

H1: When using BIM models for LCA of buildings, the overall Level of Development (LOD) of the model, due to its variability, is influencing the results substantially. Thus, model quality and completeness have to be taken into account in BIM-based LCA in order to provide complete and representative results.

Three hypotheses were derived from the main hypothesis:

- H1.1: The scope of the model (modelled and un-modelled elements) as well as the information provided within the modelled elements both significantly influence LCA results.
- H1.2: Differences in quantity take-off used for establishing the LCI result from different ways in which BIM models are evaluated in early and developed design stages.
- H1.3: The mentioned differences in both, scope and quantity take-off method can be taken into account by applying correction factors that compensate for information that is not available or not extracted from the model at an early design stage.

Moreover, four Research Questions (RQ) were derived as a focus for the research:

- RQ1: What information is required to conduct an LCA on the basis of a BIM Model (LOD 300)?
- RQ2: How can this information be integrated into or connected to the the model in order to support a (semi-)automated assessment?
- RQ3: What are the effects of different ways of quantity take-off on the results of the LCA? What conclusions can be drawn about the assessment in different design stages?
- RQ4: What is the influence of un-modelled elements on the LCI?

1.3 Approach

These research questions were answered by conducting a case study in which LCAs were based on BIM models with different LODs. The LCI and LCA results were then compared.
A LOD 300 model was the basis for the Base Case (Case A) and Case B, and a simpler version with LOD 100, corresponding to conceptual design, was used for Case C. The difference between these two models can be seen in Figure 5.4. The graphic representation of the models and the list of elements contained in the scope show that the LOD 100 model contains significantly fewer types of model elements than the LOD 300 model.

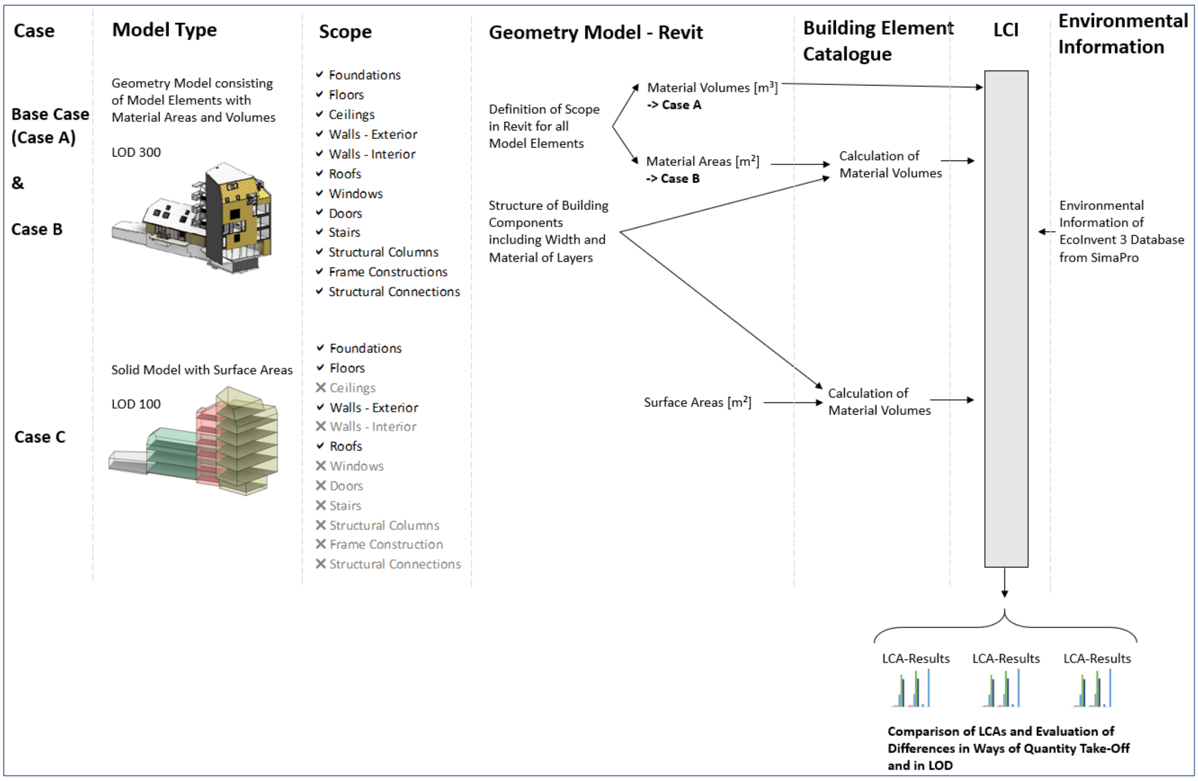


Figure 1.1: Overview

In all cases the BIM models were the source of the material information and quantities, i.e. material definition, area, and volume. In the Base Case (A) all of this information, including the material volumes, was used. In Case B, the material areas multiplied by the thickness of each material layer to give the material volumes. Since the LOD 100 model provided only material areas, Case C followed the same approach as Case B and used these areas in combination with the structure of building components of the LOD 300 model to calculate the material volumes.
Then, material volumes were multiplied by their specific weights to calculate the mass and the

LCA scenarios for the life cycle of each of the materials were defined. These scenarios included the production, the transport, and End-of-Life (EoL) of the material. Moreover, scenarios for the replacement of materials, and energy and water use were described.
Subsequently, all of this information was supplemented by environmental information from the EcoInvent 3.3 database [2].
Finally, the LCA results were calculated and compared to test the hypotheses and answer the research questions.

1.4 Structure

This thesis was structured to go increasingly deeper into the subject. Starting with an explanation of basic concepts (Chapter 2) and expanding with the current state of the art (Chapter 3), it then describes the methodology (Chapter 4). Chapter 5 describes the case study performed, followed by the results (Chapter 6).
In chapter 7 "*Discussion*" the results are summarized, analyzed, and interpreted. The thesis then finishes with conclusions and outlook in chapter 8.

2 Description of Basic Concepts

2.1 Building Information Modelling

BIM, short for Building Information Modelling, "*is a business process for generating and leveraging building data to design, construct and operate the building during its lifecycle*" [3]. The building data includes the geometry as a three-dimensional representation of the building but does not stop there. It also contains non-geometrical information e.g. material information, costs, and technical properties [4].

All of this data is gathered and managed in a building information model, also abbreviated as BIM, although sometimes clarified by adding "model", e.g. BIM model. This notation will be further used in this thesis. BIM as a process serves the building during its whole life-cycle. It facilitates computer-assisted work in design, construction and use, by enabling direct communication between BIM authoring software and specialized design software, and acts as a centre for all the information processed. As centre of building information it ensures consistency of the entire design and prevents the loss of information between design stages [4]. Figure 2.1 shows the visual representation of the BIM model that has been used in this thesis.

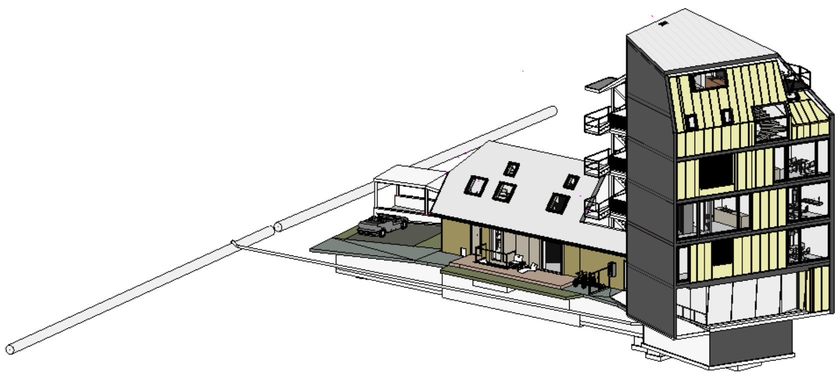


Figure 2.1: BIM model

2.1.1 Level of Development

BIM models are constantly evolving over the course of the design stages. While a BIM model might be quite a rough representation of the building in early design, it includes more and increasingly accurate, as well as reliable, information in later stages. This process is described by the Level of Development (LOD).

The American Institute of Architects (AIA) defines the LOD as "*the degree to which the element's geometry and attached information have been thought through*" [3]. They specify five steps of

LOD from LOD 100 to LOD 500 [5]:

LOD 100 Generic representation, also by means of symbols, which shows the existence of the component, without deepening the shape, size, or its precise location.

LOD 200 Representation of generic systems with approximate size, quantities, shape, location and orientation

LOD 300 Well-defined systems for specific size, quantities, shape, location and orientation, intended to be measured directly from the model without reference to non-modeled information

LOD 400 Representation of specific systems in terms of size, quantities, shape, location and orientation, with the addition of information related to the assembly and installation for the manufacture of the component itself

LOD 500 Corresponding to the as-built model, since it belongs to the field of the representation of the elements checked in the building site

This list was extended by the BIMForum in its "*BIM Level Forum of Development Specification*" by another entry, LOD 350, "*to better address the information levels required for effective trade coordination.*" [5]
Definitions of European origin consist of only five steps for the better part. For example, van Treeck et al. divide the LOD into four aspects, each of which has five steps [6].
Swiss standards also specify five steps of LOD, from LOD 100 to LOD 500. Moreover, they separate the LOD into two aspects, Level of Geometry (LOG) and the Level of Information (LOI). The LOG specifies the amount of geometrical information of a model element, whereas the LOI defines how much non-geometrical information, e.g. material definition and the specific weight, is included [7].
Swiss standards also specify five steps of LOD, from LOD 100 to LOD 500. Moreover, they separate the LOD into two aspects, Level of Geometry (LOG) and the Level of Information (LOI). The LOG specifies the amount of geometrical information of a model element, whereas the LOI defines how much non-geometrical information, e.g. material definition and the specific weight, is included [7].

Fig 2.2 shows an overview over a definition of five-step LOD, put together by Cavalliere C. et al. in 2016 [8].
The red arrow and label "*Design Process*" was added to this overview to emphasize that the LOD advances together with the design process. Starting with a LOD 100 model in early design, the model evolves with the design choices being made until it represents the building as-built. This means that, inverted to the design process, the potential for change decreases.

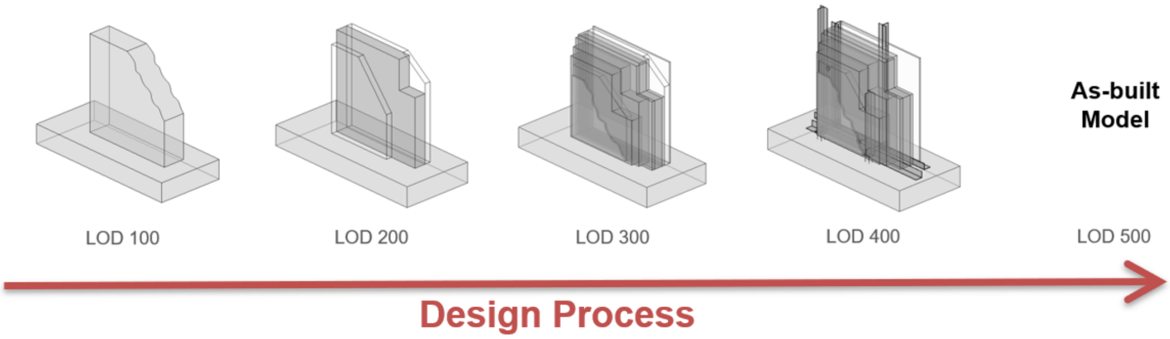


Figure 2.2: Steps of LOD [8]

2.1.2 Information Exchange

The American National Institute of Building Sciences (NIBS) specifies in its National BIM Standard (NBIMS) "*that the BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms.*"[3] This enables the BIM model to be the centre piece of construction projects using BIM. But this ideal is challenged by the many software firms that use different proprietary data formats in their product families. To connect all of these software programs, another data format is needed that is independent of software programs and establishes the common ground required to allow free data exchange. [9, 4]
BuildingSMART created such an exchange file format, called the Industry Foundation Classes (IFC). It allows the exchange of entire BIM models, and can be adopted to support the exchange of just a specific set of information. This exchange can be developed by the Information Delivery Manual (IDM) for any set of information needed. The IDM accurately describes the exchange process by defining the model elements to be exchanged, including attributes and information quality, as well as the timing of exchange [10]. The IDM results in a graphical notation of the whole exchange process. This notation also illustrates the Exchange Requirements (ER) that have to be implemented into the software, e.g. the access to very specific information of all doors modelled, like the handle installed. The software is then adapted according to the IDM, including the ER, creating a Model View Definition (MVD) in the process. Compared to the exchange of entire BIM models via IFC, MVD enables the exchange of a specific set of information. [4]

2.2 Sustainability

Sustainability is the state that we move towards by sustainable development [11], which the United Nations (UN) World Commission on Environment and Development (WCED) defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*" [12]. The UN further defined three aspects of sustainability. These are the economic, environmental, and social aspect (See figure 2.3). The following definitions are from the report of the UN General Assembly 24 Oct 2005 [13]:

- **Environmental sustainability** is the ability to maintain rates of renewable resource harvest, pollution creation, and non-renewable resource depletion that can be continued indefinitely.
- **Economic sustainability** is the ability to support a defined level of economic production indefinitely.
- **Social sustainability** is the ability of a social system, such as a country, to function at a defined level of social well being indefinitely.

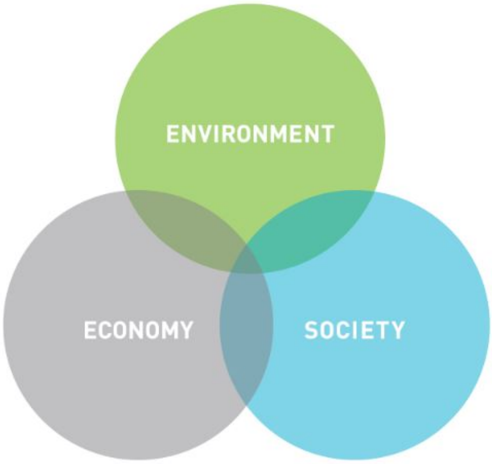


Figure 2.3: Pillars of Sustainability [14]

2.3 Life Cycle Assessment

LCA, short for Life Cycle Assessment, is a method for investigating and quantifying the environmental aspect of products. EN ISO 14040 defines it as "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*". A product's life cycle includes "*raw material acquisition through production, use, end-of-life treatment, recycling and final disposal*" [1]. EN ISO 14040 lists the following four purposes of an LCA:

- "*identifying opportunities to improve the environmental performance of products at various points in their life cycle,*"
- "*informing decision-makers in industry, government or non-government organizations,*",
- "*the selection of relevant indicators of environmental performance, including measurement techniques, and*"
- "*marketing*", e.g. ecolabeling

An LCA study consists of four phases, as shown in Figure 2.4.

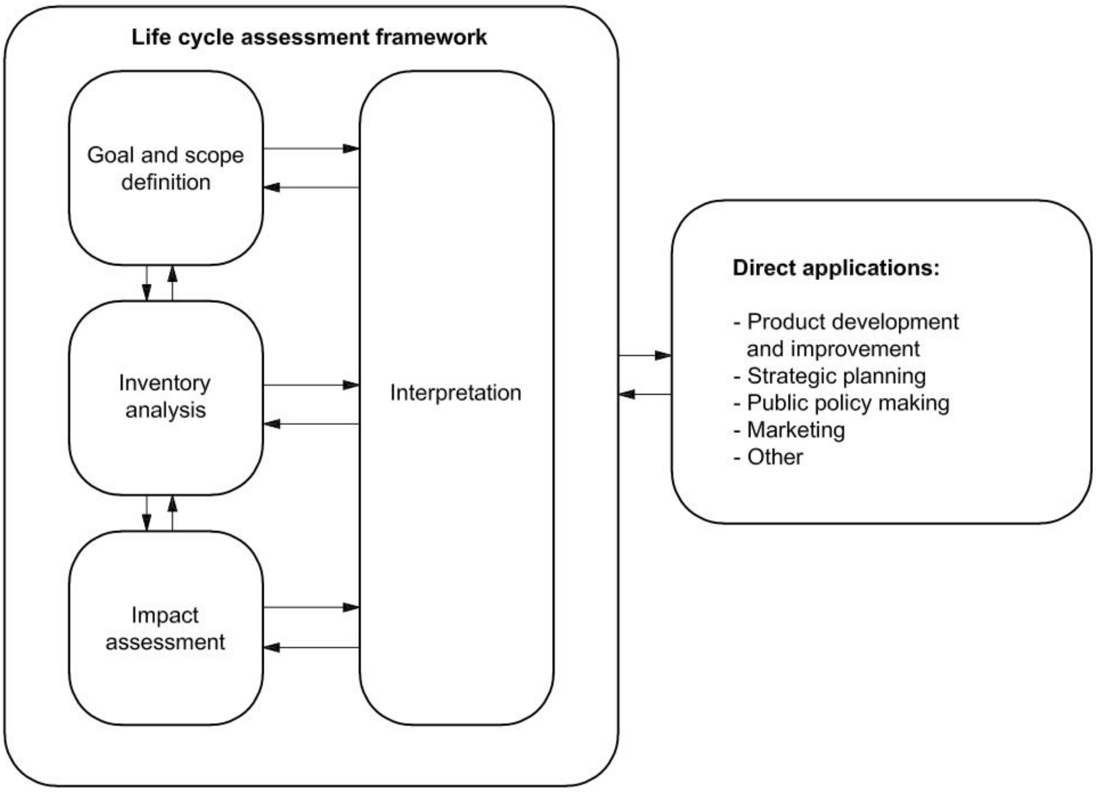


Figure 2.4: Framework LCA [1]

- In first phase, the goal and scope definition, the product system and its boundaries are defined. The boundaries include cut-off criteria by mass, energy, or environmental significance to sort out influences of minor magnitude. Furthermore, the Life Cycle Impact Assessment (LCIA) methodology, the types of impact, and data requirements, as well as the functional unit are stated. This is the "*quantified performance of a product system for use as a reference unit*" [1].
- The second phase, Life Cycle Inventory (LCI) analysis focuses on collecting and calculating data, and the allocation of inputs and outputs to the different products.
- The third phase, LCIA, is about the "*selection of impact categories, category indicators and characterization models, assignment of LCI results to the selected impact categories (classification), calculation of category indicators results (characterization)*" [15].
- And the final phase, Life Cycle Interpretation, reflects on the previous steps by identifying significant issues, and checking for completeness, sensitivity and consistency. It also contains the conclusions, limitations, and recommendations of the study.

2.3.1 Life Cycle Assessment of Buildings

Buildings are complex products, comprising of numerous smaller products in large quantities. In addition, in contrast to factory-made products, a building's factory is the construction site, and it is different for every construction project. European Standard EN 15978 acknowledges the specific challenges that are connected with LCA of buildings and proposes a specific framework. This framework expands on the framework of the LCA described in EN ISO 14040. Two of the most notable modifications are the adaptation of the four original steps of the LCA framework and the expansion of the LCS.

The LCA framework described in EN ISO 14044 divides the entire life cycle into materials production, manufacturing process, use phases and "*others*". Figure 2.5 is from EN 15978 and shows the suggested Life Cycle Stages (LCS) for buildings. The life cycle is split into product stage, construction process stage, use stage, and end of life stage, each consisting of multiple more detailed stages. The product stage includes environmental impacts occurring during raw material supply, transport, and manufacturing and associated processes. This is defined as cradle to gate in EN 15804 [16].

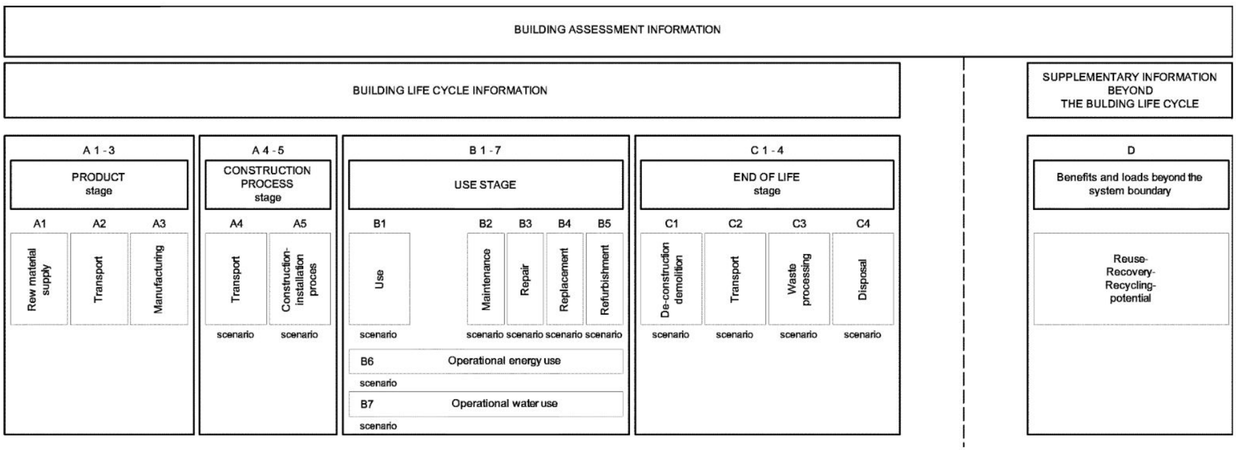


Figure 2.5: Life Cycle Stages of Building LCA [17]

The case study performed in this thesis follows the framework of EN 15978. Figure 2.6 shows a summary of this framework.

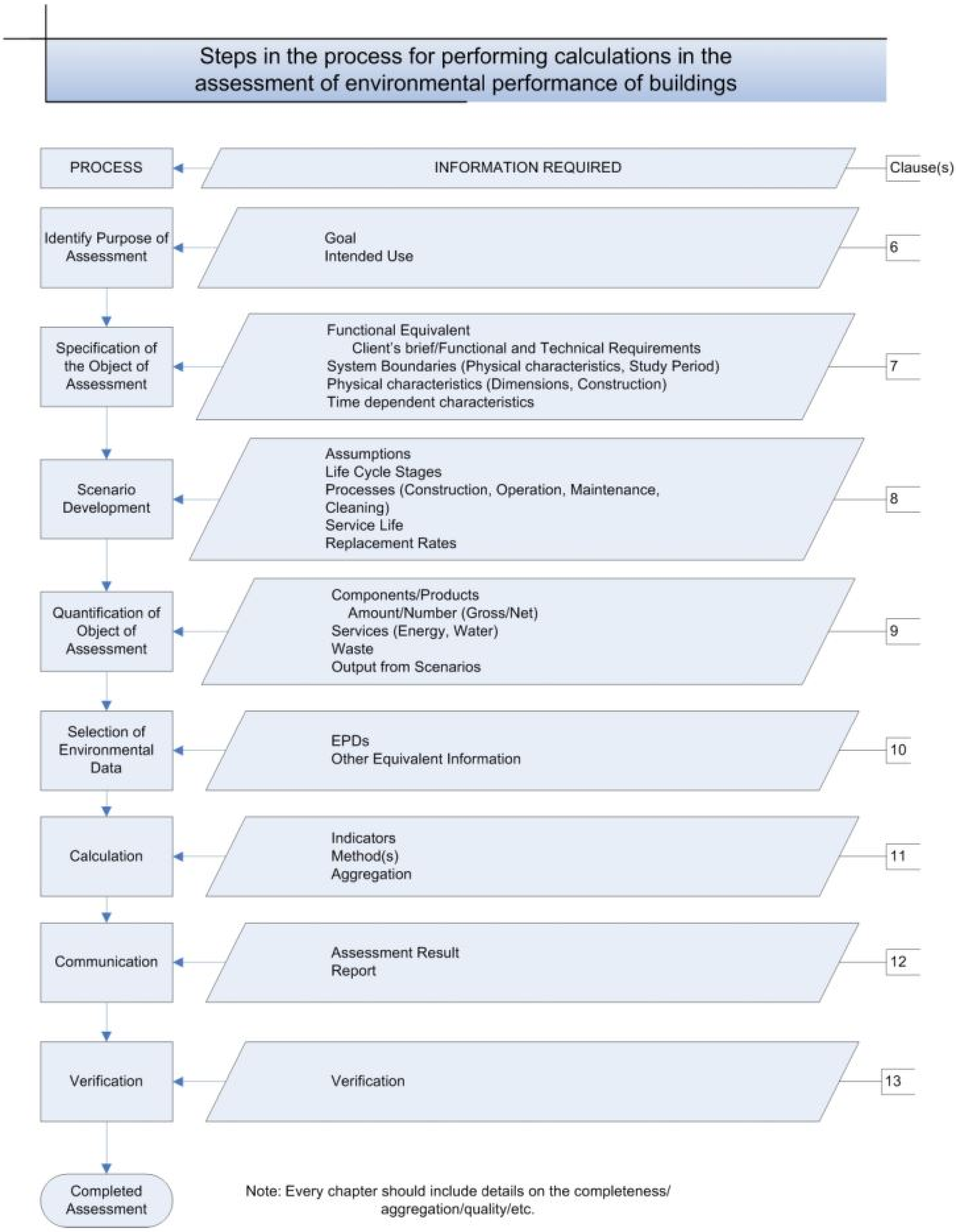


Figure 2.6: Steps of Building LCA [17]

3 State of the Art of BIM-based LCA

Based on the foundations explained in the previous chapter, we can now go deeper into specific subjects. In this chapter, the current state of two subjects that are essential to the thesis have been researched. These are the state of BIM-LCA application and the corresponding tools, and information requirements.

3.1 Stage of Application and Tools

Although BIM and LCA software seems to be a good match, one providing the data and the other evaluating it, the existing software lacks interoperability. But the last few years showed an increasing number of methods with proofs of concept that were developed to bridge this gap [18, 19, 20]. Already in 2015, Kreiner et al. "*acknowledged the integration of LCA in BIM as a way of improving sustainability performance of buildings*"[21, 22]

Andriamamonjy et al. [23] worked on the integration of BIM in Building Energy Performance Simulation (BEPS), which can be compared to the demands of the coupling of BIM and LCA.
In their 2018 article they list three ways of using BIM as an information source for BEPS:

- First, integrating a tool directly into the BIM software or using an Application Programming Interface (API) for direct coupling.
- Second, export the relevant information, e.g. material information and quantities, from the BIM software to a file, e.g. using the Green Building XML schema (gbXML).
- Third, export of parts or the entire BIM model to the IFC format and subsequent import into a simulation software.

In 2016, a literature review of Soust-Verdaguer et al. [22] revealed that up to that time, most BIM-LCA solutions can be assigned to the third type. They investigated articles concerning frameworks and software tools for the coupling of BIM and LCA and compared 11 tools according to various parameters, e.g. input data (see table 3.1).

3.1 Stage of Application and Tools

LCA input summary of reviewed papers.

	Country	BIM model		LCA method							
		Building typology	LOD	Functional unit	Life span	Database	LCA phases				
							Product A1–A3	Construction A4–A5	Use B1–B7	End of life C1–C4	Recycling D
Ajayi et al. [33]	US	Two-storey primary school building	200	Complete building	30 years	ATHENA Impact Estimator [71]	X	X	X	X	–
Basbagill et al. [49]	US	Residential building	–	Complete building	–	Athena Eco Calculator [71]	X	–	X	–	–
Georges et al. [66]	Norway	Typical two-storey single-family house and office building	–	1m2 of heated floor area	60 years/temporal	Ecoinvent Version 2.2	X	–	X B1 B4 B6	–	–
Houlihan et al. 2014	Norway	Single-family house	–	1m2 of heated floor area	30 years Solar panels	Ecoinvent Version 2.2	X	–	B4 B6	–	–
Iddon & Firth [65]	UK	Single-family house	–	Complete building	60 years	ICE database [72]	X	–	B6	–	–
Jalaei & Jrade [57]	Canada	Three-storey office building	–	Complete building	–	ATHENA Impact Estimator [71]	X	–	B6	–	–
Jrade & Jalaei [58]	Canada	Six-storey apartment building	–	Complete building	–	ATHENA Impact Estimator [71]	X	–	X	–	–
Lee et al. [59]	Republic ofKorea	A standard 18 storey Korean apartment building	300	Complete building	–	Korea life-cycle inventory [73]	X	X	X	X	–
Peng [64]	China	Run Run Shaw Architectural building	–	Complete building	–	ICE database [72]	X	X	X	X	–
Shafiq et al. [70]	Malasia	Two-storey office building	–	Complete building	–	ICE database [72]	X	X A4	–	–	–
Shin et al., 2015	Republic ofKorea	11-storey office building	–	Complete building	–	Korea Life Cycle Inventory [73]	X	–	B1-B6	–	–

Table 3.1: BIM LCA Input Data [22]

In most of the articles investigated, the data of the BIM model was first exported to a spreadsheet before being entered into one of various LCA software tools like SimaPro [24] or Athena [25]. This corresponds to the second way of BIM and LCA integration as defined by Andriamamonjy [23]. Although missing a direct link, this first step of the data import is significant on its own for it makes the data of the BIM model available to LCA tools.
Since then, the following methods have been developed and published. This is a non-exhaustive list.

In 2017, Tsikos et al. [26] presented an integrated dynamic model to export building information from the BIM model and conduct an LCA based on it. This model functions as a design tool, using Revit, its Visual Programming Language (VPL) Dynamo [27], Excel, and an external LCI database consisting of environmental impacts per m2 or m3. It creates a permanent link between the Revit materials and the materials of the LCI database through a unique material ID in both cases. A Dynamo script uses the material information and the quantities of the geometry model to calculate an LCA. The results are then saved and visualized in an Excel spreadsheet.
In an effort to verify the results, the same calculations were performed with established LCA software like LCAbyg [28] and Tally [29]. The comparison of the Global Warming Potential (GWP) output revealed only minimal deviation in case of LCAbyg, but of more than 50% in case of Tally. This difference was explained by Tally using an American database and different LCA method [26].
In total, this integrated dynamic model results in equal quality and precision as established LCA tools while being faster.

In 2018, Soust-Verdaguer et al. [30] created a semi-automatic spreadsheet-based tool that uses a bill of material quantities from geometry models to conduct an LCA.

Their LCI comprised of three stages: First the material quantities were exported from the BIM software via bill of quantities. Then, the supplementary data was added, including the packaging of the materials, the distances and means of transport, the auxiliary and maintenance materials, and waste production in construction and use phases. Third, the materials were regrouped into basic materials. The LCI finished, the environmental database EcoInvent version 3.3 was linked to the materials and the LCA calculated. The established spreadsheet was the centre of theses steps, and the link to all external data. As a case study, this approach was applied to a single family house in Urugay, including the "*fabrication of building materials (A1-A3), construction (A4-A5), use (B2, B3, B6), demolition, and end-of-life phases*" .

In 2018, Röck et al. [31] established "*an automated, bidirectional link between the building element library in Microsoft Excel and the BIM model in Autodesk Revit*" through a script in Autodesk Dynamo. This script extracts the bill of quantities and, using the data from the building element library, calculates the environmental impacts of the building. A case study using a BIM model with LOG 200 was then performed. This study included the following elements: foundation slab, external walls, floor and roof elements as well as windows and partition walls.

An issue was raised by IEA EBC Annex 57 [32, 33] which includes the detailed comparative analysis of over 80 international case studies. The results show a high variability (up to 100 times) of embodied GHG emissions due to the methodological differences employed in the LCA. These differences include the LCA method used, the system boundaries, the assumed future scenarios for the service life of materials and end-of-life treatments, the reference study period, and the source of data.

Resch et al. [34] provided an answer to this issue by "*presenting a database tool that systematizes embodied emission assessments of buildings by characterizing buildings as a hierarchical set of building elements, themselves composed of materials, to offer a high-resolution breakdown of their embodied emissions.*" One goal of this tool is too improve consistency and comparability. In the course of this study, the authors used it on 11 different buildings.

Röck et al. [35] emphasized the importance of having the common granularity in both LCA data and BIM elements as well as a common naming of elements to enable automated data exchange and processing.

In summary, there are numerous promising approaches to the integration of BIM in LCA. Since the 2016 literature review of Soust-Verdaguer et al. [22] which showed that the majority of tools were used to export data to software like Excel, the level of automatization significantly increased. During the same time other issues, like the lack of comparability between LCA studies based on BIM and standardization arose.

3.2 Information Requirements for LCI

The information required for an LCI is the foundation of an LCA. It is especially important when trying a new approach like including a BIM model as principal data source. But most of the tools and frameworks mentioned above do not describe these information requirements.

However, there is agreement in that a well-detailed BIM model can be used as main information source for LCA. [36, 37]
And still, in the literature some approaches on the description of the information requirements of LCA and BIM can be found.

In 2018, Resch et al. [34] have developed a database tool that facilitates comparing embodied emission LCA results across system boundaries. The database is adapted at the information required for LCAs. They put together an extensive table of information requirements split into three main components: building information, materials, and embodied emission results (See table 3.2) .

Building information		Materials	Embodied emission results	
Building	Study	Materials	Inventory	Building elements
Typology	Name	Name	Material	Element name
Construction type	Project	Generic/Specific	Quantity	Hierarchy
Location	Calculation method	Source type	Lifetime	Parent element
Energy ambition level	Main data source	Source	Mode(s) of transport	A1-A3
Heated floor area	Study type	Data year	Distance(s) transport	A4
Heated volume	Study year	Functional unit (FU)	A1-A3	A5
Area footprint	Lifetime	Density	A4	B4 materials
Area roof	GWP B6	GWP/FU A1-A3	B4 materials	B4 transport
Area wall	GWP B7	Lifetime	B4 transport	Other life cycle modules
Area windows and doors	Built status	Material category	Other life cycle modules	
Heat loss number		Location production	Location production	
Stories above ground				
Stories below ground				
Occupants				

Table 3.2: Database Structure of LCA Comparing Tool [34]

Petrova et al. [38] define specific exchange requirements for a BIM-LCA workflow. These requirements include :

- General information like project ID, Site ID, building ID, location, orientation, heated floor area, heated basement, hours of operation, heat supply, ...
- Building envelope: External walls, roofs, floors, foundations, exterior doors, windows, abd window joints
- Spatial information: zones
- HVAC systems: Ventilation, internal heat supply, lighting, domestic hot water, and more.
- Materials

Each type of information consists of one or more properties with specific data types and units. See Table 3.3 for an excerpt of the exchange requirements.

Type of Information	Properties	Description/Comments	Data Type	Units
Building envelope				
External walls **Roofs** **Floors**	○ Identification	Unique ID	string	n/a
	○ Construction type	Materials	string	n/a
	○ Placement	Relative to Building Storey	real numbers	metric
	○ 3D geometry		various	metric
	○ Area		real number	m^2
	○ U-value		real number	W/m^2K

Table 3.3: Exchange Requirements [38]

Cavalliere et al. [8] researched the information requirements of a building LCA on a BIM model, and conducted an LCA as proof of concept. They created a table to show their findings (see table 3.4), found in their paper [8]. It gives an overview over the required parameters.

Variables and related parameters.

Variables	Direct parameters	Indirect parameters
Primary Resources (PR)	Dimension (Volume, Area, Length), Weight, Nature of the Resource (allocable to recycle, reuse, incineration, landfill)	Reference Service Life
Electricity/Heat (E/H)	Source, Power, Time of Use, Georeference	
Transport (TR)	Type of transport (wheel, rail, ship, etc.), Weight of transported material (depending on the design specifications, the supply method or the site construction, etc.), Distance, Capacity, Class, Dimension (Volume, Area, Length)	
Co-Products (CP) or Secondary Raw Materials (SRM)	Dimension (Volume, Area, Length), Weight, Nature of Co-Products/Secondary Raw Materials, Time of Use	Residual Performance, Economic Residual Value
Emission (EM)	Nature of the Emission, Amount	
Recyclability (RE)	Nature of the Resource	Residual Performance, Georeference
Assembly (AS)		Connection type (Dry or Wet-assembly)

Table 3.4: BIM LCA Information Requirements [8]

All of these information requirements can be used as the basis of an MVD. In 2018, Pinheiro et al. [39] already laid the foundation for an LCA MVD by developing a link between BIM and BEPS.

They made use of the potential of IFC 4 Addendum 2 and created a MVD for the data required for a BEPS. The IFC MVD supports most of the exchange requirements, but there are 49 specific properties that had to be added, including the transmission coefficient of windows and the design water flow rate of the boiler. Since the set of information required for an LCA is greatly overlapping with the information required for a BEPS, the research of Pinheiro et al. [39] shows that such an approach is possible for an LCA MVD as well.

Dupois et al. [40] addressed another way to define the information requirements. They define the minimum level of data required to conduct an LCA as the quantities of every significant material item required for the building as well as the amount of energy to operate the building. Quite important in the context of this thesis is their description of the information needed to perform an LCA based on the LOD (see table 3.5) [40, 41].

LOD	Missing information
100	All information, except global information on the building
200	The Specific object's type
300	The assembly description

Table 3.5: BIM LCA Information Requirements [40]

According to Dupois et al. [40] LOD 100 and LOD 200 provide no specific object information. Therefore, at least LOD 300 is required for the use in an LCA.

In their 2016 article, Soust-Verdaguer et al. [22] voiced a similar notion. Related to the LOD of the BIM model, the article evidences that the integration of BIM-LCA seems to be appropriate in models which have defined the most relevant materials and components, including: wall thickness (including component layers), and the definition of structural elements in their actual engineered sizes, shapes, and locations. According to this, the LOD 300 seems to be the most appropriate to verify the environmental impacts during the early stages of design.

But LOD 300 hints at a high LOG, and Röck et al. [31] discovered that "*in early design stages BIM models generally only provide a low Level of Geometry (LOG)*". Most studies using BIM to conduct LCA during early design stages have faced the same problem as the LCA performed without BIM: the LOG and information necessary for LCA is not yet available in the model.

This would limit the integration of BIM in LCA to more developed design stages. And indeed, Röck et al. [35] wrote that "*currently LCA is limited to being descriptive in hindsight, rather than* *providing feedback and guidance on how to effectively improve the building during design*".

But there is an increasing interest in solving this issue and integrating "*LCA in the building design process as soon as possible to provide design guidance and monitor the effect of design decisions*" [31].

Röck et al. [35] suggest that in order "*to foster BIM-integrated LCA throughout the design process the specification of information requirements for both energy simulation as well as assessment of material impacts is needed for different types of LCA*".
Three types of LCA were established: screening LCA, simplified LCA and complete LCA [42, 22]. The screening LCA is an LCA study in an early design stage, whereas the complete LCA is based on the finished design and building.

Coming back to the LOD, these types of LCA also represent the gradual increase of the LOD throughout the design process, starting with a screening LCA based on a BIM model of LOD 100.

Summarized, of all the information requirements the LOD of the BIM model has a special position. In 2016, Soust-Verdaguer et al. [22] specified the LOD as significant characteristic for BIM-based LCAs. In their review paper, the LOD was used as a main characteristic for comparing the data input of the investigated BIM-LCA workflows and case studies. However, the review revealed that only two of the eleven articles investigated mention the LOD of the BIM model in their case study. Still, they concluded that "*according to reviewed papers, the level of development (LOD) and the modeling of objects can be considered a key point during the application of LCA.*"

Furthermore, tackling a more detailed aspect of the LOD, the LOG, Röck et al stated that "*while BIM models are very useful to establish the inventory for LCA further research is required as open questions remain e.g. on how to account for un-modelled elements and how to include complex construction details when establishing a BIM-based LCI*". [35]

This thesis investigates whether un-modelled elements can be accounted for by correction factors.

4 Methodology

The LCA studies conducted follow the guidelines of European Standard EN 15978 and reflects the structure suggested there (See chapter 2.3).

4.1 Purpose of Assessment

The definition of the purpose is the first step in any building LCA. It consists of three parts, goal, scope, and intended use. The goal is the answer to what the study is trying to accomplish and it is always "*to quantify the environmental performance of the object of assessment*". [17]
The scope defines what is taken into account, which is the object of assessment with all the restrictions applied. It defines what building parts are included as well as the period of time considered. According to EN 15978 "*The object of assessment is the building, including its foundations and external works within the perimeter of the building's site, over its life cycle.*" In essence, this includes the entire building over its whole life cycle. However, in this LCA study some restrictions were applied, both on the building and the life-cycle considered (See chapter 4.2)
Since the definition of the scope requires extensive specification of details and has considerable impact on the outcome of the LCA, it is important to keep the intended use of the study in mind. In this case, the intended use is to provide data to test the hypotheses of this thesis (See chapter 1.3).

4.2 Specification of Object of Assessment

The object of assessment is the building. For this study, the author was provided with the BIM model of the assessed building. And since this thesis investigates the connection of BIM and LCA, all the information processed during the LCA is drawn from the BIM model. There are very few exceptions, all of which are stated explicitly.
The functional unit of this LCA is the building, as defined in the scope, with a Reference Service Life (RSL) of 50 years. The Reference Study Period (RSP) was set to 50 years.
The three most significant restrictions of the scope are:

- The MEP systems including all HVAC systems were excluded from the scope.
- The underground garage that is on the neighbouring site and connected via a single aisle was excluded from the scope.
- Furniture is not part of the scope.

All the other details required to define the scope are described in the following subchapters.
The scope includes the whole life cycle, except for the following LCS. They were not included in the scope because specific information was not available.

- LCS A5: Construction installation process
- LCS B1-B3 and B5: Use, maintenance, repair, and refurbishment
- LCS C1: Deconstruction and demolition

Figure 4.1 shows an overview of the LCS considered.

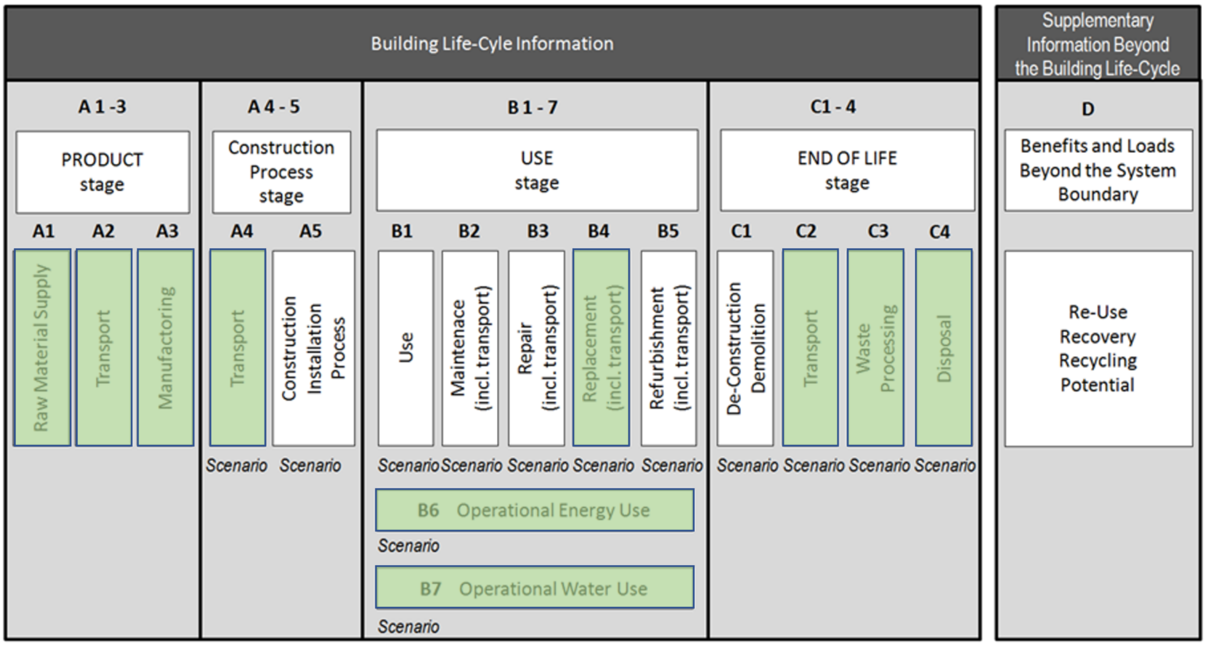


Figure 4.1: LCS in Scope [43]

4.3 Scenario Development

4.3.1 LCS A1-A3: Product Stage

The environmental impacts were exported from the EcoInvent database (Version 3.3), using the LCA software SimaPro, and are given per unit of volume, area, weight of material, or per piece.

4.3.2 LCS A4: Transport to Construction Site

For the modelling of the transport to the construction site, default scenarios as stated in the Austrian Product Category Rules (PCRs) for construction products [44] were used. The transport is divided into either a direct transport from the factory to the site or the sum of the transports from the factory to the supplier and from the supplier to the site. Each transport is defined by the distance and the class of lorry used. The framework supports four classes of lorries that vary in the amount of freight in tons. There are 3.5 to 7.5 tons, 7.5 to 16 tons, 16 to 32 tons, and 32 tons and greater. It is assumed that all of the lorries observe European emission standard EURO 5 [45, 46].

On a second axis, the transported goods are sorted by product group and material category according to the PCRs. The product groups are summarized in table 4.1. The framework and its application on this thesis can be found in Appendix A.

Product group/material category (acc. PCR AT)
Bricks, Roof ties, and other products made of clay
Poured concrete
Concrete prefabricated
Anhydrite Floor
Double flooring system
Mortar
Waterproofing
Reinforcement Steel
Bulk materials for structural work (e.g. cement, sand, gravel, ...)
Prefabricated products for structural work (e.g. beams, columns, ...)
Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)
Insulation
finishing products: floor coverings(e.g. carpet, linoleum, ceramic tiles, ...)
finishing products: plasters (e.g. gypsum plaster, external plaster, ...)
finishing products: cabinet work (e.g. window frames, stairs, ...)
finishing products: paints and varnishes
installations (e.g. heating boiler,radiators, ventilation, ...)

Table 4.1: Product Groups for LCS A4-Scenario: Transport to the Construction Site

4.3.3 LCS B4: Replacement

The replacement of building elements is modelled by assigning an Expected Service Life (ESL) to every material category in the building. A catalogue of ESL provided the minimum and maximum values for an extensive list of building components, elements, and materials [47]. Based on this, the arithmetical mean of the minimum and maximum ESL was calculated, which was then used for calculating the amount of replacements during the RSP.

Calculating the number of replacements on the basis of material categories is a simplified approach. But a more accurate approach is obstructed by the detail of the data provided and more importantly the choice of environmental data (See chapter 4.5. Moreover, reinforced concrete, brickwork, and metal make up the main materials since being the core layer of walls, floors, foundations, and some roofs, and have an ESL significantly greater than the RSP of this study. Therefore, this simplification was assessed as suitable.

Each replacement consists of the whole modelled life-cycle of the material. In this thesis, this includes LCS A1-A3, A4, C2, and C3 or C4. The number of replacements is calculated by dividing the ESL by the RSP. The result is rounded up.

Table 4.2 shows the list of materials, and the selected ESL-class, followed by the ESL, and the number of replacements required during the RSP of 50 years. The ESL-code is linked to the implemented framework and returns the name of the ESL-class in the next column.

Materials	Life Cycle Stage B4			
			RSP = 50	
Materials (Revit)	ESL Code	ESL class	ESL [y]	Replacements [#]
Aluminium Alloy	ESL_BE_038-01	Blechabdeckungen	40	1.0
Reinforced Concrete	ESL_BE_202-02	Stahlbetonkonstruktionen	80	0.0
Concrete	ESL_BE_202-02	Stahlbetonkonstruktionen	80	0.0
Reinforcement	ESL_BE_202-02	Stahlbetonkonstruktionen	80	0.0
Bitumen seal	ESL_BE_040-02	Bodenabdichtungen gegen nicht drückendes Wasser	40	1.0
Roof Tile	ESL_BE_053-12	Dachdeckungen	55	0.0
Double Glazing	ESL_BE_084-03	Fenster	25	1.0
Triple Glazing	ESL_BE_084-03	Fenster	25	1.0
Steel, chromium steel	ESL_BE_202-04	Stahlbetonkonstruktionen	100	0.0
Epoxy resin	ESL_BE_042-08	Bodenbeläge	20	2.0
Flat glass, coated	ESL_BE_353-02	Verglasungen	30	1.0
Gravel, crushed	ESL_BE_042-04	Bodenbeläge	30	1.0
Hardwood	ESL_BE_306-02	Imprägniertes Weichholz	15	3.0
Brickwork	ESL_BE_246-01	Ziegelmauerwerk	100	0.0
Bricks	ESL_BE_246-01	Ziegelmauerwerk	100	0.0
Mortar	ESL_BE_246-01	Ziegelmauerwerk	100	0.0
Brass	ESL_BE_002-08	Abdeckungen	75	0.0
Softwood	ESL_BE_117-02	Holzkonstruktionen	40	1.0
PE foil	ESL_BE_003-04	Abdichtungen	50	0.0
Plaster	ESL_BE_169-02	Putze	40	1.0
PVC, hard	ESL_BE_084-03	Fenster	25	1.0
Steel, unalloyed	ESL_BE_203-03	Stahlkonstruktionen	60	0.0
Rock wool	ESL_BE_237-07	Wärmedämmungen	40	1.0
Plasterboard	ESL_BE_098-01	Gipskartonplatten	30	1.0
Polystyrene extruded (XPS)	ESL_BE_237-06	Wärmedämmungen	30	1.0
Cement cast plaster floor	ESL_BE_078-04	Estriche	30	1.0

Table 4.2: Scenario LCS B4

4.3.4 LCS B6 and B7: Operational Energy Use and Operational Water Use

The data required for the calculation of the operational water use, as well as the operational energy use, was provided by the building owner in the form of bills from cost accounting. The data includes energy and water use of the entire year 2016. Since the the bills feature costs and not amounts of water in cubic meter [m3] or energy in kilowatt hours [kWh], the costs were converted using prices of local energy and water suppliers.

A cubic meter of water cost 1.92€ from Holding Graz [48], a kilowatt hour of electric energy was billed with 0.16€ according to e-control.at [49], and a megawatt hour of heat energy via district heating was sold for 99.54€ (equalling 0.10€ per kilowatt hour) by Energy Graz [50]. All of these prices were valid in the fall of 2018.

4.3.5 LCS C2, C3, and C4: Transport to End-of-Life Scenario, Waste Processing, and Disposal

The transport to the End-of-Life (EoL)-Scenario (C2) is directly linked to the Waste Processing (C3) and the Disposal (C4). Every element and material has to be allocated to one of four EoL-Scenarios. These are reuse, recycling, landfill, and incineration. The material's EoL-Scenario determines the transport distances (C2) and influences the subsequent LCS (C3 and C4).

A framework based on the default scenarios as stated in the PCRs [44] was used to allocate the used materials to locally common EoL-Scenarios. The framework identifies the fitting scenario in two steps; first the product group or waste category, and then a detailed description of a single material or a subgroup. Figure 4.3 shows this two-step definition. Each line then continues with the division of the entire waste into one of the four material's EoL-Scenarios. Appendix B contains the complete framework.

Product group/ Waste category	Description
Stony & Glass	Bricks, roof tiles
	Bulk materials (e.g. sand, gravel, expanded clay grains)
	Concrete
	Flat glass
	Other stony waste (e.g. tiles, natural stone, slates, sand-lime blocks)
	Porcelain and ceramics (e.g. toilet, bath, washbasin)
Wood	Chemically treated,impregnated wood (e.g. railway sleepers, outdoor playsets,garden screens)
	Composite wood products (e.g. fibreboards (like plywood, chipboard, OSB, MDF), veneer, laminate)
	Surface treated, solid wood (e.g. painted or varnished (like window frames, solid parquet))
	Untreated, uncontaminated wood (e.g. roofs, structures, formworks, auxiliary timber)
Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)
Packaging (on construction site)	EPS packaging
	Pallets
	Paper and cardboard packaging
	Plastic films packaging
Insulation Materials	Mineral insulation materials (e.g. stone wool, glass wool)
	Organic insulation materials (e.g. vegetable fibres (like wood, coconut, hemp, flax), cellulose,(in bulk or blankets), sheep wool, cork (in bulk or boards))
	Synthetic insulation materials (e.g. polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), phenolic foam, expanded polystyrene (EPS))
Fibre cement products	Fibre cement products (e.g. fibre cement slabs or slates)
Areated/celluar concrete	Aerated autoclaved concrete (e.g. elements, blocks)
Gypsum elements	Gypsum elements (e.g. gypsum blocks, gypsum (fibre/plaster)boards)
Bitumen	Bitumen (e.g. bituminous roofing, vapour barrier, waterproofing membrane)
Polyoelfins (PP,PE)	Polyolefins (PP, PE) (e.g. kraft paper or polyethylene (PE) vapour barrier, ducts), excluding packaging
Elastomers	Elastomers (e.g. EPDM roofing)
PVC	PVC cabling (e.g. electric cables and wire insulation)
	PVC pipes (e.g. for sewerage)4
	PVC profiles (e.g. window frames)
	PVC sheets (e.g. PVC roofing, waterproofing membranes (like for swimming pools))
Supple Flooring	Supple flooring (e.g. linoleum, fixed carpet, vinyl)
Finishing Layers	Finishing layer fixed to stony waste (e.g. plaster (like gypsum plaster, calcareous plaster,loam plaster), paint, coatings, adhesives)
	Finishing layer fixed to wood, plastic or metal (e.g. paint, coatings, adhesives)
Remaining Waste	Combustible remaining waste
	Non-combustible remaining waste
Other hazardous waste	Aerosols and kits (e.g. PU foam, silicones)
	Asbestos (bounded, unbounded)
	Fluorescent lamps
	Liquid construction site waste (e.g. paints, adhesives, resins, form mould oil, white spirit)

Table 4.3: End-of-Life Scenario - Classification

The framework then proposes an average transport distance based on the distances from the demolition site to the sorting facilities. If the material is not going to be reused or recycled, it also includes the transport distances from the sorting facility to the landfill or incineration facilities. The framework builds on the assumption that the materials being processed in a landfill or incineration facility pass through a sorting facility. This deviates from the chosen approach in this study. Figure 4.2 illustrates the difference. However, since the transports is only a minor share of the total results, this deviation was noted but not assessed as significant.

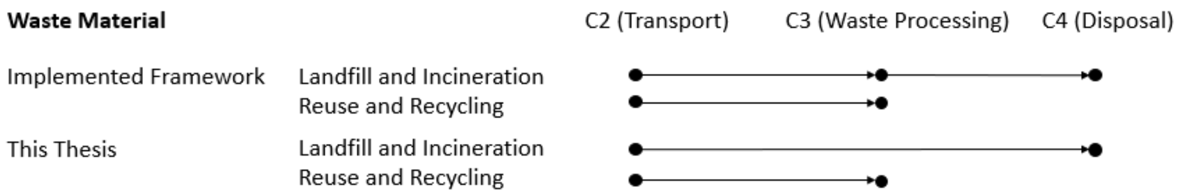


Figure 4.2: Modelling of End-of-Life LCS

The framework applied on the case study is shown in table 4.4. The framework's second step of identifying the fitting scenario is cut short in this table. The complete scenario can be found in Appendix C.

Materials	Life Cycle Stage C2							
Materials (Revit)	choose product group/ waste	Description	Landfill [%]	Incineration [%]	Reuse [%]	Recycle [%]	EoL total	Distance [tkm]
Aluminium Alloy	Metals	Metals: iron, ste	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Reinforced Concrete			#NV	#NV	#NV	#NV	#NV	#NV
Concrete	Stony & Glass	Concrete	5,00%	0,00%	0,00%	95,00%	100,00%	31,38
Reinforcement	Metals	Metals: iron, ste	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Bitumen seal	Bitumen	Bitumen (e.g. bi	85,00%	5,00%	0,00%	10,00%	100,00%	77,50
Roof Tile	Stony & Glass	Bricks, roof tiles	5,00%	0,00%	0,00%	95,00%	100,00%	31,38
Double Glazing	Stony & Glass	Flat glass	5,00%	0,00%	0,00%	95,00%	100,00%	31,45
Triple Glazing	Stony & Glass	Flat glass	5,00%	0,00%	0,00%	95,00%	100,00%	31,45
Steel, chromium steel	Metals	Metals: iron, ste	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Epoxy resin	Finishing Layers	Finishing layer f	5,00%	0,00%	0,00%	95,00%	100,00%	32,50
Flat glass, coated	Stony & Glass	Flat glass	5,00%	0,00%	0,00%	95,00%	100,00%	31,45
Gravel, crushed	Stony & Glass	Bulk materials (	5,00%	0,00%	95,00%	0,00%	100,00%	31,15
Hardwood	Wood	Surface treated,	0,00%	85,00%	0,00%	15,00%	100,00%	104,80
Brickwork			#NV	#NV	#NV	#NV	#NV	#NV
Bricks	Stony & Glass	Bricks, roof tiles	5,00%	0,00%	0,00%	95,00%	100,00%	31,38
Mortar	Stony & Glass	Bulk materials (	5,00%	0,00%	95,00%	0,00%	100,00%	31,15
Brass	Metals	Metals: iron, ste	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Softwood	Wood	Untreated, unco	0,00%	25,00%	0,00%	75,00%	100,00%	52,00
PE foil	Polyoelfins (PP,PE)	Polyolefins (PP, I	10,00%	85,00%	0,00%	5,00%	100,00%	120,00
Plaster	Stony & Glass	Bulk materials (	5,00%	0,00%	95,00%	0,00%	100,00%	31,15
PVC, hard	PVC	PVC profiles (e.g	10,00%	45,00%	0,00%	45,00%	100,00%	80,00
Steel, unalloyed	Metals	Metals: iron, ste	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Rock wool	Insulation Materials	Mineral insulati	50,00%	50,00%	0,00%	0,00%	100,00%	105,00
Plasterboard	Gypsum elements	Gypsum elemen	80,00%	0,00%	0,00%	20,00%	100,00%	62,80
Polystyrene extruded (XPS)	Insulation Materials	Synthetic insula	5,00%	95,00%	0,00%	0,00%	100,00%	127,50
Cement cast plaster floor	Stony & Glass	Concrete	5,00%	0,00%	0,00%	95,00%	100,00%	31,38

Table 4.4: Scenario LCS C2, C3, and C4

4.4 Quantification of the Object of Assessment

The quantification of the object of assessment was achieved by extracting the material definition and quantities, i.e. material area and volume, from the BIM models. This information was then saved in a spreadsheet.

The details of this step are specific to the case study and can be found in chapter 5.2.

4.5 Selection of Environmental Data

The EcoInvent 3.3 database [2] was the source of all environmental data. The methods used were EF 1.0.3 and EPD 2017. The selected data was extracted from SimaPro as environmental performance of 1 unit, e.g. m3, m2, or pcs, and saved in an Excel spreadsheet. Appendix D contains a complete list of selected environmental data per LCS.

4.6 Calculation

The calculation of the LCA results can be performed in dedicated software tools, e.g. SimaPro. But since it is just a multiplication of the material quantities and the corresponding environmental data, in consideration of the scenarios, other software, including Excel, can be used as well. In this thesis an Excel spreadsheet was used.

5 Case Study

The previous chapter explained the approach to an LCA, as defined in EN 15978, and applied it to the case study of this thesis. But detailed information concerning the case study is described in this chapter.

This thesis investigates a specific effect of the combination of BIM and LCA. Therefore, a BIM model is the source of almost all of the information, with only few exceptions which are summarized in chapter 6.5.

The first part of this chapter focuses on the used BIM model, followed by the method and results of the quantification of the object of assessment. Afterwards, the Excel tool that was created during the course of this thesis for calculating the LCI, is explained.

5.1 Description of the BIM Model

The BIM model was created as an example of highly detailed modelling, and as such features a total LOD of 300. Figure 5.1 is a horizontal section through the BIM Model and shows the amount and quality of geometrical detail.

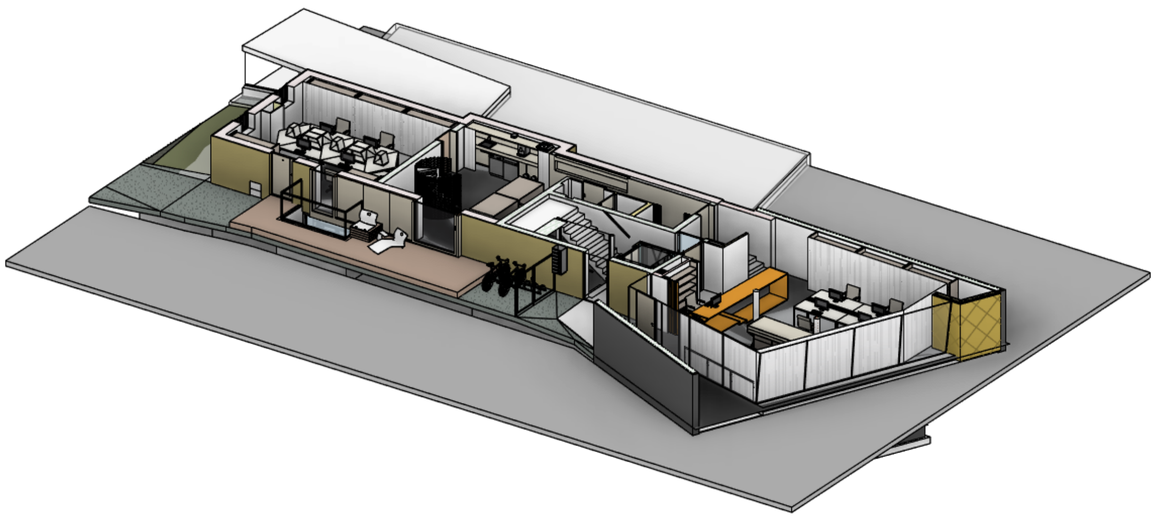


Figure 5.1: Horizontal Section of BIM Model

However, there are exceptions to this, and the non-geometrical information contained in the model elements is not as complete (See Appendix E).

But since the information contained allows the definition of generic materials, LOI 200 is fitting for this model. It is noteworthy that both, the LOG and the LOI, are constant throughout the model.

As defined in chapter 4.1, the scope of the LCA is the building on the site as represented in the BIM model. This excludes the neighbouring buildings and the underground garage. The garage is situated on a neighbouring site and connected to the basement of the building via underground aisle. This aisle is considered to be part of the garage and the limit is set to the exterior wall of the building's basement. Figure 5.2 shows this in the picture in the bottom right corner. Moreover, since Mechanical, Electrical, and Plumbing (MEP) systems including Heating, Ventilation, and Air Conditioning (HVAC) systems are not modelled fully, they are excluded from the scope. Finally, all furnishing is excluded from the scope.

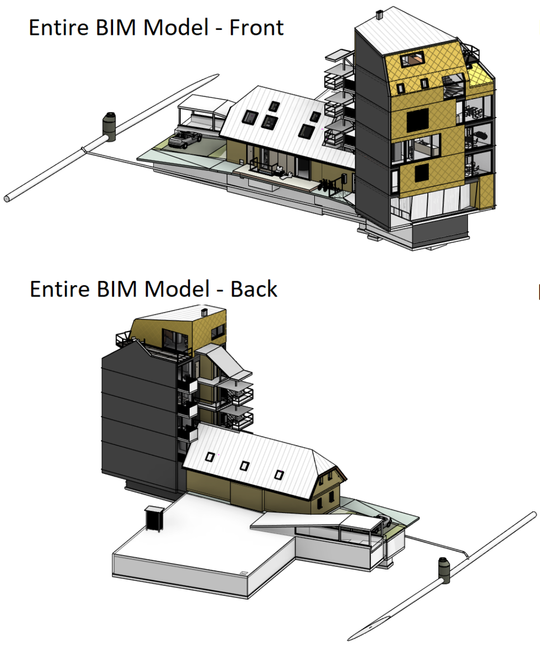


Figure 5.2: BIM Model in Scope

So, the scope is limited by the site and does not include MEP systems and interior furnishing. In addition to these general restrictions, another approach to the definition of the scope was undertaken. The approach centered on the extraction of a list of model elements in the BIM model, that was summarized and sorted by model element categories (See Table 5.1).

Autodesk Revit Category	Included in Scope?
Casework	Not Included: Furniture
Ceilings	Included
Curtain Panels	Included
Doors	Included
Electrical Equipment	Not Included: Computer equipment
Entourage	Not Included: Vehicles
Floors	Included
Furniture	Not Included: Furniture
Generic Models	Not included (with six exception): Mostly on neighbouring sites
Lighting Fixtures	Not Included: MEP
Plumbing Fixtures	Not Included: MEP
Roofs	Included
Site	Not Included: North arrow in model
Specialty Equipment	Not Included: Computer equipment
Stairs	Included
Structural Columns	Included
Structural Connections	Included
Structural Foundations	Included
Structural Framing	Included
Walls	Included
Windows	Included

Table 5.1: Categories of Model Elements in Scope

5.2 Quantification

The quantification of the object of assessment was accomplished in three steps.
First, the quantities had to be extracted from the BIM Model.
Second, the extracted information was checked for its quality and against the scope defined in chapters 4.1, 4.2, and 5.1.
Finally, the checked information was refined to facilitate the allocation of environmental data and further processing in the LCI.

The first step, the extraction of the quantities from the BIM Model, was achieved with a standard feature of the BIM-authoring tool used, Autodesk Revit. This feature, "*Multi-Category Material Takeoff*", creates a list with all material areas and volumes per model element. This list can be exported and further worked on in Microsoft Excel. Moreover, it can include all the information in the BIM model that is connected to model elements, e.g. categories, levels, custom parameters, and weights. Weights are essential in conducting of LCAs since a lot of environmental data is based on weight, rather than volume or area. However, in this case this information was not provided by the BIM model and had to be added by hand later on.
The option of adding custom parameters was paramount when going through the model elements in Autodesk Revit and deciding whether they are part of the scope or not. A simple check box per model element to mark if the element is within the scope (checked; 1) or not (unchecked; 0)

facilitated the classification. Using Autodesk Revit's filter and view options allowed showing model elements of only a certain category and make them invisible when classified.
Having finished this classification, the material take-off included most importantly the category, material name, material area, material volume, and scope of the model elements within scope. Figure 5.3 is a screenshot of this first step in Excel. Each row represents one material of one element. This means that a single element consisting of multiple materials will be listed several times in this matrix, once for each material.

_DA_MatTOScope														
Category	Familie und Typ	Material: Name	Material: Area	[m²]	Material: Volume	[m³]	Material: Unit weight	Count	_CodeElement	_GUID	_LCA Scope	_ON B 1801	_TypeKey
Ceilings	Compound Ceiling: Abgehängte Decke 25	Trockenbau - Gipsplatte	1,35 m²	1,35	0,03 m³	0,03	10,8 kN/m³	1	FL_08	7dacbb3	Yes	4D.03	4D.03-T01
Ceilings	Compound Ceiling: Abgehängte Decke 25	Trockenbau - Gipsplatte	1,94 m²	1,94	0,05 m³	0,05	10,8 kN/m³	1	FL_08	7dacbb3	Yes	4D.03	4D.03-T01
Ceilings	Compound Ceiling: Abgehängte Decke 160	Holz - 225-153-51	36,18 m²	36,18	5,73 m³	5,73	0,0 kN/m³	1	FL_10	6294b6c	Yes	4D.03	4D.03-T03
Ceilings	Compound Ceiling: Abgehängte Decke 200	Lack - weiß 241-240-234	1,95 m²	1,95	0,39 m³	0,39	0,0 kN/m³	1	FL_24	18a5618	Yes	4D.03	4D.03-T04
Ceilings	Compound Ceiling: Abgehängte Decke 200	Lack - weiß 241-240-234	4,97 m²	4,97	0,99 m³	0,99	0,0 kN/m³	1	FL_24	18a5618	Yes	4D.03	4D.03-T04
Ceilings	Compound Ceiling: Abgehängte Decke 200	Lack - weiß 241-240-234	7,82 m²	7,82	1,56 m³	1,56	0,0 kN/m³	1	FL_24	18a5618	Yes	4D.03	4D.03-T04
Ceilings	Compound Ceiling: Abgehängte Decke 200	Lack - weiß 241-240-234	1,29 m²	1,29	0,26 m³	0,26	0,0 kN/m³	1	RF_03	18a5618	Yes	4D.03	4D.03-T04
Ceilings	Compound Ceiling: Abgehängte Decke 200	Lack - weiß 241-240-234	2,71 m²	2,71	0,54 m³	0,54	0,0 kN/m³	1	RF_03	18a5618	Yes	4D.03	4D.03-T04

Figure 5.3: Multi-Category Material Takeoff in Microsoft Excel

The second step was about checking the extracted data and verifying the scope by comparing a list of model elements within the scope to the list of all model elements. Thus, another Multi-Category Material Takeoff with all the model elements in the BIM Model was performed. Both matrices were then summarized by Revit categories and compared (See table 5.2). The column in the matrix with the header "*Included in Vol%*" contains the share of volume per category that is included in the scope. The explanatory notes name the reasons for not including the entirety of a category , e.g. "*Casework*" in the first row that is not included at all because it contains only furniture.
Step one and two had to be iterated multiple times until the scope was implemented fully.

Autodesk Revit Category	Entire BIM Model			Scope				Explanatory Notes
	Area [m²]	Volume [m³]	Count [#]	Area [m²]	Volume [m³]	Count [#]	Included in Vol%	
Casework	179,80	8,13	24	-	-	-	-	Not Included: Furniture
Ceilings	180,05	27,71	36	180,02	27,70	36	100%	
Curtain Panels	334,73	15,14	327	296,32	15,08	187	100%	
Doors	380,20	8,73	137	371,78	8,61	135	99%	Outside of site: underground garage
Electrical Equipment	6,66	0,05	50	-	-	-	-	Not Included: Computer equipment
Entourage	184,56	11,64	43	-	-	-	-	Not Included: Vehicles
Floors	26.783,66	4.805,58	235	3873,8	274,45	216	6%	Outside of site; underground garage and surrounding buildings
Furniture	1.699,95	35,80	463	-	-	-	-	Not Included: Furniture
Generic Models	42.168,10	82.614,04	31	6,24	0,07	6	0%	Outside of site; especially surrounding buildings
Lighting Fixtures	132,33	2,83	71	-	-	-	-	Not Included: Furnishing
Plumbing Fixtures	48,75	0,89	36	-	-	-	-	Not Included: Vehicles
Roofs	1.985,82	94,41	52	1838,71	87,08	48	92%	Outside of site; especially surrounding buildings
Site	175,47	10,85	2	-	-	-	-	Not Included: North arrow in model
Specialty Equipment	260,04	0,24	80	-	-	-	-	Not Included: Computer equipment
Stairs	231,31	14,46	17	193,52	12,78	15	88%	Outside of site: underground garage
Structural Columns	163,65	4,48	81	132,51	3,13	66	70%	Outside of site: underground garage
Structural Connections	17,78	0,09	1.619	8,80	0,00	74	0%	Only connections of roof structure included; Modelling of other connections is incomplete
Structural Foundations	623,99	167,61	15	265,6	60,1	13	36%	Outside of site: underground garage
Structural Framing	334,32	6,67	255	334,19	6,52	255	98%	
Walls	4.364,56	451,79	578	4051,43	346,86	537	77%	Outside of site: underground garage
Windows	552,92	10,05	176	533,58	9,8	158	98%	
Total:	**80.808,66**	**88.291,18**	**4.328**	**12086,50**	**852,18**	**1746**		

Table 5.2: Quantities in Scope

The third and final step of the quantification aimed at preparing the checked data for the LCI. Since

the LCI is based on materials, the data of the first two steps had to be transformed to show the material areas and volumes per material. Together with the number of model elements that include a certain material, this served as a basis for the condensation of the provided materials. In table 5.3 the materials and quantities are on the left side and the further processing is on the right side. Since this LCA is based on material volume information, materials with less than 0.01 cubic meter were cut-off. This affected "*Glas - orange 255-128-0, Holz - HSB-Schnittflächen, Kunststoff - grau 192-192-192, Metall - Baustahl S 235, Metall - Stahl verzinkt*", and "*Textil - Gold*". Furthermore, the material "*Fußboden - Fußbodenaufbau*" (german for flooring - structure of flooring) does not contain sufficient information for consideration in the LCA and was therefore excluded. Moreover, the BIM Model included the material "*Air*" in its model elements, which was excluded as well because of having no influence on the environmental impact assessed in this LCA.
Then, the remaining materials were further condensed, already checking for possible matches in the environmental information database. This process included making assumptions based on the name of the material and the location of the corresponding model elements within the BIM model. Some of the materials were described by their location and function, e.g. "*Dachdeckung - Dampfbremse*" (german for Roofing - Steam brake). Then, the assumption included likely materials for this use; in this case "*PE foil*".
Or the material had to be further specified to find matching environmental data, e.g. "*Fußboden - Estrich*" (german for Flooring - Screed) was assumed to be a cement cast plaster floor.
All of these assumptions are marked in table 5.3 in the rightmost column.

	LOD 300 Model							
	Case 1 (Base Case)			cut-off?	Condensing Materials		Assumption?
	[m3]	[m2]	[#]		German	English	
Total:	852.18	12,086.50	1,746				
Dachdeckung - Blech	0.69	68.10	2		Aluminium Legierung	Aluminium Alloy	
Dachdeckung - Dampfbremse	0.00	149.55	3		PE-Folie	PE foil	assumption
Dachdeckung - Holz	9.06	422.91	7		Nadelholz	Softwood	
Dachdeckung - Trennlage	0.10	49.56	1		Bitumen	Bitumen seal	assumption
Dachdeckung - Ziegel	6.87	172.53	1		Dachziegel	Roof Tile	
Dämmung - hart	69.92	1,118.63	108		XPS	Polystyrene extruded (XPS)	
Dämmung - weich	85.91	1,174.08	223		Steinwolle	Rock wool	assumption
Fußboden - Epoxidharzbeschichtung	1.81	623.56	34		Epoxidharz	Epoxy resin	
Fußboden - Estrich	0.39	5.76	3		Zementestrich	Cement cast plaster floor	assumption
Fußboden - Fußbodenaufbau	24.47	117.52	15	not sufficient information		-	
Fußboden - Heizestrich	32.33	475.48	24		Zementestrich	Cement cast plaster floor	assumption
Fußboden - PE-Folie	0.82	412.43	25		PE-Folie	PE foil	
Fußboden - Schüttung	3.43	68.82	2		Kies	Gravel, crushed	
Fußboden - Terrasse Teakholz	4.09	18.21	1		Laubholz	Hardwood	
Fußboden - Trittschalldämmung	9.85	475.53	24		XPS	Polystyrene extruded (XPS)	assumption
Geländearbeiten - Gebundene Schüttung	15.50	406.89	22		Zementestrich	Cement cast plaster floor	assumption
Geländearbeiten - Rollierung - Schuettung	0.00	0.00	0		Kies	Gravel, crushed	
Glas - Isolierverglasung 2-fach	0.30	15.35	2		Doppelverglasung	Double Glazing	
Glas - Isolierverglasung 3-fach	4.91	241.26	36		Dreifachverglasung	Triple Glazing	
Glas - Isolierverglasung klar	0.13	33.49	9		Doppelverglasung	Double Glazing	assumption
Glas - klar	1.27	52.93	14		Flachglas	Flat glass, coated	
Glas - matt	0.72	20.52	8		Flachglas	Flat glass, coated	
Glas - orange 255-128-0	0.00	0.00	21	<<	-	-	
Holz	0.00	0.00	0		Nadelholz	Softwood	
Holz - 140-100-70	2.97	126.09	29		Nadelholz	Softwood	
Holz - 180-173-157	7.89	167.38	22		Nadelholz	Softwood	
Holz - 225-153-51	5.73	36.18	1		Nadelholz	Softwood	
Holz - Dunkelbraun 90-80-70	0.00	0.20	2		Nadelholz	Softwood	
Holz - HSB-Balken	6.05	221.29	153		Nadelholz	Softwood	
Holz - HSB-Schnittflächen	0.00	0.09	7	<<	-	-	
Holz - HSB-Steher	0.28	10.56	24		Nadelholz	Softwood	
Holz - Weißeiche natur	0.16	7.78	2		Laubholz	Hardwood	
Kunststoff - dunkelgrau 40-38-36	0.08	16.69	8		PVC, hart	PVC, hard	assumption
Kunststoff - Eierschale	4.82	220.62	51		PVC, hart	PVC, hard	assumption
Kunststoff - grau 192-192-192	0.00	0.05	1	<<	-	-	
Kunststoff - grau 50-50-50	0.00	1.18	1		PVC, hart	PVC, hard	assumption
Kunststoff - grau 70-70-70	1.10	27.44	3		PVC, hart	PVC, hard	assumption
Kunststoff - grau matt 64-64-64	3.70	213.72	32		PVC, hart	PVC, hard	assumption
Kunststoff_80-80-80	0.00	5.11	3		PVC, hart	PVC, hard	assumption
Lack - weiß 241-240-234	17.75	88.74	27		Nadelholz	Softwood	assumption
Luftschicht	32.23	564.70	17	Air	-	-	
Mauerwerk - mit Daemmeigenschaften	11.21	95.51	43		Mauerwerk	Brickwork	
Mauerwerk - ohne Daemmeigenschaften	102.42	196.64	17		Mauerwerk	Brickwork	
Mauerwerk - Paneel ausgeschäumt Betonopt	0.08	2.70	12		Mauerwerk	Brickwork	
Metall - Baustahl S 235	0.00	8.80	74	<<	-	-	
Metall - Baustahl S 355	0.60	143.83	112		Stahl, unlegiert	Steel, unalloyed	
Metall - Baustahl S 355 - weiss	0.11	22.34	7		Stahl, unlegiert	Steel, unalloyed	
Metall - Edelstahl gebürstet	0.00	3.87	36		Edelstahl	Steel, chromium steel	
Metall - Edelstahl Satiniert	0.01	8.27	50		Edelstahl	Steel, chromium steel	
Metall - Gitterrost	1.64	61.50	9		Stahl, unlegiert	Steel, unalloyed	
Metall - Goldfassade Brass	0.05	26.11	72		Messing	Brass	
Metall - Goldfassade Brass Schindeln	0.96	174.83	31		Messing	Brass	
Metall - Maschendraht Gold	0.29	102.44	16		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl	0.02	1.71	1		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl 345 MPa	0.12	27.54	3		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl schwarz	1.13	22.53	1		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl verzinkt	0.00	1.24	3	<<	-	-	
Ortbeton - bewehrt geschliffen	14.15	197.14	25		Stahlbeton	Reinforced Concrete	
Ortbeton - C30/37	112.29	561.01	35		Stahlbeton	Reinforced Concrete	
Ortbeton - C30/37 Verputzt	230.42	1,036.53	71		Stahlbeton	Reinforced Concrete	
Putz - gold	5.03	200.65	29		Putz	Plaster	
Putz - grau	1.13	76.29	15		Putz	Plaster	
Textil - Gold	0.00	0.00	0	<<	-	-	
Trockenbau - Gipsplatte	15.19	1,284.09	116		Trockenbau - Gipsplatte	Plasterboard	
					Bewehrung	Reinforcement	
					Light Clay Brick	Cement Mortar	

Table 5.3: Preparation of Extracted Quantities for LCI (Base Case)

Finally, this matrix was sorted by the newly assigned materials (See table 5.4). The cells marked with grey colour highlight the breakdown of the composite materials into their constituents. The composite materials are reinforced concrete and brickwork.

Material Name		LOD 300 Model Case 1 (Base Case)	
		[m^3]	[m^2]
German	English	795.48	11,394.10
Aluminium Legierung	Aluminium Alloy	0.69	68.10
Stahlbeton	Reinforced Concrete	356.86	1794.68
Beton	Concrete	354.40	
Bewehrung	Reinforcement	2.46	
Bitumen	Bitumen seal	0.10	49.56
Dachziegel	Roof Tile	6.87	172.53
Doppelverglasung	Double Glazing	0.43	48.84
Dreifachverglasung	Triple Glazing	4.91	241.26
Edelstahl	Steel, chromium steel	0.01	12.14
Epoxidharz	Epoxy resin	1.81	623.56
Flachglas	Flat glass, coated	1.99	73.45
Kies	Gravel, crushed	3.43	68.82
Laubholz	Hardwood	4.25	25.99
Mauerwerk	Brickwork	113.71	294.85
Ziegel	Bricks	84.15	
Mörtel	Mortar	29.56	
Messing	Brass	1.01	200.94
Nadelholz	Softwood	49.73	1073.35
PE-Folie	PE foil	0.82	561.98
Putz	Plaster	6.16	276.94
PVC, hart	PVC, hard	9.70	484.76
Stahl, unlegiert	Steel, unalloyed	3.91	381.89
Steinwolle	Rock wool	85.91	1174.08
Trockenbau - Gipsplatte	Plasterboard	15.19	1284.09
XPS	Polystyrene extruded (XPS)	79.77	1594.16
Zementestrich	Cement cast plaster floor	48.22	888.13

Table 5.4: Material Quantities (Base Case)

Reinforced concrete was split into concrete and reinforcement, assuming that 0.69 percent volume of the total is reinforcement. This assumption is based on the reference values of reinforcement per building element developed by E. Petzschmann [51]. Table 5.5 builds on his research of the minimum and maximum reinforcement per building element and calculates the mean reinforcement ratio for the building in this case study.

Building Element		kg of Reinforcment per m3 Concrete			Reinforced Concrete in Building		Mean Reinforcement weighted by Share in Building
German	English	Min	Max	Mean	Amount	Share	
-	-	[kg/m3]	[kg/m3]	[kg/m3]	[m3]	%	[kg/m3]
Fundamente	Foundation	30	60	45	60.10	16.84%	7.58
Wände	Walls	20	60	40	127.32	35.68%	14.27
Decken	Floors	50	80	65	155.34	43.53%	28.29
Balken	Beams	80	100	90	11.61	3.25%	2.93
Stützen	Columns	100	130	115	2.49	0.70%	0.80
		280	**430**	**355**	**356.86**	**100.00%**	**53.87**
Mean Reinforcement in this Building						53.87	[kg/m3]
Specific Weight of Steel						7850	[kg/m3]
m3 Reinforcement per m3 Concrete						0.006863	[m3/m3]
m3 Reinforcement per m3 Concrete in Percent						0.69%	[%]

Table 5.5: Reinforcement Ratio

The brickwork was broken down into bricks and plaster, with plaster being 26 percent of the total volume. This value builds on the assumption that the average thickness of brickwork walls is 24cm, and the reference values of a construction company [52].

Table 5.4 was then used in the LCI of the Base Case, also named Case A. There are two other cases investigated, Case B and Case C that deviate in their way of quantity takeoff and source model respectively. All three cases are specified below.

5.3 Three Cases of Material Quantity Take-Off

The BIM model contains comprehensive information on the building that can be extracted and used in a building LCA in multiple ways. Since this thesis looks into a possible correlation of the LCA based on a BIM Model in early stages and one in a developed stage, there are three different cases to investigate:

Case A (Base Case): Table 5.4 is the input for the LCI of the Base Case, also named Case A. The Base Case uses the LOD 300 model as source and works with the volumes exported from this model. Some environmental data is implemented to work with material areas only, for example glazing. In this case the material area was used. But these are exceptions.
The process described to this point is focussed on this Base Case but applies to the other two cases as well.

Case B: In contrast to the Base Case, Case B uses material areas as far as possible. These areas are multiplied by their corresponding thickness to calculate volumes again. Case B considers all model elements that can be quantified in this way. These are: foundations, floors, exterior and interior walls, roofs, windows, doors, and stairs. It also takes into account structural columns and frame constructions, but in these cases material volumes were used. The expected differences to Case A result, amongst others, from the little model elements contained in a detailed BIM Model that cannot be expressed in areas.

Case C: This case uses an early-stage BIM Model (LOD 100) of the same building as basis for an LCA, in this case a surface model, which corresponds to conceptual design. This surface model consists of only foundations, floors, exterior walls, and roofs. These surfaces were extracted as areas and then multiplied with the corresponding thickness of each layer. In Case B these areas were extracted per layer but in Case C there is only one area for an entire structure, e.g. an entire wall comprising of multiple layers. So apart from the layer thickness, information concerning the structure of the building element is required. Since, in terms of LOD, this is a simpler model of the same building, the areas are not as accurate as in Case B and the structures and layers can not be assigned as precisely as in Case B. Windows, doors, and other comparatively small model elements are not modelled in the LOD 100 model and, therefore, not considered in this case.

Figure 5.4 illustrates the three cases. The geometry models were the source for the material information and quantities. The complete geometry model was used for the Base Case (Case A) and Case B, and the solid model with the surface areas was used for Case C.

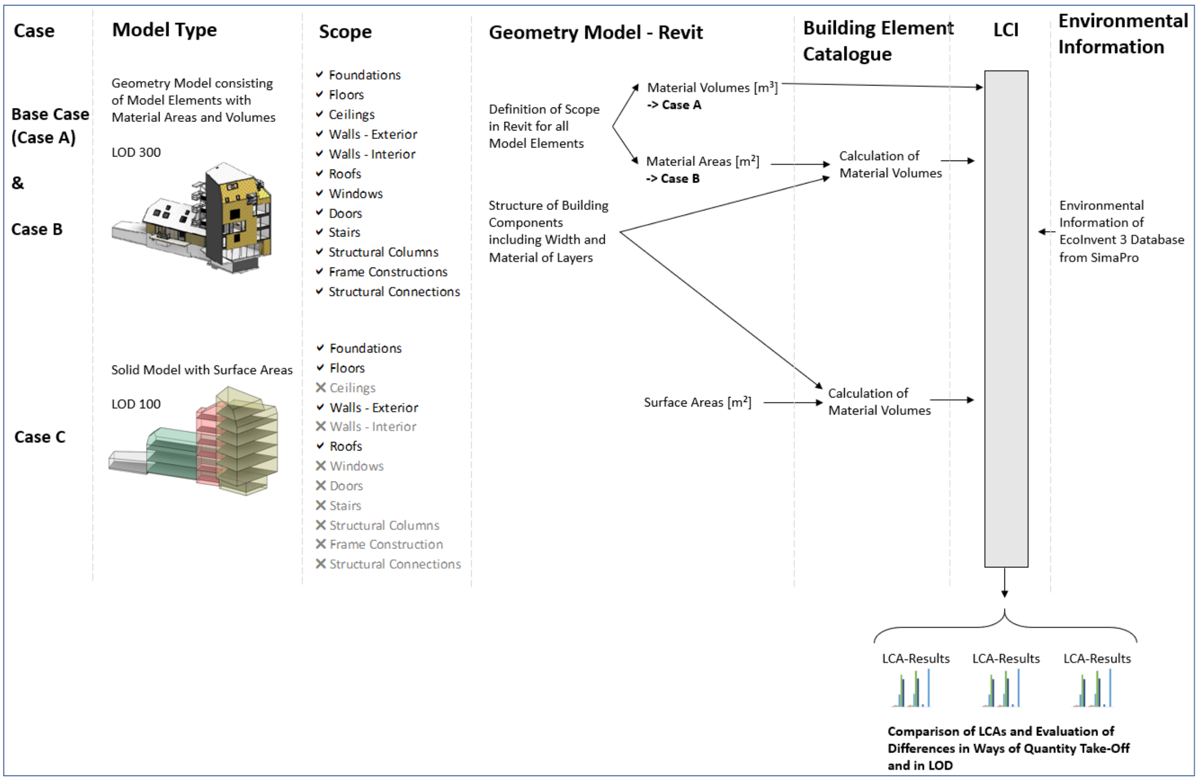


Figure 5.4: Workflow

Case B and Case C, both use material areas and the layer thickness to get the material volume. In addition, Case C requires the entire structure of the building elements, the build-up of all building elements. Extracting the material areas from Revit works the same way as with material volumes and has already been shown in the previous subchapters. The build-ups, however, had to be re-created in Excel explicitly to make Case B and Case C work. All build-ups were read manually from Revit and collected in Excel spreadsheets. Table 5.6 shows the build-up used for the floors of Case B. Each line in this table represents one material of the structure, specified in the first column. These structures are uniquely identified by the Revit parameter "*Family and type*". The thickness of each layer was added by hand and the area was automatically filled in by the Excel worksheet from the quantity takeoff. Based on this, the volume was calculated.

Family and Type	Material: Name	Area [m²]	Thickness [m]	Volume [m³]
Geschossdecke: FB - GN_160	Dämmung - hart	61.360	0.05	3.068
Geschossdecke: FB - GN_160	Fußboden - Epoxidharzbeschichtung	61.360	0.003	0.184
Geschossdecke: FB - GN_160	Fußboden - Heizestrich	61.360	0.06	3.682
Geschossdecke: FB - GN_160	Fußboden - PE-Folie	61.360	0.002	0.123
Geschossdecke: FB - GN_160	Fußboden - Trittschalldämmung	61.360	0.02	1.227
Geschossdecke: FB - GN_160	Geländearbeiten - Gebundene Schüttung	61.360	0.025	1.534
Geschossdecke: FB - GN_180	Dämmung - hart	229.200	0.05	11.460
Geschossdecke: FB - GN_180	Fußboden - Epoxidharzbeschichtung	229.200	0.003	0.688
Geschossdecke: FB - GN_180	Fußboden - Heizestrich	229.200	0.07	16.044
Geschossdecke: FB - GN_180	Fußboden - PE-Folie	229.200	0.002	0.458
Geschossdecke: FB - GN_180	Fußboden - Trittschalldämmung	229.200	0.02	4.584
Geschossdecke: FB - GN_180	Geländearbeiten - Gebundene Schüttung	229.200	0.035	8.022
Geschossdecke: FB - GN_190	Dämmung - hart	43.100	0.05	2.155
Geschossdecke: FB - GN_190	Fußboden - Epoxidharzbeschichtung	42.830	0.003	0.128
Geschossdecke: FB - GN_190	Fußboden - Heizestrich	42.960	0.07	3.007
Geschossdecke: FB - GN_190	Fußboden - PE-Folie	42.970	0.002	0.086
Geschossdecke: FB - GN_190	Fußboden - Trittschalldämmung	43.010	0.02	0.860
Geschossdecke: FB - GN_190	Geländearbeiten - Gebundene Schüttung	43.190	0.045	1.944
Geschossdecke: FB - GN_200	Dämmung - hart	73.140	0.05	3.657

Table 5.6: Build-up Floors

Table 5.7 contains the quantities of all three cases. This table has the same layout as table 5.3 but includes not just the Base Case (A), but also Case B and Case C.

5.3 Three Cases of Material Quantity Take-Off

	LOD 300 Model			LOD 100				
	Base Case (A)	Case B		Case C	cut-off?	Condensing Materials		Assumption?
	[m3]	[m2]	[m3]	[m3]		German	English	
Total:	852,18 #	12.086,50	877,24	779,22				
Dachdeckung - Blech	0,69	68,10	0,68	0,78		Aluminium Legierung	Aluminium Alloy	
Dachdeckung - Dampfbremse	0,00	149,55	0,30	0,36		PE-Folie	PE foil	assumption
Dachdeckung - Holz	9,06	422,91	11,47	0,00		Nadelholz	Softwood	
Dachdeckung - Trennlage	0,10	49,56	0,10	0,10		Bitumen	Bitumen seal	assumption
Dachdeckung - Ziegel	6,87	172,53	6,90	5,31		Dachziegel	Roof Tile	
Dämmung - hart	69,92	1.118,63	71,15	70,96		XPS	Polystyrene extruded (XPS)	
Dämmung - weich	85,91	1.174,08	104,42	51,19		Steinwolle	Rock wool	assumption
Fußboden - Epoxidharzbeschichtung	1,81	623,56	1,87	2,78		Epoxidharz	Epoxy resin	
Fußboden - Estrich	0,39	5,76	0,40	0,00		Zementestrich	Cement cast plaster floor	assumption
Fußboden - Fußbodenaufbau	24,47	117,52	0,00	0,00	not sufficient information		-	
Fußboden - Heizestrich	32,33	475,48	32,32	45,79		Zementestrich	Cement cast plaster floor	assumption
Fußboden - PE-Folie	0,82	412,43	0,82	1,01		PE-Folie	PE foil	
Fußboden - Schüttung	3,43	68,82	3,43	8,70		Kies	Gravel, crushed	
Fußboden - Terrasse Teakholz	4,09	18,21	4,19	0,00		Laubholz	Hardwood	
Fußboden - Trittschalldämmung	9,85	475,53	9,85	14,47		XPS	Polystyrene extruded (XPS)	assumption
Geländearbeiten - Gebundene Schüttung	15,50	406,89	15,52	19,11		Zementestrich	Cement cast plaster floor	assumption
Geländearbeiten - Rollierung - Schuettung	0,00	0,00	0,00	0,00		Kies	Gravel, crushed	
Glas - Isolierverglasung 2-fach	0,30	15,35	0,12	0,00		Doppelverglasung	Double Glazing	
Glas - Isolierverglasung 3-fach	4,91	241,26	1,93	0,00		Dreifachverglasung	Triple Glazing	
Glas - Isolierverglasung klar	0,13	33,49	0,27	0,00		Doppelverglasung	Double Glazing	assumption
Glas - klar	1,27	52,93	0,42	3,43		Flachglas	Flat glass, coated	
Glas - matt	0,72	20,52	0,16	0,00		Flachglas	Flat glass, coated	
Glas - orange 255-128-0	0,00	0,00	0,00	0,00	<<	-	-	
Holz	0,00	0,00	0,91	5,35		Nadelholz	Softwood	
Holz - 140-100-70	2,97	126,09	3,36	0,00		Nadelholz	Softwood	
Holz - 180-173-157	7,89	167,38	9,67	0,00		Nadelholz	Softwood	
Holz - 225-153-51	5,73	36,18	5,79	0,00		Nadelholz	Softwood	
Holz - Dunkelbraun 90-80-70	0,00	0,20	0,02	0,00		Nadelholz	Softwood	
Holz - HSB-Balken	6,05	221,29	9,58	12,51		Nadelholz	Softwood	
Holz - HSB-Schnittflächen	0,00	0,09	0,00	0,00	<<	-	-	
Holz - HSB-Steher	0,28	10,56	0,28	0,00		Nadelholz	Softwood	
Holz - Weißeiche natur	0,16	7,78	0,39	0,00		Laubholz	Hardwood	
Kunststoff - dunkelgrau 40-38-36	0,08	16,69	0,50	0,00		PVC, hart	PVC, hard	assumption
Kunststoff - Eierschale	4,82	220,62	4,61	0,00		PVC, hart	PVC, hard	assumption
Kunststoff - grau 192-192-192	0,00	0,05	0,00	0,00	<<	-	-	
Kunststoff - grau 50-50-50	0,00	1,18	0,02	0,00		PVC, hart	PVC, hard	assumption
Kunststoff - grau 70-70-70	1,10	27,44	1,10	0,80		PVC, hart	PVC, hard	assumption
Kunststoff - grau matt 64-64-64	3,70	213,72	6,41	0,00		PVC, hart	PVC, hard	assumption
Kunststoff_80-80-80	0,00	5,11	0,01	0,00		PVC, hart	PVC, hard	assumption
Lack - weiß 241-240-234	17,75	88,74	17,75	0,00		Nadelholz	Softwood	assumption
Luftschicht	32,23	564,70	0,00	0,00	Air	-	-	
Mauerwerk - mit Daemmeigenschaften	11,21	95,51	12,04	115,34		Mauerwerk	Brickwork	
Mauerwerk - ohne Daemmeigenschaften	102,42	196,64	117,69	0,00		Mauerwerk	Brickwork	
Mauerwerk - Paneel ausgeschäumt Betonopt	0,08	2,70	0,65	0,00		Mauerwerk	Brickwork	
Metall - Baustahl S 235	0,00	8,80	0,00	0,00	<<	-	-	
Metall - Baustahl S 355	0,60	143,83	0,60	0,00		Stahl, unlegiert	Steel, unalloyed	
Metall - Baustahl S 355 - weiss	0,11	22,34	0,11	0,00		Stahl, unlegiert	Steel, unalloyed	
Metall - Edelstahl gebürstet	0,00	3,87	0,01	0,00		Edelstahl	Steel, chromium steel	
Metall - Edelstahl Satiniert	0,01	8,27	0,02	0,00		Edelstahl	Steel, chromium steel	
Metall - Gitterrost	1,64	61,50	1,57	0,00		Stahl, unlegiert	Steel, unalloyed	
Metall - Goldfassade Brass	0,05	26,11	0,12	0,00		Messing	Brass	
Metall - Goldfassade Brass Schindeln	0,96	174,83	1,05	1,22		Messing	Brass	
Metall - Maschendraht Gold	0,29	102,44	0,31	0,07		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl	0,02	1,71	0,01	0,00		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl 345 MPa	0,12	27,54	0,12	0,00		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl schwarz	1,13	22,53	1,13	0,00		Stahl, unlegiert	Steel, unalloyed	
Metall - Stahl verzinkt	0,00	1,24	0,00	0,00	<<	-	-	
Ortbeton - bewehrt geschliffen	14,15	197,14	15,18	0,00		Stahlbeton	Reinforced Concrete	
Ortbeton - C30/37	112,29	561,01	127,76	228,42		Stahlbeton	Reinforced Concrete	
Ortbeton - C30/37 Verputzt	230,42	1.036,53	233,13	180,12		Stahlbeton	Reinforced Concrete	
Putz - gold	5,03	200,65	5,37	4,99		Putz	Plaster	
Putz - grau	1,13	76,29	1,14	0,00		Putz	Plaster	
Textil - Gold	0,00	0,00	0,00	0,00	<<	-	-	
Trockenbau - Gipsplatte	15,19	1.284,09	32,51	6,42		Trockenbau - Gipsplatte	Plasterboard	
						Bewehrung	Reinforcement	
						Light Clay Brick	Cement Mortar	

Table 5.7: Preparation of Extracted Quantities for LCI

5.4 Life Cycle Inventory

In the LCI the material quantities, scenarios, and environmental data are combined to calculate the environmental impact of the object as defined in the scope. The previous two chapters 5.2 and 5.3 were about getting the quantities, chapter 4.3 explained the selected scenarios, and 4.5 described the environmental data used.

LCA softwares like SimaPro [24] were designed to do this calculation. The data gathered so far was all stored in Excel spreadsheets, which would allow an automatic connection to SimaPro. And due to the large amount of input data, such a connection would speed up the process significantly. But this is not a standard feature of SimaPro and no tool with such functionality was found. That is why, in the course of this thesis another Excel spreadsheet was created that models the LCI process and seamlessly fits into the work completed so far. The essential data needed from SimaPro was the environmental data for each material. Therefore, SimaPro was set up to calculate an LCA for each material in the building, each for 1 unit of volume, area, or energy. The result was then implemented in the LCI spreadsheet.

Figure 5.5 shows the input tab of this spreadsheet. The first few columns are where the material names and quantities are entered. Then, the specific weights of the materials had to be added to calculate the total weight per material. This was necessary, since this BIM Model did not include this information, even though it would be supported by the software. Thus, the specific weights were added [53]. The next two columns "*Eurostats*" and "*PCRs*" are not essential to the LCA, but they add another aspect to the investigation of the LCA results and make choosing the EoL-Scenarios easier. Finally, there is the "*ESL-Code*", which stands for Expected Service Life - Code. This is linked to a material database with standard ESL values, as explained in chapter 4.3 (Scenerio Development). When entering the code, the ESL is set for LCS B4. The spreadsheet then continues with all the information required for each LCS, like environmental data or transport distances.

Materials		General Information						Categorizations		
			795.48	11,394.10			1,256,607.08			
ID	Materials (Revit)	le	Vol [m³]	Area [m2]	ρ [kg/m³]	Source [tkm/kg]	Weight [tkm/kg]	Eurostats [tkm/kg]	PCRs	ESL Code Default
E001	-	y	-	-	-	-	-	-	-	-
W001	-	y	-	-	-	-	-	-	-	-
Tra001	-	y	-	-	-	-	-	-	-	-
Tra002	-	y	-	-	-	-	-	-	-	-
Tra003	-	y	-	-	-	-	-	-	-	-
Tra004	-	y	-	-	-	-	-	-	-	-
M001	Aluminium Alloy	y	0.69	68.10	8,900	baubook.info;	6,141.00	Metal materials	2.16.3. Produkte aus Aluminium und Aluminiumlegierungen	
M002	Reinforced Concrete	n	356.86	1,794.68			0.00			
M002-1	Concrete	y	354.40		2,400	baubook.info;	850,554.40	Non-metallic mineral material:	2.17. Beton und Betonelemente	
M002-2	Reinforcement	y	2.46		7,800	baubook.info;	19,206.21	Metal materials	2.16.1. Baumetalle	
M003	Bitumen seal	y	0.10	49.56	1,050	baubook.info;	105.00	Fossil energy materials	2.1.2. Kunststoffmodifizierte Bitumendickbeschichtungen (KMB) zur Bau	
M004	Roof Tile	y	6.87	172.53	1,800	baubook.info;	12,366.00	Non-metallic mineral material:	2.5.3. Dachziegel	
M005	Double Glazing	y	0.43	48.84	2,500	baubook.info;	1,075.00	Non-metallic mineral material:	2.9.1.1. Flachglas im Bauwesen	
M006	Triple Glazing	y	4.91	241.26	2,500	baubook.info;	12,275.00	Non-metallic mineral material:	2.9.1.1. Flachglas im Bauwesen	
M007	Steel, chromium steel	y	0.01	12.14	7,800	baubook.info;	78.00	Metal materials	2.16.1. Baumetalle	
M008	Epoxy resin	y	1.81	623.56	1,420	baubook.info;	2,570.20	Fossil energy materials	2.2.2. Reaktionsharzprodukte	
M009	Flat glass, coated	y	1.99	73.45	2,500	baubook.info;	4,975.00	Non-metallic mineral material:	2.9.1.1. Flachglas im Bauwesen	
M010	Gravel, crushed	y	3.43	68.82	1,800	baubook.info;	6,174.00	Non-metallic mineral material:	1.4.1.1 Gesteinskörnungen	
M011	Hardwood	y	4.25	25.99	780	baubook.info;	3,315.00	Biomass based materials	2.11. Holz	
M012	Brickwork	n	113.71	294.85			0.00	Non-metallic mineral materials		
M012-1	Bricks	y	84.15		800	IBO Massivbau	67,316.32	Non-metallic mineral material:	2.15.2. Mauerwerksziegel	
M012-2	Mortar	y	29.56		2,000	baubook.info;	59,129.20	Non-metallic mineral material:	2.15.1. Mineralische Werkmörtel	
M013	Brass	y	1.01	200.94	8,500	baubook.info;	8,585.00	Metal materials	2.16.1. Baumetalle	
M014	Softwood	y	49.73	1,073.35	540	baubook.info;	26,854.20	Biomass based materials	2.11. Holz	
M015	PE foil	y	0.82	561.98	1,000	baubook.info;	820.00	Fossil energy materials	2.18. Produkte aus Kunststoff	
M016	Plaster	y	6.16	276.94	1,100	baubook.info;	6,776.00	Non-metallic mineral material:	2.19. Putze	
M017	PVC, hard	y	9.70	484.76	1,390	baubook.info;	13,483.00	Fossil energy materials	2.18. Produkte aus Kunststoff	
M018	Steel, unalloyed	y	3.91	381.89	7,800	baubook.info;	30,498.00	Metal materials	2.16.1. Baumetalle	
M019	Rock wool	y	85.91	1,174.08	130	baubook.info;	11,168.30	Non-metallic mineral material:	2.22.2.1. Dämmstoffe aus Mineralwolle	
M020	Plasterboard	y	15.19	1,284.09	900	baubook.info;	13,671.00	Fossil energy materials	2.10.1. Gipsplatten	
M021	Polystyrene extruded (XPS)	y	79.77	1,594.16	38	baubook.info;	3,031.26	Fossil energy materials	2.22.1.1 EPS und XPS	
M022	Cement cast plaster floor	y	48.22	888.13	2,000	baubook.info;	96,440.00	Non-metallic mineral material:	2.17. Beton und Betonelemente	

Figure 5.5: LCI Spreadsheet - Input of Essential Data

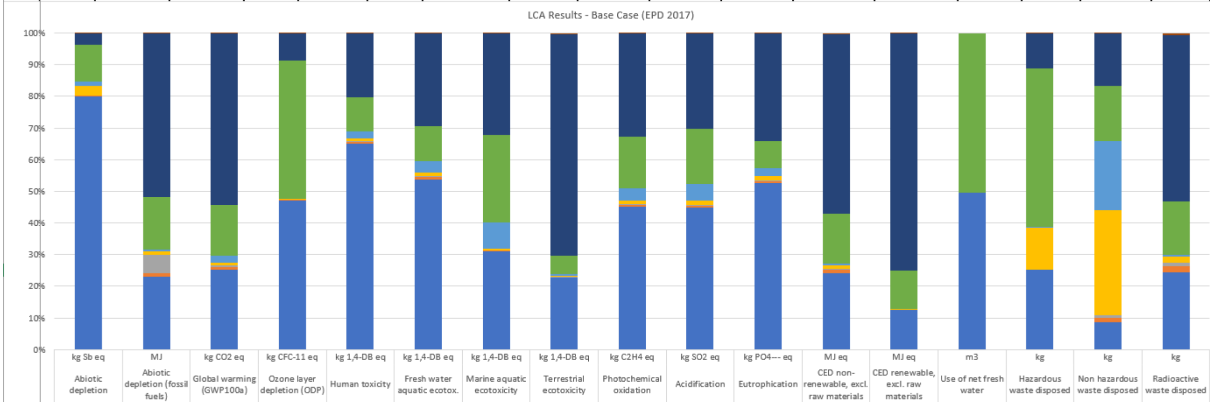
All the information needed for the LCA are gathered in a single tab. The next tabs are dedicated to specific LCS and databases, but they are either automatic or static and don't require manual change or input.

The environmental data is then multiplied by the material quantities within the framework of the scenarios. The result is the environmental impact of the building per LCS, and given in specific values of impact indicators. They are calculated in another tab with prepared diagrams. Figure 5.6 gives an overview of this tab, with the results of the LCA visible as table and diagram. The following chapter (Chapter 6) investigates the LCA results in detail.

LCA-Results

EPD 2017 - complete

	Abiotic deple kg Sb eq	Abiotic depletion (MJ	Global warming (G kg CO2 eq	Ozone layer kg CFC-11 eq	Human toxicity kg 1,4-DB eq	Fresh water a kg 1,4-DB eq	Marine aquatic ecoto kg 1,4-DB eq	Terrestrial ecoto kg 1,4-DB eq	Photochemical o kg C2H4 eq	Acidification kg SO2 eq	Eutrophication kg PO4--- eq	CED non-renewabl MJ eq	CED renewable, exc MJ eq	Use of net fresh m3	Hazardous wa kg	Non hazardous w kg	Radioactive w kg
A1-A3	32.4557	5,155,510.3002	450,414.0942	0.6138	437,275.5719	8,893.5761	436,909,590.0755	2,816.0054	219.7622	3,995.3640	848.7513	5,698,383.8705	1,322,847.6285	509.0133	72.1629	50,711.0569	40.3881
A4	0.0779	247,897.3644	16,076.8601	0.0028	3,729.4332	139.5728	3,437,644.9291	24.3444	2.7833	51.4269	7.9042	238,813.7176	3,958.0094	0.0000	0.1720	7,358.4788	3.2044
C2	0.0191	1,330,770.6925	6,940.0354	0.0013	1,952.3348	71.4913	1,069,326.4641	9.5032	1.1325	22.3496	3.6523	106,899.1493	1,506.0879	0.0000	0.0575	5,044.9232	1.4929
C3	1.2195	254,658.3050	17,638.9604	0.0028	4,778.4785	175.7200	6,605,827.6980	57.1092	4.3797	121.4449	24.1542	263,530.5505	15,407.7721	0.0000	37.8381	195,211.8167	3.1483
C4	0.5844	111,727.3467	39,470.2475	0.0016	16,222.4079	605.4469	117,487,295.1605	56.9494	19.6184	479.4435	38.8172	120,049.3558	13,093.2027	0.0000	0.9035	126,623.5597	1.0031
B4	4.6392	3,721,940.3797	284,122.8575	0.5678	71,332.5872	1,833.8108	388,615,169.0485	731.1245	78.8398	1,539.0365	136.3363	3,703,791.2768	1,271,347.1231	515.1064	142.4363	102,508.6236	27.9537
B6	1.5138	11,592,927.6550	969,868.7828	0.1147	136,112.1185	4,828.6991	453,566,322.0056	8,686.8500	158.1135	2,690.2891	549.7470	13,454,638.4953	7,931,830.7315	0.0000	32.0791	96,814.1210	86.3292
B7	0.0159	27,317.0479	2,347.0551	0.0006	833.0514	28.4781	1,054,116.3021	50.3775	0.9403	10.9025	1.4120	67,460.1528	11,289.9175	0.0000	0.1188	731.3025	1.3192
Total	40.5255	22,442,749.0915	1,786,878.8929	1.3053	672,235.9834	16,576.7952	1,408,745,291.6834	12,432.2635	485.5698	8,910.2569	1,610.7744	23,653,566.5685	10,571,280.4727	1,024.1198	285.7682	585,003.8823	164.8387
Embodie	34.3566	7,100,564.0088	530,540.1975	0.6223	463,958.2263	9,885.8072	565,509,684.3273	2,963.9115	247.6762	4,670.0288	923.2792	6,427,676.6436	1,356,812.7006	509.0133	111.1339	384,949.8352	49.2368



	kg Sb eq Abiotic depletion	MJ Abiotic depletion (fossil fuels)	kg CO2 eq Global warming (GWP100a)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity	kg 1,4-DB eq Fresh water aquatic ecotox.	kg 1,4-DB eq Marine aquatic ecotoxicity	kg 1,4-DB eq Terrestrial ecotoxicity	kg C2H4 eq Photochemical oxidation	kg SO2 eq Acidification	kg PO4--- eq Eutrophication	MJ eq CED non-renewable, excl. raw materials	MJ eq CED renewable, excl. raw materials	m3 Use of net fresh water	kg Hazardous waste disposed	kg Non hazardous waste disposed	kg Radioactive waste disposed
B7	0.0159	27,317.0479	2,347.0551	0.0006	833.0514	28.4781	1,054,116.302	50.3775	0.9403	10.9025	1.4120	67,460.1528	11,289.9175	0.0000	0.1188	731.3025	1.3192
B6	1.5138	11,592,927.65	969,868.7828	0.1147	136,112.1185	4,828.6991	453,566,322.0	8,686.8500	158.1135	2,690.2891	549.7470	13,454,638.49	7,931,830.731	0.0000	32.0791	96,814.1210	86.3292
B4	4.6392	3,721,940.379	284,122.8575	0.5678	71,332.5872	1,833.8108	388,615,169.0	731.1245	78.8398	1,539.0365	136.3363	3,703,791.276	1,271,347.123	515.1064	142.4363	102,508.6236	27.9537
C4	0.5844	111,727.3467	39,470.2475	0.0016	16,222.4079	605.4469	117,487,295.1	56.9494	19.6184	479.4435	38.8172	120,049.3558	13,093.2027	0.0000	0.9035	126,623.5597	1.0031
C3	1.2195	254,658.3050	17,638.9604	0.0028	4,778.4785	175.7200	6,605,827.698	57.1092	4.3797	121.4449	24.1542	263,530.5505	15,407.7721	0.0000	37.8381	195,211.8167	3.1483
C2	0.0191	1,330,770.692	6,940.0354	0.0013	1,952.3348	71.4913	1,069,326.464	9.5032	1.1325	22.3496	3.6523	106,899.1493	1,506.0879	0.0000	0.0575	5,044.9232	1.4929
A4	0.0779	247,897.3644	16,076.8601	0.0028	3,729.4332	139.5728	3,437,644.929	24.3444	2.7833	51.4269	7.9042	238,813.7176	3,958.0094	0.0000	0.1720	7,358.4788	3.2044
A1-A3	32.4557	5,155,510.300	450,414.0942	0.6138	437,275.5719	8,893.5761	436,909,590.0	2,816.0054	219.7622	3,995.3640	848.7513	5,698,383.870	1,322,847.628	509.0133	72.1629	50,711.0569	40.3881

Figure 5.6: Spreadsheet - LCA-Results

6 Results

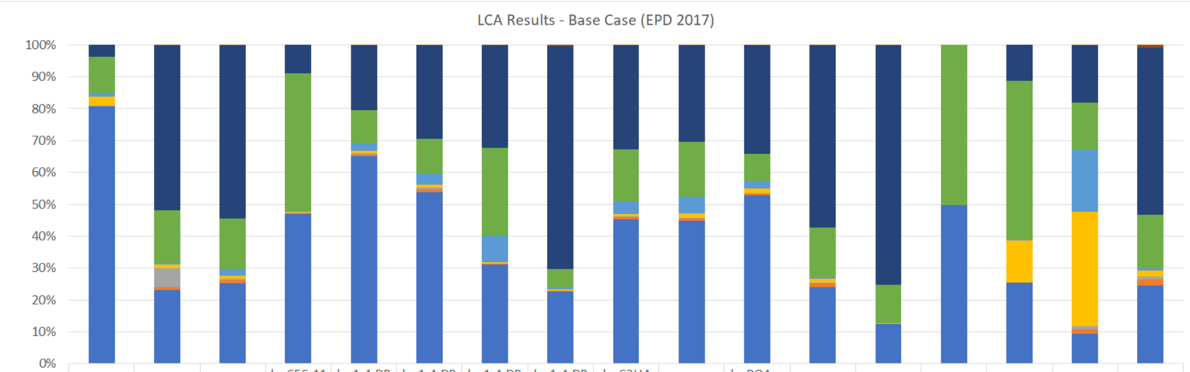
This chapter presents the LCA results of the three cases. This was the basis to test the hypotheses and answer the research questions of this thesis, defined in chapter 1.2.

6.1 Life Cycle Assessment

The LCA results of the Base Case (Case A) will be shown and investigated per dominance analysis. Then the results will be compared to the results of the other two cases (Case B and Case C). In addition, a sensitivity analysis can be found in appendix G.

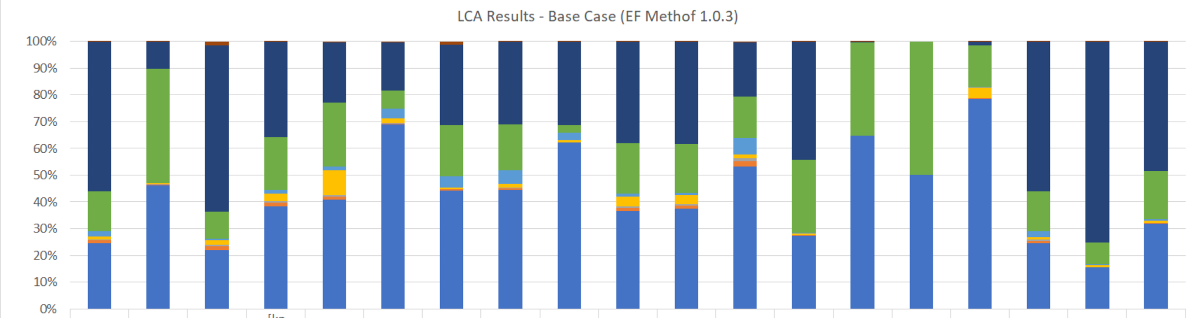
6.1.1 Base Case (Case A)

The building LCA described in the previous chapters was evaluated using the EPD 2017 method and the EF 1.0.3 method. Figures 6.1 and 6.2 show plots of the results. Each column illustrates one impact indicator for all LCS included.



	kg Sb eq Abiotic depletion	MJ Abiotic depletion (fossil fuels)	kg CO2 eq Global warming (GWP100a)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity	kg 1,4-DB eq Fresh water aquatic ecotox.	kg 1,4-DB eq Marine aquatic ecotoxicity	kg 1,4-DB eq Terrestrial ecotoxicity	kg C2H4 eq Photoche mical oxidation	kg SO2 eq Acidificati on	kg PO4--- eq Eutrophica tion	MJ eq CED non-renewable , excl. raw materials	MJ eq CED renewable , excl. raw materials	m3 Use of net fresh water	kg Hazardous waste disposed	kg Non hazardous waste disposed	kg Radioactiv e waste disposed
B7	0,0159	27.317,04	2.347,055	0,0006	833,0514	28,4781	1.054.116	50,3775	0,9403	10,9025	1,4120	67.460,15	11.289,91	0,0000	0,1188	731,3025	1,3192
B6	1,5138	11.592.92	969.868,7	0,1147	136.112,1	4.828,699	453.566.3	8.686,850	158,1135	2.690,289	549,7470	13.454.63	7.931.830	0,0000	32,0791	96.814,12	86,3292
B4	4,5110	3.708.033	281.858,3	0,5675	70.859,76	1.806,625	388.102.3	721,9509	78,5154	1.533,024	135,1863	3.689.821	1.269.510	515,1064	141,6987	80.383,25	27,8291
C4	0,4563	97.820,02	37.205,76	0,0012	15.749,58	578,2617	116.974.5	47,7758	19,2940	473,4313	37,6672	106.079,9	11.256,33	0,0000	0,1659	104.498,1	0,8786
C3	1,2195	254.658,3	17.638,96	0,0028	4.778,478	175,7200	6.605.827	57,1092	4,3797	121,4449	24,1542	263.530,5	15.407,77	0,0000	37,8381	195.211,8	3,1483
C2	0,0191	1.330.770	6.940,035	0,0013	1.952,334	71,4913	1.069.326	9,5032	1,1325	22,3496	3,6523	106.899,1	1.506,087	0,0000	0,0575	5.044,923	1,4929
A4	0,0779	247.897,3	16.076,86	0,0028	3.729,433	139,5728	3.437.644	24,3444	2,7833	51,4269	7,9042	238.813,7	3.958,009	0,0000	0,1720	7.358,478	3,2044
A1-A3	32,4557	5.155.510	450.414,0	0,6138	437.275,5	8.893,576	436.909.5	2.816,005	219,7622	3.995,364	848,7513	5.698.383	1.322.847	509,0133	72,1629	50.711,05	40,3881

Figure 6.1: LCA Results Base Case for the Entire Building - EPD Method

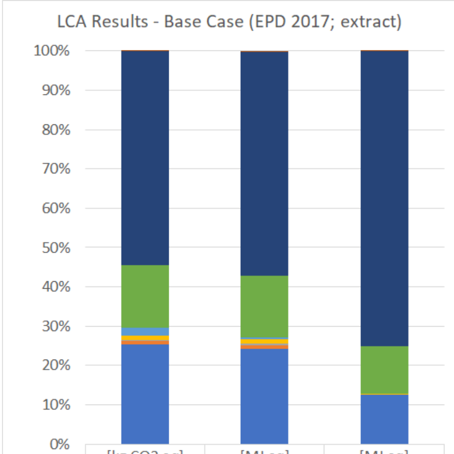


	[kg CO2 eq] Climate change	[kg CFC11 eq] Ozone depletion	[kBq U-235 eq] Ionising radiation, HH	[kg NMVOC eq] Photochemical ozone formation, HH	[disease inc.] Respiratory inorganics	[CTUh] Non-cancer human health effects	[CTUh] Cancer human health effects	[mol H+ eq] Acidification terrestrial and freshwater	[kg P eq] Eutrophication freshwater
B7	2.428,43	0,0004	1.074,52	9,1414	0,0002	0,0018	0,0005	13,1970	0,1523
B6	994.227,	0,1091	47.408,3	1.774,95	0,0174	0,0901	0,0118	3.251,90	105,9049
B4	262.524,	0,4647	7.832,95	982,7727	0,0183	0,0335	0,0076	1.817,89	9,1615
C4	37.449,4	0,0013	415,0124	72,4192	0,0011	0,0177	0,0017	525,8340	10,3772
C3	17.925,1	0,0033	1.238,49	149,1054	0,0070	0,0083	0,0002	157,5967	2,1824
C2	7.013,15	0,0016	490,6870	27,8873	0,0005	0,0010	0,0001	28,5852	0,0951
A4	16.263,6	0,0035	1.051,07	56,8827	0,0009	0,0020	0,0002	64,6525	0,3417
A1-A3	437.260,	0,5022	16.700,4	1.918,56	0,0313	0,3435	0,0174	4.681,39	210,8281

	[kg N eq] Eutrophication marine	[mol N eq] Eutrophication terrestrial	[CTUe] Ecotoxicity freshwater	[Pt] Land use	[m3 depriv.] Water scarcity	[MJ] Resource use, energy carriers	[kg Sb eq] Resource use, mineral and metals	[kg CO2 eq] Climate change - fossil	[kg CO2 eq] Climate change - biogenic	[kg CO2 eq] Climate change - land use and transform.
B7	2,3804	26,4699	6.023,56	23.031,0	17.802,7	0,0000	0,0120	2.388,61	7,6711	3,7465
B6	512,4425	6.116,38	278.219,	26.748.9	28.855,4	0,0000	0,3738	987.436,	3.666,54	1.148,46
B4	253,3109	2.911,76	215.029,	16.654.2	4.091.83	410.084,	3,8372	261.018,	399,5302	430,9848
C4	14,5378	174,3583	86.294,5	144.119,	222,6223	0,0000	0,0143	37.373,5	21,3961	13,0677
C3	48,3407	537,2105	17.219,7	315.327,	294,8655	0,0000	1,0232	17.801,6	35,9289	15,7481
C2	8,2107	90,6102	17.271,8	108.869,	24,6309	0,0000	0,0126	6.987,28	1,3653	2,4891
A4	16,4663	182,6922	26.671,3	169.809,	65,1776	0,0000	0,0515	16.196,8	4,1524	8,9263
A1-A3	492,8457	5.977,68	733.884,	16.505.1	7.599.53	410.084,	19,4537	432.368,	751,9290	754,2214

Figure 6.2: LCA Results Base Case for the Entire Building - EF Method

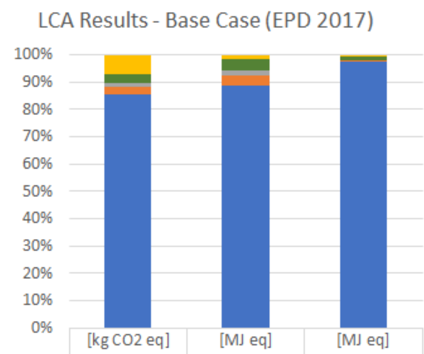
For the further investigation of the results, we will focus on three impact indicators included in the EPD 2017 method. These three are Global Warming Potential (GWP) in [kg CO2 eq.], non-renewable Cumulative Energy Demand (CEDnr) in [MJ], and renewable Cumulative Energy Demand (CEDr) in [MJ] (See figure 6.3).



	[kg CO2 eq] Global warming (GWP100a)	[MJ eq] CED non-renewable, excl. raw materials	[MJ eq] CED renewable, excl. raw materials
B7	2.347	67.460	11.290
B6	969.869	13.454.638	7.931.831
B4	281.858	3.689.822	1.269.510
C4	37.206	106.080	11.256
C3	17.639	263.531	15.408
C2	6.940	106.899	1.506
A4	16.077	238.814	3.958
A1-A3	450.414	5.698.384	1.322.848

Figure 6.3: LCA Results Base Case for the Entire Building - EPD

Moreover, to improve comparability only the embodied impacts excluding LCS B4 were investigated (See figure 6.4). Life Cycle Stage B4 was excluded because it is based on the other embodied impacts and, as such is a dependent variable, which does not contribute to the accuracy of the further analysis of this case study.



	[kg CO2 eq] Global warming (GWP100a)	[MJ eq] CED non-renewable, excl. raw materials	[MJ eq] CED renewable, excl. raw materials
C4	37.206	106.080	11.256
C3	17.639	263.531	15.408
C2	6.940	106.899	1.506
A4	16.077	238.814	3.958
A1-A3	450.414	5.698.384	1.322.848

Figure 6.4: LCA Results Base Case for the Entire Building - EPD - Only Embodied Impacts

6.1.2 Dominance Analysis

The goal of this dominance analysis was to find the major influences in this LCA study. Sankey diagrams facilitate a clear representation of a multitude of links between various datasets. Therefore, a series of such illustrations was produced during this analysis using an online tool [54].

Figure 6.5 and 6.6 illustrate the flow of materials in kilogram across different classification systems, like Eurostat materials, PCRs, waste categories, ÖNorm B 1801-1 categories, and Revit categories.

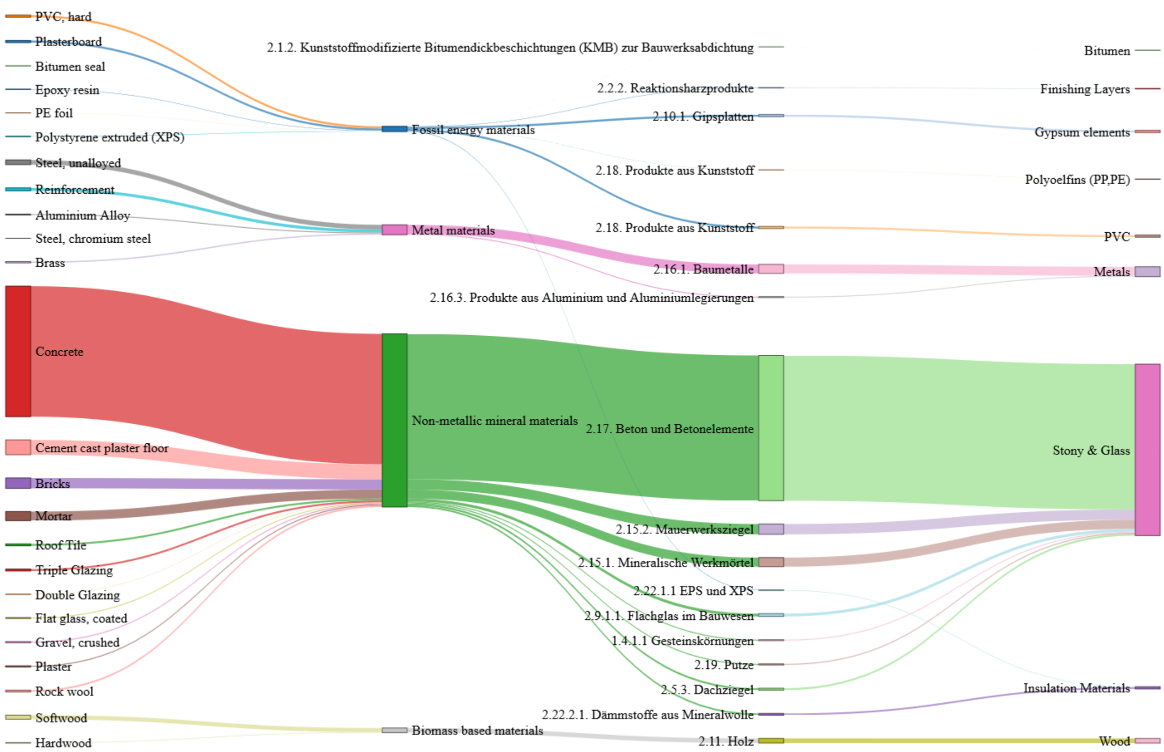


Figure 6.5: Sankey Diagram: Materials - Eurostat - PCR - Waste Categories in kg for the Entire Building

Concrete makes up the biggest part in terms of mass across all classification systems. Second and significantly smaller is the share of metals, as can be seen in the Eurostat classification or waste category.

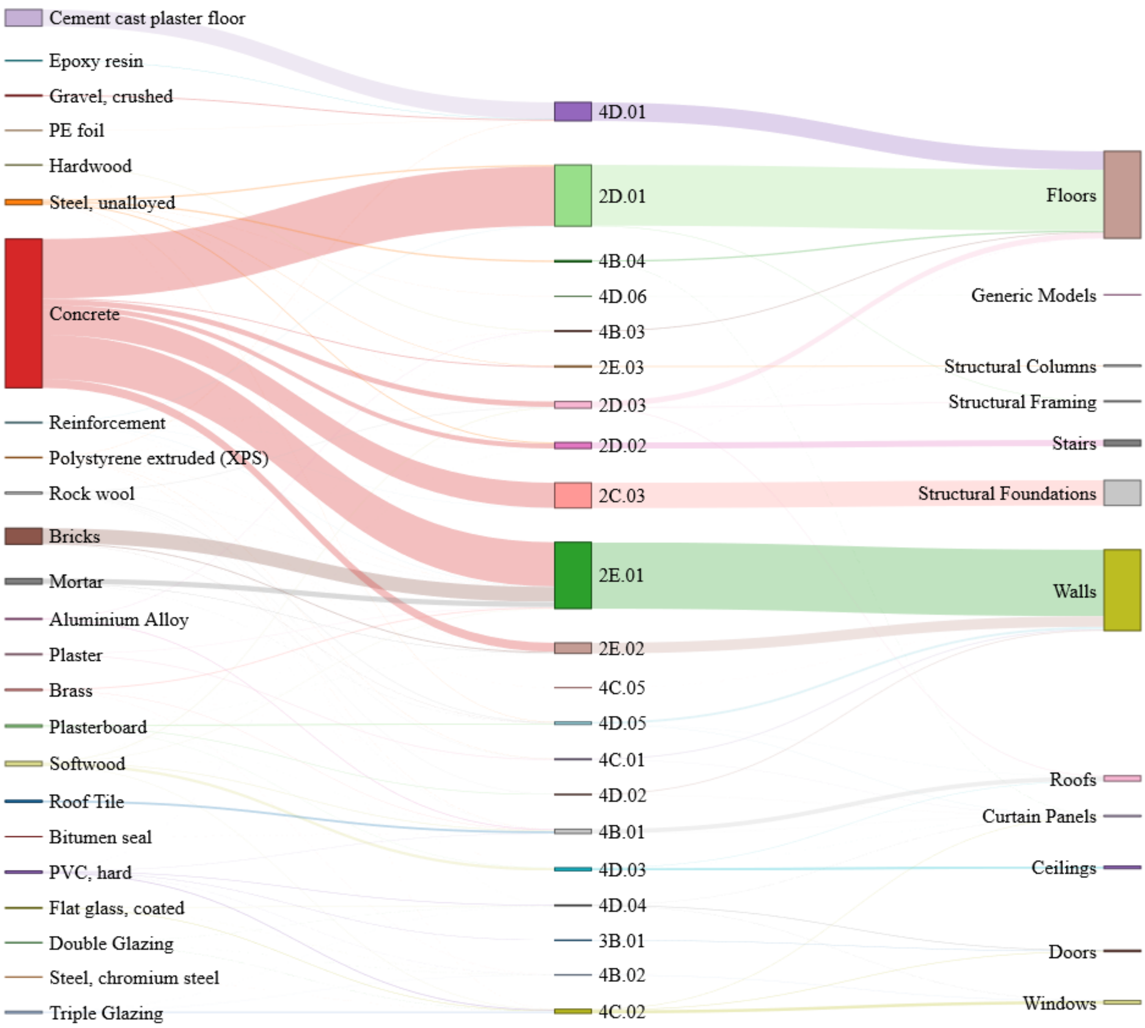


Figure 6.6: Sankey Diagram: Materials - ÖNorm B 1801-1 - Revit Categories in kg for the Entire Building

Figure 6.6 shows what type of building elements make up the material mass. The vast majority of concrete elements are either floors, walls, or structural foundations. In this diagram, the relevant Revit categories align quite well with the categories of the ÖNorm B 1801-1 classification system. 2D.01 contains only floors, 2C.03 are structural foundations, 2E.01 however includes only exterior walls. The interior walls are represented by 2E.02.

4D.01 are floorings, which in terms of the Revit categories is part of the floor.

The following chart (Figure 6.7) shows the distribution of the GWP across materials and LCS. The LCS A1-A3 clearly is the predominant factor of the life-cycle limited to embodied impacts. But when assigning the GWP to the materials, the results are spread more evenly. Again, concrete is the biggest share, followed by multiple metals, insulation, and reinforcement.

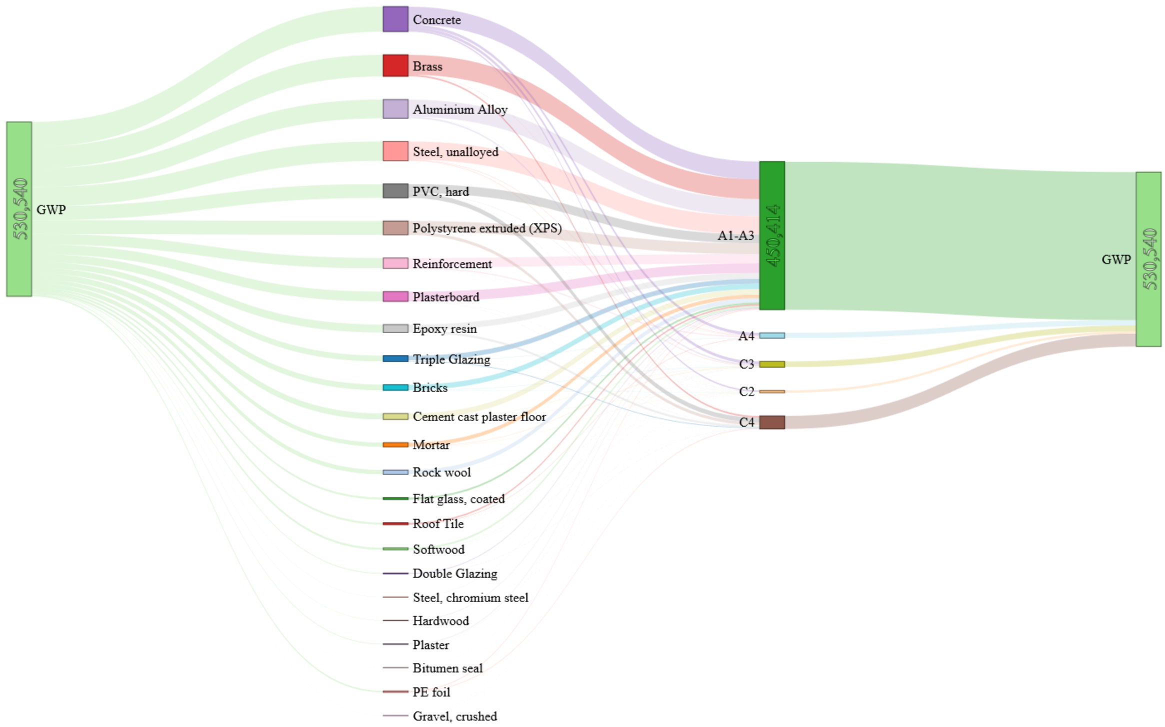


Figure 6.7: Sankey Diagram: GWP - Materials - LCS in kg CO2 eq. for the Entire Building

Figure 6.8 shows the same charts for CEDnr and CEDr, although smaller. They illustrate a similar pattern as the GWP-chart. The full-size charts can be found in appendix F.

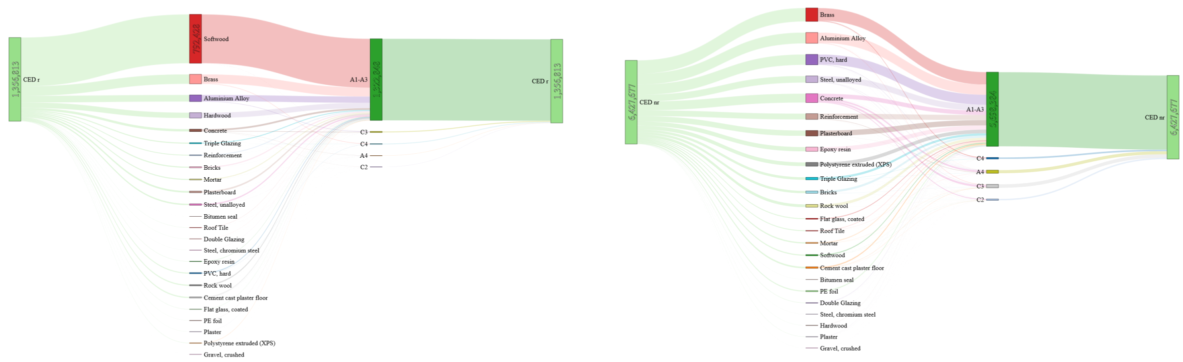


Figure 6.8: Sankey Diagrams: CEDr and CEDnr - Materials - LCS in MJ eq. for the Entire Building

Until now only the LCA results of the Base Case (Case A) have been presented. To answer the research questions and test the hypotheses the Base Case is compared to Case C and then to Case B.

Figure 6.9 shows the LCA results of all three cases in comparison. It only includes the GWP, the CEDnr, and the CEDr and only the embodied impacts. The complete LCA results of Case B and Case C, for both EPD 2017 and EF 1.0.3, can be found in Appendix I and J.

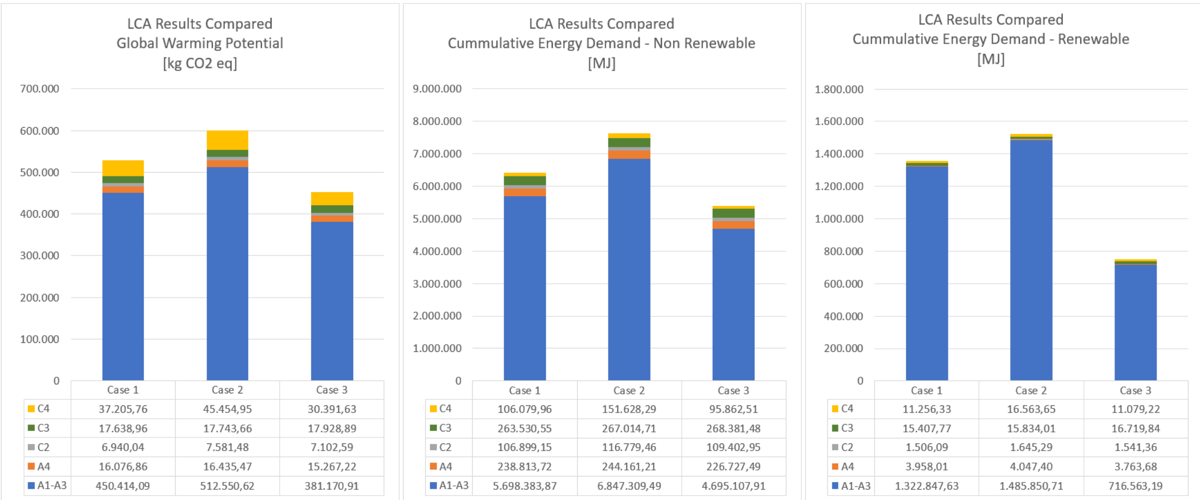


Figure 6.9: LCA Results - All Cases Compared

In all three impact categories, Case B has the highest results (See figure 6.9), even though Case A and Case B are of the same BIM model and only the way of quantity take-off is different.

Case C shows the lowest results. Since it is based on another geometry model, the material quantities differ significantly, leading to the discrepancy compared to Case A.

6.2 Base Case and Case C

In this subchapter the LCI and LCA results of the Base Case (A) and Cae C are compared. Table 6.1 shows the exact differences in quantities by Revit category and by material. In addition, it highlights the values that can be traced back to model elements that are not contained in the surface model.

Case A compared to Case C in [m3]													
Materials	**Revit Categories**										**Total**		
												absolute values	
	Foundation	Floor	Walls	Roofs	Frame Construction	Window	Door	Structural Columns	Stairs	Generic Models	all elements	all elements	un-modelled
Aluminium Alloy	0,00	0,19	0,00	-0,28	0,00	0,00	0,00	0,00	0,00	0,00	-0,09	0,47	0,00
Reinforced Concrete	0,47	-13,45	-31,65	-21,15	0,00	0,00	0,00	2,49	11,61	0,00	-51,68	80,81	14,10
Bitumen seal	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Roof Tile	0,00	0,00	0,00	1,56	0,00	0,00	0,00	0,00	0,00	0,00	1,56	1,56	0,00
Double Glazing	0,00	0,00	0,00	0,00	0,00	0,07	0,36	0,00	0,00	0,00	0,43	0,43	0,43
Triple Glazing	0,00	0,00	0,00	0,00	0,00	4,91	0,00	0,00	0,00	0,00	4,91	4,91	4,91
Steel, chromium steel	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,01	0,01	0,01
Epoxy resin	0,00	-0,97	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,97	0,97	0,00
Flat glass, coated	0,00	0,00	-2,16	0,00	0,00	0,72	0,00	0,00	0,00	0,00	-1,44	2,88	0,72
Gravel, crushed	0,00	-5,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-5,27	5,27	0,00
Hardwood	0,00	4,09	0,00	0,00	0,00	0,00	0,16	0,00	0,00	0,00	4,25	4,25	0,16
Brickwork	0,00	0,00	-1,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-1,63	1,63	0,00
Brass	0,00	0,00	-0,24	-0,02	0,00	0,05	0,00	0,00	0,00	0,00	-0,21	0,31	0,05
Softwood	0,00	27,99	-2,42	-2,16	6,05	0,04	3,46	0,28	0,29	0,00	33,53	42,69	10,12
PE foil	0,00	-0,19	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,19	0,19	0,00
Plaster	0,00	0,00	1,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,17	1,17	0,00
PVC, hard	0,00	0,00	0,00	0,30	0,00	4,01	4,59	0,00	0,00	0,00	8,90	8,90	8,60
Steel, unalloyed	0,00	1,82	0,21	0,00	0,47	0,00	0,03	0,36	0,88	0,07	3,84	3,84	1,81
Rock wool	0,00	0,00	31,67	3,06	0,00	0,00	0,00	0,00	0,00	0,00	34,72	34,72	0,00
Plasterboard	0,00	0,08	9,09	1,26	0,00	0,00	0,00	0,00	0,00	0,00	10,43	10,43	0,00
Polystyrene extruded (XPS)	0,00	-6,61	3,59	-2,64	0,00	0,00	0,00	0,00	0,00	0,00	-5,66	12,84	0,00
Cement cast plaster floor	0,00	-16,68	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-16,68	16,68	0,00
Total	0,47	-9,00	7,63	-20,07	6,52	9,80	8,61	3,13	12,78	0,07	**19,94**		
Total (absolut values)	0,47	77,34	83,83	32,42	6,52	9,80	8,61	3,13	12,78	0,07		**234,97**	
Total (un-modelled elements in Surface Model; absolute values)	0,00	0,00	0,00	0,00	6,52	9,80	8,61	3,13	12,78	0,07			**40,91**

Table 6.1: Material Quantities of Case A Compared to Case C

When just taking the sum of the differences, the resulting total of material volume is 19.94 m3. However, this does not reflect the difference of material type caused by the much simpler modelling of the elements in the surface model (Case C). Instead of containing several different wall structures that can change multiple times in a single wall surface, the surface model was calculated with a single wall structure. The modelling is greatly simplified. This means that there are fewer materials of greater quantities. This is quite obvious when comparing the material quantities of walls in table 6.1. Case A includes less reinforced concrete (-31.65 m3) and more rock wool (+31.67 m3). Despite the similarity of these two numbers serving as a good example, it can not be deducted that the volume of rock wool of Case A is reinforced concrete in Case C. The actual distribution of the materials from Case C to Case A does not follow a 1:1 ratio from rock wool to reinforced concrete, but includes all the materials. The total of absolute values, 234.97 m3, reflects this restructuring.

The surface model does not include the following Revit categories: Frame construction, windows, doors, structural columns, stairs, and generic model elements. In terms of absolute numbers, this makes up 40.91 m3, consisting mostly of reinforced concrete (14.10 m3), softwood (10.12 m3), and PCV (hard; 8.60 m3).

Table 6.2 has the same layout as table 6.1 (above) but instead of differences in material volume, it contains the impact these volume differences have on the total GWP of the base case (Case A).

Case A compared to Case C in GWP													
Materials	**Revit Categories**										**Total**		
												absolute values	
	Foundation	Floor	Walls	Roofs	Frame Construction	Window	Door	Structural Columns	Stairs	Generic Models	all elements	all elements	un-modelled
Aluminium Alloy	0,00%	2,96%	0,00%	-4,33%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-1,38%	7,29%	0,00%
Reinforced Concrete	0,03%	-0,77%	-1,80%	-1,21%	0,00%	0,00%	0,00%	0,14%	0,66%	0,00%	-2,95%	4,61%	0,80%
Bitumen seal	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Roof Tile	0,00%	0,00%	0,00%	0,24%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,24%	0,24%	0,00%
Double Glazing	0,00%	0,00%	0,00%	0,00%	0,00%	0,03%	0,32%	0,00%	0,00%	0,00%	0,35%	0,35%	0,35%
Triple Glazing	0,00%	0,00%	0,00%	0,00%	0,00%	2,93%	0,00%	0,00%	0,00%	0,00%	2,93%	2,93%	2,93%
Steel, chromium steel	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,07%	0,00%	0,00%	0,00%	0,07%	0,07%	0,07%
Epoxy resin	0,00%	-2,42%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-2,42%	2,42%	0,00%
Flat glass, coated	0,00%	0,00%	-1,17%	0,00%	0,00%	0,39%	0,00%	0,00%	0,00%	0,00%	-0,78%	1,57%	0,39%
Gravel, crushed	0,00%	-0,03%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,03%	0,03%	0,00%
Hardwood	0,00%	0,12%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,12%	0,12%	0,00%
Brickwork	0,00%	0,00%	-0,08%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,08%	0,08%	0,00%
Brass	0,00%	0,00%	-2,96%	-0,23%	0,00%	0,61%	0,00%	0,00%	0,00%	0,00%	-2,58%	3,81%	0,61%
Softwood	0,00%	0,65%	-0,06%	-0,05%	0,14%	0,00%	0,08%	0,01%	0,01%	0,00%	0,78%	0,99%	0,23%
PE foil	0,00%	-0,19%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,19%	0,19%	0,00%
Plaster	0,00%	0,00%	0,06%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,06%	0,06%	0,00%
PVC, hard	0,00%	0,00%	0,00%	0,24%	0,00%	3,28%	3,76%	0,00%	0,00%	0,00%	7,29%	7,29%	7,04%
Steel, unalloyed	0,00%	5,18%	0,60%	0,00%	1,34%	0,00%	0,09%	1,02%	2,50%	0,20%	10,92%	10,92%	5,15%
Rock wool	0,00%	0,00%	0,91%	0,09%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	1,00%	1,00%	0,00%
Plasterboard	0,00%	0,03%	3,35%	0,46%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	3,84%	3,84%	0,00%
Polystyrene extruded (XPS)	0,00%	-0,66%	0,36%	-0,26%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,56%	1,28%	0,00%
Cement cast plaster floor	0,00%	-1,17%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-1,17%	1,17%	0,00%
Total	0,03%	3,69%	-0,80%	-5,04%	1,48%	7,25%	4,32%	1,17%	3,17%	0,20%	**15,47%**		
Total (absolut values)	0,03%	14,17%	11,35%	7,12%	1,48%	7,25%	4,32%	1,17%	3,17%	0,20%		**50,26%**	
Total (un-modelled elements in Surface Model; absolute values)	0,00%	0,00%	0,00%	0,00%	1,48%	7,25%	4,32%	1,17%	3,17%	0,20%			**17,59%**

Table 6.2: GWP of Case A Compared to Case C

The cells with white background color can be assigned to the restructuring of materials from Case C to Case A. This restructuring occurs because of a lack of information in early design stages. Put in different words, there is a gap in the LOI from Case C to Case A.

The cells with light green background color show the influence of the elements that are not modelled in Case C. These un-modelled elements can be ascribed to the low LOG of Case C's geometry model.

The percentages are given in relation to the total GWP of Case A. This means that the GWP of Case A has to be altered by the given shares to result in the GWP of Case C. This approach was chosen deliberately since Case A is the Base Case of this thesis. However, in order to see the changes of the GWP from Case C to Case A, table 6.5 in chapter 6.4 was established. The values in table 6.5 could be called correction factors since they can be of use when trying to project the GWP results of an early stage LCA to the results of a more complete LCA.

In summary, both the restructuring of materials (LOI) and the un-modelled elements (LOG) clearly influence the GWP. However, when looking more closely it is obvious that the major impact results from the un-modelled elements.

While the change of materials make up 234.97 m3 in absolute numbers (See table 6.1) or -19.94 m3 as simple total, the impact on the GWP is only 2.12 % of the total GWP of Case C. The addition of 40.91 m3 caused by the change of LOG results in 17.59 %. Put together, the GWP of Case C has to be increased by 15.47.30 % to give the GWP of Case A.
Thus, the hypothesis H1.1 can be partially confirmed, since the change because of LOI (-2.12 %) might be considered minor, while the change ascribed to the LOG (17.59 %) is a major impact.

6.3 Base Case and Case B

A big difference between Case C and Case A is the quantity take-off method. While the detailed geometry model of Case A enabled the use of materials volumes, the simple surface model of Case C provided only areas that had to be complemented by the structure of the specific building element type (wall, roof, floor, foundation).
In order to quantify the impact of this difference, Case B was calculated based on the detailed information of the complete geometry model but using the same approach as in Case C, i.e. areas and the structure of the building elements. The gap in material volume was collected in table 6.3 and the impact on the GWP in table 6.4.

Case A compared to Case B in [m3]													
Materials	Revit Categories										Total		
												absolute values	
	Foundation	Floor	Walls	Roofs	Frame Construction	Window	Door	Structural Columns	Stairs	Generic Models	all elements	all elements	un-modelled
Aluminium Alloy	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,01	0,00
Reinforced Concrete	-15,41	-2,05	-1,74	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-19,20	19,20	0,00
Bitumen seal	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Roof Tile	0,00	0,00	0,00	-0,03	0,00	0,00	0,00	0,00	0,00	0,00	-0,03	0,03	0,00
Double Glazing	0,00	0,00	0,00	0,00	0,00	0,04	0,00	0,00	0,00	0,00	0,04	0,04	0,00
Triple Glazing	0,00	0,00	0,00	0,00	0,00	2,98	0,00	0,00	0,00	0,00	2,98	2,98	0,00
Steel, chromium steel	0,00	0,00	0,00	0,00	0,00	-0,01	-0,02	0,00	0,00	0,00	-0,03	0,03	0,00
Epoxy resin	0,00	-0,06	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,06	0,06	0,00
Flat glass, coated	0,00	0,00	0,85	0,00	0,00	0,56	0,00	0,00	0,00	0,00	1,40	1,40	0,00
Gravel, crushed	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Hardwood	0,00	-0,10	0,00	0,00	0,00	0,00	-0,23	0,00	0,00	0,00	-0,33	0,33	0,00
Brickwork	0,00	0,00	-16,67	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-16,67	16,67	0,00
Brass	0,00	0,00	-0,09	-0,09	0,00	0,02	0,00	0,00	0,00	0,00	-0,16	0,20	0,00
Softwood	0,00	-0,06	-0,90	-6,11	0,00	-0,41	-1,60	0,00	0,00	0,00	-9,08	9,08	0,00
PE foil	0,00	0,00	0,00	-0,30	0,00	0,00	0,00	0,00	0,00	0,00	-0,30	0,30	0,00
Plaster	0,00	0,00	-0,32	-0,03	0,00	0,00	0,00	0,00	0,00	0,00	-0,36	0,36	0,00
PVC, hard	0,00	0,00	-0,01	0,00	0,00	-3,50	0,55	0,00	0,00	0,00	-2,95	4,06	0,00
Steel, unalloyed	0,00	0,00	-0,01	0,00	0,00	0,00	0,01	0,00	0,00	0,07	0,07	0,10	0,07
Rock wool	0,00	0,00	-23,30	4,78	0,00	0,00	0,00	0,00	0,00	0,00	-18,51	28,08	0,00
Plasterboard	0,00	0,00	-16,48	-0,84	0,00	0,00	0,00	0,00	0,00	0,00	-17,32	17,32	0,00
Polystyrene extruded (XPS)	0,00	-0,03	-1,06	-0,14	0,00	0,00	0,00	0,00	0,00	0,00	-1,23	1,23	0,00
Cement cast plaster floor	0,00	-0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,03	0,03	0,00
Total	-15,41	-2,32	-59,74	-2,75	0,00	-0,33	-1,28	0,00	0,00	0,07	-81,76		
Total (absolut values)	15,41	2,33	61,44	12,33	0,00	7,51	2,41	0,00	0,00	0,07		101,50	
Total (un-modelled elements in Surface Model; absolute values)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07			0,07

Table 6.3: Material Quantities of Case A Compared to Case B

The quantities of Case B deviate considerably from the quantities of Case A, but the only difference is the quantity take-off method. Case A uses the material volumes directly while Case B takes the material areas and multiplies them by their respective thickness for each material layer.

One of the biggest deviations is the reinforced concrete of the foundations (-15.41 m3). This can be traced back to specified thickness of the foundation not matching the actual thickness.
Walls show three large deviations: brickwork (-16.67 m3), rock wool (-23.30 m3), and plasterboard (-16.48 m3).
The brickwork is used in three different types of wall, each clearly specifying their width, and the area of these walls is exported directly from Revit. An explanation for this gap could be cut-outs that partially reduce the width of the wall, since they would not affect the wall area. This material is used in walls that are 0.33 to 0.80 meters wide, so cut-outs would not necessarily affect the entire wall.
Rock wool and plasterboard are mostly part of interior walls or wood frame walls with gaps filled by insulation. Since the interior walls are often made up of just these two materials, they are the likely source of the deviation. However, the explanation given for the gap of the brickwork applies here as well. The quantities of the areas were exported directly from Revit and the wall type includes the thickness of the layer. Once again, the reason might be found in cut-outs that do not change the area of the layer.
These deviations lead to an increase in GWP (kg CO2 eq.) of 17% from the results of the Base Case (Case A) in absolute values. Table 6.4 holds the detailed changes. The share of the un-modelled elements is minor, making up only 0.20 %.
So, the way of quantity take-off influences the LCA results measurably and hypothesis H1.2 can be confirmed.

Case A compared to Case B in GWP													
Materials	Revit Categories										Total		
												absolute values	
	Foundation	Floor	Walls	Roofs	Frame Construction	Window	Door	Structural Columns	Stairs	Generic Models	all elements	all elements	un-modelled
Aluminium Alloy	0,00%	0,07%	0,00%	0,07%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,14%	0,14%	0,00%
Reinforced Concrete	-0,88%	-0,12%	-0,10%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-1,09%	1,09%	0,00%
Bitumen seal	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Roof Tile	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Double Glazing	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Triple Glazing	0,00%	0,00%	0,00%	0,00%	0,00%	0,06%	0,00%	0,00%	0,00%	0,00%	0,06%	0,06%	0,00%
Steel, chromium steel	0,00%	0,00%	0,00%	0,00%	0,00%	-0,04%	-0,16%	0,00%	0,00%	0,00%	-0,19%	0,19%	0,00%
Epoxy resin	0,00%	-0,14%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,14%	0,14%	0,00%
Flat glass, coated	0,00%	0,00%	0,46%	0,00%	0,00%	0,30%	0,00%	0,00%	0,00%	0,00%	0,76%	0,76%	0,00%
Gravel, crushed	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Hardwood	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,01%	0,00%	0,00%	0,00%	-0,01%	0,01%	0,00%
Brickwork	0,00%	0,00%	-0,82%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,82%	0,82%	0,00%
Brass	0,00%	0,00%	-1,15%	-1,05%	0,00%	0,21%	0,00%	0,00%	0,00%	0,00%	-2,00%	2,41%	0,00%
Softwood	0,00%	0,00%	-0,02%	-0,14%	0,00%	-0,01%	-0,04%	0,00%	0,00%	0,00%	-0,21%	0,21%	0,00%
PE foil	0,00%	0,00%	0,00%	-0,29%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,30%	0,30%	0,00%
Plaster	0,00%	0,00%	-0,02%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,02%	0,02%	0,00%
PVC, hard	0,00%	0,00%	-0,01%	0,00%	0,00%	-2,86%	0,45%	0,00%	0,00%	0,00%	-2,42%	3,33%	0,00%
Steel, unalloyed	0,00%	0,00%	-0,04%	0,00%	0,00%	0,00%	0,04%	0,00%	0,00%	0,20%	0,19%	0,28%	0,20%
Rock wool	0,00%	0,00%	-0,67%	0,14%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,53%	0,81%	0,00%
Plasterboard	0,00%	0,00%	-6,07%	-0,31%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-6,38%	6,38%	0,00%
Polystyrene extruded (XPS)	0,00%	0,00%	-0,11%	-0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,12%	0,12%	0,00%
Cement cast plaster floor	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Total	-0,88%	-0,20%	-8,55%	-1,60%	0,00%	-2,34%	0,29%	0,00%	0,00%	0,20%	-13,08%		
Total (absolut values)	0,88%	0,34%	9,47%	2,02%	0,00%	3,49%	0,68%	0,00%	0,00%	0,20%		17,08%	
Total (un-modelled elements in Surface Model; absolute values)	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,20%			0,20%

Table 6.4: GWP of Case A Compared to Case B

Addressing Research Question 3, the influence of different ways of quantity take-off on the results of the LCA has to be evaluated. In this case study it resulted in a significant increase of the material volume and the GWP.

Concerning the assessment in different stages, the following is of note:

- The un-modelled elements in early stage geometry models have significant influence on the LCA results.
- The change of element structures, e.g. flooring layers, influences the final LCA results considerably. However, the actual impact varies greatly. In the comparison of Case A and Case C its influence is minor (-2.12 % of total GWP of the Base Case), but when comparing Case A and Case B it is a major factor (-13.28 % of total GWP of the Base Case).
- Even though the biggest changes of material volume can be found in reinforced concrete and softwood, the difference in GWP from Case C to Case A can be traced back to insulation (PVC, hard), unalloyed steel, and triple glazing.

6.4 Correction Factors

The increase of GWP from Case C to Case A is collected in table 6.5. More specifically, it contains the differences in material volume between Case C and Case A as percent of the total volume of

Case C. So, if applied to the material volumes of Case C, it would return the material volumes of Case A (See figure 6.10 and Appendix H). Since these percentages solve the gap between the material volumes of the early stage model (Case C) and the more developed model (Case A), they could be called correction factors. Therefore, table 6.5 can be considered evidence for Hypothesis H1.3.

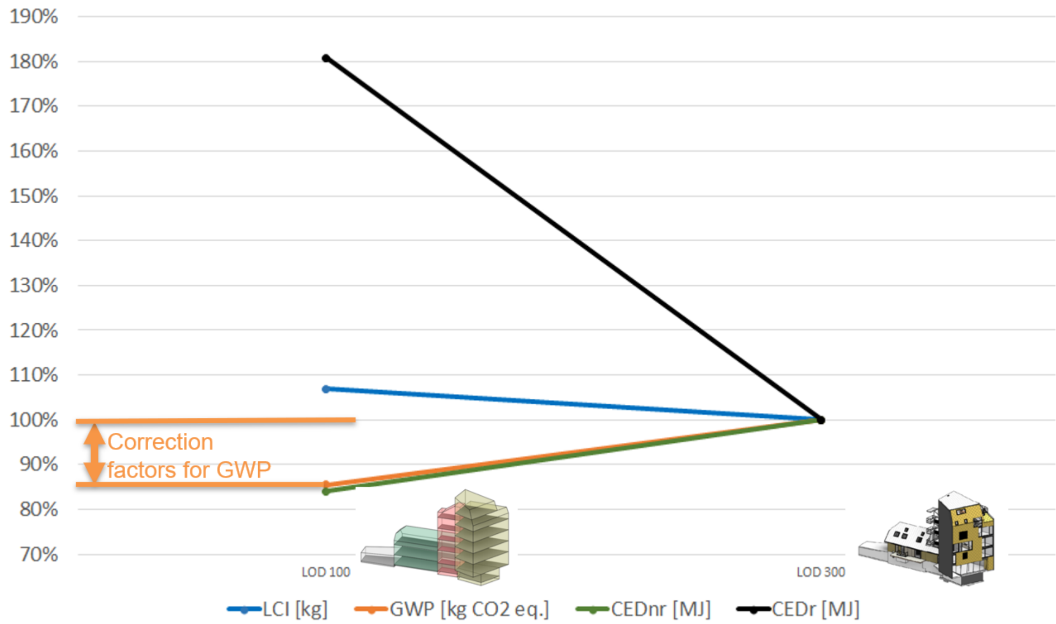


Figure 6.10: Correction Factors

Case C -> Case A: GWP Correction factors in percent of the total building volume											
Materials	**Revit Categories**										**Total**
	Foundation	Floor	Walls	Roofs	Frame Construction	Window	Door	Structural Columns	Stairs	Generic Models	all elements
Aluminium Alloy	0,00%	0,02%	0,00%	-0,03%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,01%
Reinforced Concrete	0,05%	-1,53%	-3,61%	-2,41%	0,00%	0,00%	0,00%	0,28%	1,32%	0,00%	-5,89%
Bitumen seal	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Roof Tile	0,00%	0,00%	0,00%	0,18%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,18%
Double Glazing	0,00%	0,00%	0,00%	0,00%	0,00%	0,01%	0,04%	0,00%	0,00%	0,00%	0,05%
Triple Glazing	0,00%	0,00%	0,00%	0,00%	0,00%	0,56%	0,00%	0,00%	0,00%	0,00%	0,56%
Steel, chromium steel	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Epoxy resin	0,00%	-0,11%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,11%
Flat glass, coated	0,00%	0,00%	-0,25%	0,00%	0,00%	0,08%	0,00%	0,00%	0,00%	0,00%	-0,16%
Gravel, crushed	0,00%	-0,60%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,60%
Hardwood	0,00%	0,47%	0,00%	0,00%	0,00%	0,00%	0,02%	0,00%	0,00%	0,00%	0,48%
Brickwork	0,00%	0,00%	-0,19%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,19%
Brass	0,00%	0,00%	-0,03%	0,00%	0,00%	0,01%	0,00%	0,00%	0,00%	0,00%	-0,02%
Softwood	0,00%	3,19%	-0,28%	-0,25%	0,69%	0,00%	0,39%	0,03%	0,03%	0,00%	3,82%
PE foil	0,00%	-0,02%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,02%
Plaster	0,00%	0,00%	0,13%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,13%
PVC, hard	0,00%	0,00%	0,00%	0,03%	0,00%	0,46%	0,52%	0,00%	0,00%	0,00%	1,01%
Steel, unalloyed	0,00%	0,21%	0,02%	0,00%	0,05%	0,00%	0,00%	0,04%	0,10%	0,01%	0,44%
Rock wool	0,00%	0,00%	3,61%	0,35%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	3,96%
Plasterboard	0,00%	0,01%	1,04%	0,14%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	1,19%
Polystyrene extruded (XPS)	0,00%	-0,75%	0,41%	-0,30%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-0,65%
Cement cast plaster floor	0,00%	-1,90%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	-1,90%
Total	0,05%	-1,03%	0,87%	-2,29%	0,74%	1,12%	0,98%	0,36%	1,46%	0,01%	2,27%

Table 6.5: Correction Factors for GWP (Case C -> Case A)

The correction factors are given per material and Revit category. A simplified approach would be to just use the totals per material or Revit category. When taking into account the impacts of the differences between Case A and Case C on the GWP (see table 6.2), it is possible to restrict the choice of correction factors to a select few. Concerning materials, the limit could be an impact of 3% or more. In this case, the relevant materials would be unalloyed steel, PVC (hard), and plasterboard.

This combination of the differences in quantities and the weighting based on the differences in impact indicator values allows the specific selection and adjustment of the correction factors. It is important to bear in mind that the choice of impact indicator influences the weighting of the correction factors, though.

As a simple alternative it is also possible to use total correction factors, e.g. the total factor for aluminium alloy (-0.01) or for the entire building (2.27%).

The correction factors presented so far were based on the materials and element types similar to those found in Revit. However, there are classifications that are more established than those, e.g. Level(s) or the one found in ÖNorm B 1801-1. Correction factors expressed by these two systems can be seen in table 6.6 and table 6.7.

ÖNorm B 1801-1	Correction Factors			
	Mass	GWP	CEDnr	CEDr
2C.03	0,78%	0,78%	0,78%	0,78%
2D.01	-13,55%	-2,58%	-3,27%	-5,86%
2D.02	0,00%	0,00%	0,00%	0,00%
2D.03	-31,96%	-23,47%	-9,55%	13,42%
2D.04	0,00%	0,00%	0,00%	0,00%
2E.01	-26,39%	267,39%	96,77%	590,61%
2E.02	0,00%	0,00%	0,00%	0,00%
2E.03	0,00%	0,00%	0,00%	0,00%
2E.04	0,00%	0,00%	0,00%	0,00%
3B.01	0,00%	0,00%	0,00%	0,00%
4B.01	6,06%	-12,55%	-12,33%	-6,88%
4B.02	0,00%	0,00%	0,00%	0,00%
4B.03	0,00%	0,00%	0,00%	0,00%
4B.04	0,00%	0,00%	0,00%	0,00%
4C.01	-62,58%	-63,88%	-68,82%	-84,05%
4C.02	0,00%	0,00%	0,00%	0,00%
4C.03	0,00%	0,00%	0,00%	0,00%
4C.05	-98,98%	1152,62%	-92,41%	-93,84%
4D.01	-29,45%	-29,11%	-29,70%	-28,70%
4D.02	0,00%	0,00%	0,00%	0,00%
4D.03	411,63%	307,01%	315,69%	775,07%
4D.04	0,00%	0,00%	0,00%	0,00%
4D.05	0,00%	0,00%	0,00%	0,00%
4D.06	0,00%	0,00%	0,00%	0,00%

Table 6.6: ÖNorm B 1801-1 - Correction Factors for GWP (Case C -> Case A)

Level(s)	Correction Factors			
	Mass	GWP	CEDnr	CEDr
112	-18,80%	-18,80%	-18,80%	-18,80%
121	0,00%	0,00%	0,00%	0,00%
122	-26,65%	-26,05%	-26,09%	-26,23%
123	-26,16%	18,21%	123,52%	819,69%
124	0,00%	0,00%	0,00%	0,00%
131	0,00%	0,00%	0,00%	0,00%
132	0,00%	0,00%	0,00%	0,00%
133	0,00%	0,00%	0,00%	0,00%
141	-36,79%	-31,89%	-38,01%	-29,83%
142	0,00%	0,00%	0,00%	0,00%
151	292,87%	1136,33%	1059,73%	1083,80%
152	-91,66%	-73,44%	-90,24%	-93,63%
213	0,00%	0,00%	0,00%	0,00%
214	24,66%	23,74%	24,02%	24,05%
215	-24,61%	56,27%	46,79%	90,52%
261	0,00%	0,00%	0,00%	0,00%

Table 6.7: Level(s) - Correction Factors for GWP (Case C -> Case A)

The correction factors are calculated as the difference of Case A and Case C divided by the total of Case C. For example, the mass of elements assigned to a class of ÖNorm B 1801-1 of Case C is subtracted from the corresponding value of Case A, and the resulting difference is divided by the value of Case C (See figure 6.11)

$$\text{Correction Factor (GWP)} = \frac{\text{GWP of Case A} - \text{GWP of Case C}}{\text{GWP of Case C}}$$

Figure 6.11: Calculation of Correction Factors

"*2D.01*" and "*112*" as well as other classes are empty. The reason for that is not that there is no increase from Case C to Case A but that Case C has no elements of that class. This means that in the calculation of the correction factors there is a division by zero, which cannot be done, giving 0 instead.

There are numerous ways of expressing correction factors out of the raw data. Another factor that has not been considered until now is showing the correction factors by LCS, as in table 6.8. The adequate type of correction factor depends on the intended use.

ÖN B 1801	Quantities		GWP					
[-]	[m3]	[kg]	A1-A3	A4	B4	C2	C3	C4
2C	0,78%	0,78%	0,78%	0,78%	0,00%	0,78%	0,78%	0,78%
2D	-25,99%	-45,51%	9,93%	-44,08%	-1,33%	-38,67%	-37,32%	-42,24%
2E	-25,47%	-26,39%	25,75%	-28,17%	-57,07%	-27,49%	-27,16%	1718,50%
3B	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
4B	17,23%	6,06%	-23,79%	7,19%	-29,12%	9,66%	-34,30%	-4,96%
4C	-41,49%	-161,55%	-173,48%	-172,64%	-103,87%	-143,31%	-197,14%	7322,87%
4D	470,42%	382,18%	-10,69%	-120,36%	14,38%	280,61%	1603,95%	-100,49%

Table 6.8: ÖN B 1801 - Correction Factors for GWP (Case C -> Case A)

When looking further into these correction factors, it turned out, that there is a linear correlation between the correction factors for the mass in kg and the correction factors for the individual impact categories. First, the correction factors expressed by materials were investigated that way. In the scatterplot below (See figure 6.12) each point represents the correction factors for impact categories on the x-axis and the correction factors for mass on the y-axis. Since the factors were expressed by materials, their values are the same for all three impact categories.

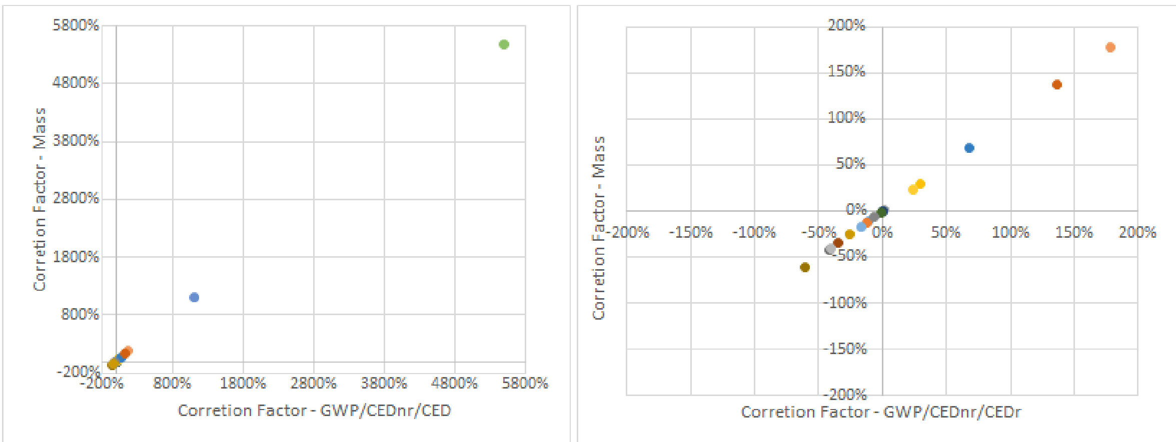
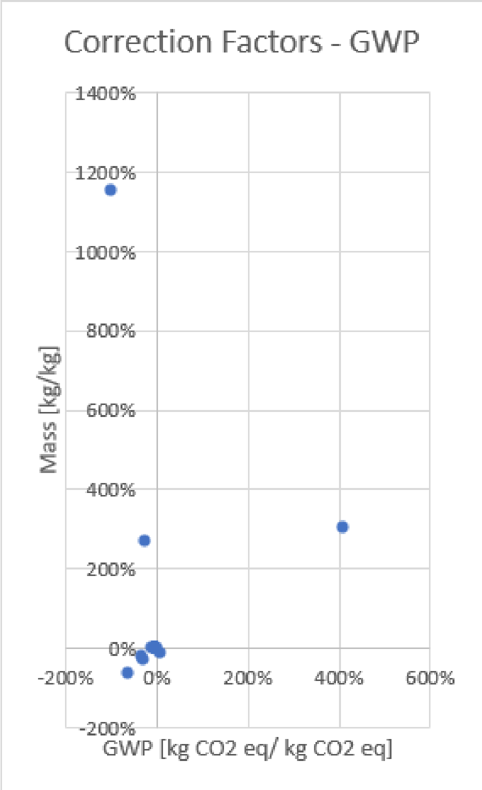
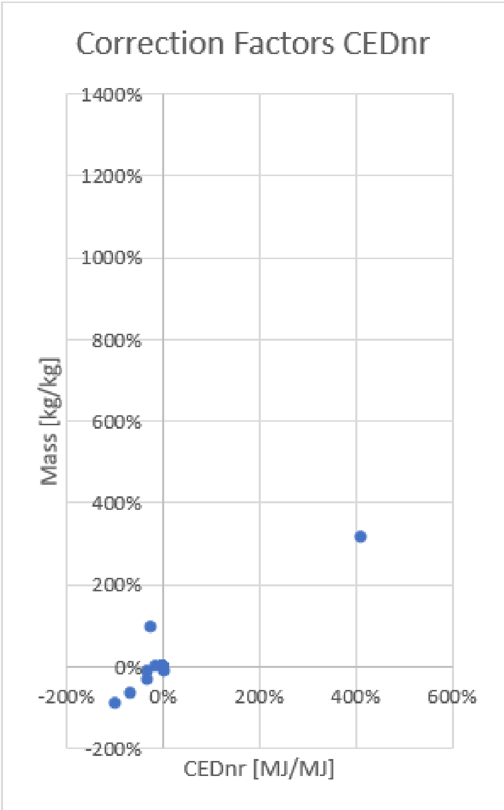


Figure 6.12: Correlation of Quantities and Impact Categories in Correction Factors (Materials)

Similar graphs for correction factors expressed by the classification system found in ÖN B 1801-1 shows the same trend, but not as smooth (See figure 6.13). As do the graphs for the correction factors by Level(s) (See appendix K).

ÖNorm B 1801-1	Correction Factors			
	Mass	GWP	CEDnr	CEDr
2C.03	0,78%	0,78%	0,78%	0,78%
2D.01	-13,55%	-2,58%	-3,27%	-5,86%
2D.02	0,00%	0,00%	0,00%	0,00%
2D.03	-31,96%	-23,47%	-9,55%	13,42%
2D.04	0,00%	0,00%	0,00%	0,00%
2E.01	-26,39%	267,39%	96,77%	590,61%
2E.02	0,00%	0,00%	0,00%	0,00%
2E.03	0,00%	0,00%	0,00%	0,00%
2E.04	0,00%	0,00%	0,00%	0,00%
3B.01	0,00%	0,00%	0,00%	0,00%
4B.01	6,06%	-12,55%	-12,33%	-6,88%
4B.02	0,00%	0,00%	0,00%	0,00%
4B.03	0,00%	0,00%	0,00%	0,00%
4B.04	0,00%	0,00%	0,00%	0,00%
4C.01	-62,58%	-63,88%	-68,82%	-84,05%
4C.02	0,00%	0,00%	0,00%	0,00%
4C.03	0,00%	0,00%	0,00%	0,00%
4C.05	-98,98%	1152,62%	-92,41%	-93,84%
4D.01	-29,45%	-29,11%	-29,70%	-28,70%
4D.02	0,00%	0,00%	0,00%	0,00%
4D.03	411,63%	307,01%	315,69%	775,07%
4D.04	0,00%	0,00%	0,00%	0,00%
4D.05	0,00%	0,00%	0,00%	0,00%
4D.06	0,00%	0,00%	0,00%	0,00%





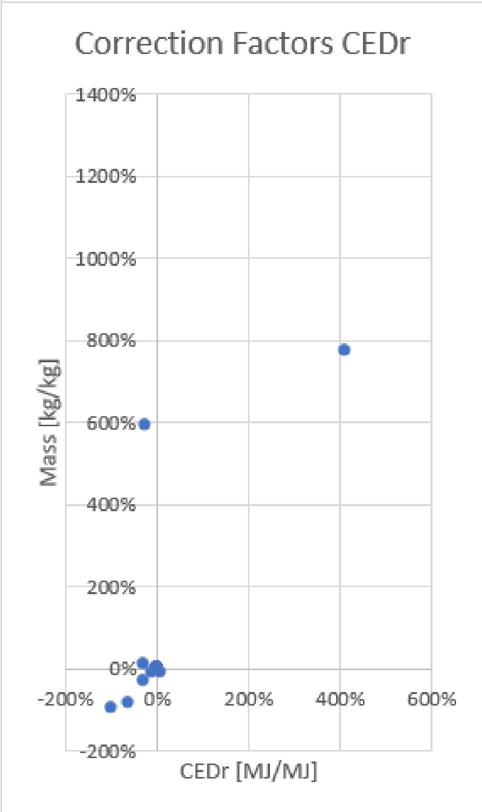


Figure 6.13: Correlation of Quantities and Impact Categories in Correction Factors (ÖNorm B 1801-1)

6.5 BIM-LCA Information Requirements

The information requirements can be deducted from figure 5.4 in chapter 5.3. In the simplest case, there are only two different requirements. On the one hand there is the material information and quantity, and on the other hand there is the environmental information. In addition, data concerning the operation of the building is required.
Summarized and addressing Research Question 1 (See chapter 1.2), table 6.9 gives an overview of the information required for the Base Case (Case A) in this LCA study and its sources.

Data Sources	RVT Model	Material Databases	Cost Accounting	EcoInvent LCIA	ESL Catalogue	PCRs
Materials Definition	x					
Materials' Specific Weight		x				
Materials' ESL					x	
Materials' Typical EoL scenario for this region						x
Quantity of Materials	x					
Impact Coefficients				x		
Operational Data (Energy and Water)			x			

Table 6.9: Data Sources

The information came from different sources. The definition of the material and quantities were extracted from the geometry model. Since the specific weight of the materials was included only very infrequently, this information was looked up in a web-based material database [53]. And the environmental information in the form of impact coefficients was sourced from the EcoInvent 3 database integrated in the LCA software SimaPro.

Addressing Research Question 2, it is now clear that most of the information mentioned above can be linked to the materials, and could be either integrated into the model or connected to it through an external source. BIM authoring software like Revit, as well as the IFC data schema, support the detailed definition of material information. Therefore, the geometry model can include not only materials definition and quantities, but also the specific weight, the ESLs, and the impact coefficients of the environmental data.
But integrating the impact coefficients linked to the materials and elements into a geometry model might turn out difficult because of the immense variation of environmental data and the dependence on the applied scenarios. In this case, it might be a more efficient approach to use an external database of impact coefficients and create links to the model elements and materials. After finishing the model, this information could then be copied and integrated into the model.
A Revit plug-in or Dynamo script linked to an Excel spreadsheet can facilitate the scenario devel-

opment and integration into the model. But at this point all the required data would either be integrated into the model or be accessible per connection and, both the Revit plug-in or the Dynamo script, would be adequate to complete the LCI and calculate the LCA results.

7 Discussion

In summary, the case study lead to the following answers to the hypotheses and the research questions.

Ad **H1.1**: In chapter 6.2 the GWP of Case A and Case C was compared. This comparison included the embodied impacts, excluding LCS B4, for the entire building. The difference in GWP that can be traced back to the LOG, i.e. the influence of un-modelled elements, makes up 20% of the GWP (embodied impacts, excluding LCS B4) of Case C.

However, the influence of the information provided within the model (LOI) is not as obvious. In the comparison of Case A and C it is a minor influence (-2.12 % GWP), but in the comparison of Case A and Case B it is significantly larger (12.88 %).

Thus, H1.1 can only be confirmed partially. The influence of the LOI still requires further research.

Ad **H1.2**: In chapter 6.3 the material quantities and GWP of Case A and Case B were compared. The LCI of Case A was established using material volumes, whereas the LCI of Case B used material areas. The other parameters of the LCA, e.g. scenarios and environmental data, were the same. Nonetheless the difference between the GWP of both cases is 13.08 % of the GWP of Case A, providing evidence to confirm H1.2.

Ad **H1.3**: It is possible to establish correction factors that compensate for information not available at an early design stage (See chapter 6.4). Therefore, H1.3 can be confirmed. However, the correction factors are different for each impact category considered in this case study.

Ad **RQ1**: In order to conduct an LCA on a BIM model, the material's definition, specific weight, quantities, ESL, and typical EoL-scenario are required. Furthermore, the environmental impact coefficients and the operational data is needed (See table 6.9). This is based on the case study performed in this thesis but the list might be extended if further LCS are included into the scope.

Ad **RQ2**: Chapter 6.5 lists the information requirements for a BIM-based LCA. The EoL-scenarios and the environmental impact coefficients currently have to be added manually to the LCI or per (semi-)automatic link. All of information that is directly linked to materials can already be integrated into a BIM model.

Ad **RQ3**: Despite being based on the same BIM model, the comparison of Case A and Case B showed that establishing the LCI via material areas leads to higher LCA results (See figure 6.9).

Ad **RQ4**: The comparison of the material quantities of Case A and Case C (See figure 6.1) revealed that the un-modelled elements which are not contained in the early stage design of Case C make up 40.91 m3, or about 5 % of the total material volume.

The results above are subject to the following limitations:

- The material information was not complete. For example, the material "*Fußboden - Estrich*" (german for Flooring - Screed) is not an accurate definition of the material. To include this in the scope, an assumption had to be made. But every assumption is a new source of uncertainty and variability in the LCA study.
- This thesis is based on the comparison of a LOD 100 model representing conceptual design and a LOD 300 model which represents a more developed design stage. But LOD 300 does not correspond to the final stage of a BIM model, this would be LOD 500 ("*as-built model*"). This thesis does not include potential changes between the design stages of a LOD 300 model and a LOD 500 model.
- This thesis includes the LCS A1-A3, A4, B4, B6, B7, C2-C4 (See figure 4.1). The results and analysis is based on the investigation of the LCS A1-A3, A4, and C2-C4.
- Conceptual design (LOD 100 model) and more developed or finished design (LOD 300-LOD 500 model) can differ significantly. However, in this case study, the design and shape of the LOD 100 model is quite similar to the LOD 300 model (See figure 5.4).
- The object of the case study is an office building with a apartments on the upper floors. Correction factors might deviate significantly for other building types.

8 Conclusion and Outlook

Correction factors can be established to compensate for information that is not available in early design. However, in this thesis, they were established on the basis of a case study and might deviate significantly for other projects. Further research and similar analysis of other BIM models is required to definitely isolate the common ground of the correction factors from features specific to a single project. Such confining of the correction factors to a set that can be applied to all buildings is one option, but considering the great variety of forms that construction projects can take it might be more efficient to define a number of subgroups of buildings and adapt the correction factors to them. An example for a subgroup would be a single family house with basement and two floors, or a factory building based on steel construction.

With research dedicated to establishing an automatic link between BIM and LCA progressing fast, the source for a pool of correction factors of similar studies appears to be close. But the BIM-LCA framework created for this study revealed two big issues.
First, the choice of environmental data, i.e. impact coefficients, is still lacking. EPDs are not common yet, and the environmental databases, although extensive, often reveal big gaps when trying to find a match for a specific building material or element. This constitutes a factor of uncertainty in this study, and presumably in general.
Second, the scenario development of an LCA goes along with numerous project specific settings that are difficult to have automated. Any software tool trying this automatization will have to decide which assumptions are made in the background and what decisions are asked of the software user.

Another issue concerning the correction factors that demands more research is the fact that they depend on the impact category considered. The dominance analysis comparing the distribution of the CEDnr and the CEDr across materials (See figure 6.8) showed significant differences between the two related impact indicators. This suggests a similar characteristic for all impact categories. The correction factors proposed in this thesis were expressed in relation to the GWP (See table 6.5).
It is possible to establish the correction factors based on information like mass, volume, or area only. The differences of volume between Case A and Case C, as seen in table 6.1, could simply be divided by the total volume of Case C to get another type of correction factor. However, the weighting, interpretation, and information granted by including an impact indicator would be missing. It

would not be clear which correction factors are significant, since a large material mass or volume not necessarily correlates with a big environmental impact. This in turn means, that the complete set of correction factors would have to be applied with little or no adoption to the specific LCA study.

Appendices

A Scenario LCS A4

Product group/material category (acc. PCR AT)	Amount	Unit	Arrangement of transportation		Means of transport							Average transport distance of transportation from			Total Transport							
			% directly from factory to site	% via an interedmediary supplier	factory to site			factory to supplier	suppplier to site			factory to site	factory to supplier	supplier to site	[A4] Transport to building site							
		[t]			Lorry 16-32 ton (Euro 5)	Lorry 7.5-16 ton (Euro 5)	Lorry 3.5-7.5 ton (Euro 5)	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)	[km]	[km]	[km]	Lorry 16-32 ton (Euro 5)	[tkm]	Lorry 7.5-16 ton (Euro 5)	[tkm]	Lorry 3.5-7.5 ton (Euro 5)	[tkm]	Lorry >32 ton (Euro 5)	[tkm]
Gebrannte Tonprodukte																						
Dachziegel incl. Zubehör (diverse Formziegel)	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	150,0	0,0	0,0	150,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Geschützte/ungeschützte Mauerziegel, Dämmstoffziegel	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	50,0	0,0	0,0	50,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Fassadenplatten aus gebranntem Ton	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Pflasterklinker inklusive Formziegel	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Deckenziegel und Einhängziegel für Ziegeldecken	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Kaminziegel	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Ziegelschalen für Überlager	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Ziegelfertigteile	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Sonstige	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0	0,0	0,0	250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Dämmstoffgefüllte Ziegel	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	250,0			250,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Poured concrete																						
Beton der Druckfestigkeitsklasse C 20/25	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	17,0	0,0	0,0	17,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Beton der Druckfestigkeitsklasse C 25/30	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	17,0	0,0	0,0	17,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Beton der Druckfestigkeitsklasse C 30/37	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	20,1	0,0	0,0	20,100	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Beton der Druckfestigkeitsklasse C 35/45	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	39,5	0,0	0,0	39,500	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Beton der Druckfestigkeitsklasse C 45/55	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	125,9	0,0	0,0	125,900	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Beton der Druckfestigkeitsklasse C 50/60	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	120,5	0,0	0,0	120,500	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Concrete prefabricated	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	49,7	0,0	0,0	49,700	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Anhydrite Floor																						
Calciumsulfatestrich	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	100,00	0,00	0,00	100,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Double flooring system															0,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Doppelbodensystem Typ LIGNA	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	500,00	0,00	0,00	500,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Mortar															0,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Cement Mortar	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	100,00	0,00	0,00	100,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Abdichtungen																						
EPDM	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	470,00	0,00	0,00	470,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Rubber	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	100,00	0,00	0,00	100,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
PVC foil	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	100,00	0,00	0,00	100,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Reinforcement Steel	1,000	t	100%	0%	100%	0%	0%	0%	0%	0%	0%	313,00	0,00	0,00	313,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Bulk materials for structural work (e.g. cement, sand, gravel, ...)	1,000	t	75%	25%	100%	0%	0%	100%	90%	10%	0%	100,00	100,00	35,00	82,875	tkm	0,875	tkm	0,000	tkm	25,000	tkm
Prefabricated products for structural work (e.g. beams, columns, ...)	1,000	t	100%	0%	100%	0%	0%	100%	100%	0%	0%	100,00	100,00	35,00	100,000	tkm	0,000	tkm	0,000	tkm	0,000	tkm
Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	1,000	t	40%	60%	100%	0%	0%	100%	85%	15%	0%	100,00	100,00	35,00	57,850	tkm	3,150	tkm	0,000	tkm	60,000	tkm
Insulation	1,000	t	40%	60%	100%	0%	0%	100%	85%	15%	0%	100,00	100,00	35,00	57,850	tkm	3,150	tkm	0,000	tkm	60,000	tkm
finishing products: floor coverings(e.g. carpet, linoleum, ceramic tiles, ...)	1,000	t	10%	90%	90%	10%	0%	100%	90%	10%	0%	100,00	100,00	35,00	37,350	tkm	4,150	tkm	0,000	tkm	90,000	tkm
finishing products: plasters (e.g. gypsum plaster, external plaster, ...)	1,000	t	40%	60%	50%	50%	0%	100%	50%	50%	0%	100,00	100,00	35,00	30,500	tkm	30,500	tkm	0,000	tkm	60,000	tkm
finishing products: cabinet work (e.g. window frames, stairs, ...)	1,000	t	90%	10%	50%	45%	5%	100%	40%	50%	10%	100,00	100,00	35,00	46,400	tkm	42,250	tkm	4,850	tkm	10,000	tkm
finishing products: paints and varnishes	1,000	t	10%	90%	0%	100%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	tkm	35,200	tkm	6,300	tkm	90,000	tkm
installations (e.g. heating boiler,radiators, ventilation, ...)	1,000	t	0%	100%	0%	0%	0%	100%	0%	80%	20%	100,00	100,00	35,00	0,000	tkm	28,000	tkm	7,000	tkm	100,000	tkm

Figure 0.1: Scenario LCS A4 Table

Materials	Life Cycle Stages A4				
		Lorries			
Materials (Revit)	choose closest match	to [tkm/kg]	to [tkm/kg]	to [tkm/kg]	> 32 to [tkm/kg]
Aluminium Alloy	Prefabricated products for structural work (e.g. beams, columns, ...)	0,1000	0,0000	0,0000	0,0000
Reinforced Concrete		#NV	#NV	#NV	#NV
Concrete	Beton der Druckfestigkeitsklasse C 30/37	0,0201	0,0000	0,0000	0,0000
Reinforcement	Reinforcement Steel	0,3130	0,0000	0,0000	0,0000
Bitumen seal	Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	0,0579	0,0032	0,0000	0,0600
Roof Tile	Dachziegel incl. Zubehör (diverse Formziegel)	0,1500	0,0000	0,0000	0,0000
Double Glazing	finishing products: cabinet work (e.g. window frames, stairs, ...)	0,0464	0,0423	0,0049	0,0100
Triple Glazing	finishing products: cabinet work (e.g. window frames, stairs, ...)	0,0464	0,0423	0,0049	0,0100
Steel, chromium steel	Prefabricated products for structural work (e.g. beams, columns, ...)	0,1000	0,0000	0,0000	0,0000
Epoxy resin	finishing products: paints and varnishes	0,0000	0,0352	0,0063	0,0900
Flat glass, coated	Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	0,0579	0,0032	0,0000	0,0600
Gravel, crushed	Bulk materials for structural work (e.g. cement, sand, gravel, ...)	0,0829	0,0009	0,0000	0,0250
Hardwood	Prefabricated products for structural work (e.g. beams, columns, ...)	0,1000	0,0000	0,0000	0,0000
Brickwork		#NV	#NV	#NV	#NV
Bricks	Geschützte/ungeschützte Mauerziegel, Dämmstoffziegel	0,0500	0,0000	0,0000	0,0000
Mortar	Cement Mortar	0,1000	0,0000	0,0000	0,0000
Brass	Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	0,0579	0,0032	0,0000	0,0600
Softwood	Prefabricated products for structural work (e.g. beams, columns, ...)	0,1000	0,0000	0,0000	0,0000
PE foil	Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	0,0579	0,0032	0,0000	0,0600
Plaster	finishing products: plasters (e.g. gypsum plaster, external plaster, ...)	0,0305	0,0305	0,0000	0,0600
PVC, hard	finishing products: cabinet work (e.g. window frames, stairs, ...)	0,0464	0,0423	0,0049	0,0100
Steel, unalloyed	Prefabricated products for structural work (e.g. beams, columns, ...)	0,1000	0,0000	0,0000	0,0000
Rock wool	Insulation	0,0579	0,0032	0,0000	0,0600
Plasterboard	Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	0,0579	0,0032	0,0000	0,0600
Polystyrene extruded (XPS)	Insulation	0,0579	0,0032	0,0000	0,0600
Cement cast plaster floor	Calciumsulfatestrich	0,1000	0,0000	0,0000	0,0000

Table 0.1: Scenario LCS A4: Transport to the Construction Site

B Scenario LCS C2-C4: Framework

Product group/ Waste category	Description	Amount	Unit	Landfill [%]	Incineration [%]	Reuse [%]	Recycling [%]	sorted on collection point [%]
			[t]					
Stony & Glass	Bricks, roof tiles	1,000	t	5%	0%	0%	95%	25%
	Bulk materials (e.g. sand, gravel, expanded clay grains)	1,000	t	5%	0%	95%	0%	10%
	Concrete	1,000	t	5%	0%	0%	95%	25%
	Flat glass	1,000	t	5%	0%	0%	95%	30%
	Other stony waste (e.g. tiles, natural stone, slates, sand-lime blocks)	1,000	t	5%	0%	0%	95%	25%
	Porcelain and ceramics (e.g. toilet, bath, washbasin)	1,000	t	15%	0%	0%	85%	25%
Wood	Chemically treated,impregnated wood (e.g. railway sleepers, outdoor playsets,garden screens)	1,000	t	0%	100%	0%	0%	60%
	Composite wood products (e.g. fibreboards (like plywood, chipboard, OSB, MDF), veneer, laminate)	1,000	t	0%	95%	0%	5%	60%
	Surface treated, solid wood (e.g. painted or varnished (like window frames, solid parquet))	1,000	t	0%	85%	0%	15%	60%
	Untreated, uncontaminated wood (e.g. roofs, structures, formworks, auxiliary timber)	1,000	t	0%	25%	0%	75%	60%
Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	1,000	t	5%	0%	0%	95%	15%
Packaging (on construction site)	EPS packaging	1,000	t	10%	30%	0%	60%	50%
	Pallets	1,000	t	0%	40%	20%	40%	50%
	Paper and cardboard packaging	1,000	t	0%	5%	0%	95%	50%
	Plastic films packaging	1,000	t	5%	60%	0%	35%	50%
Insulation Materials	Mineral insulation materials (e.g. stone wool, glass wool)	1,000	t	50%	50%	0%	0%	100%
	Organic insulation materials (e.g. vegetable fibres (like wood, coconut, hemp, flax), cellulose,(in bulk or blankets), sheep wool, cork (in bulk or boards))	1,000	t	5%	95%	0%	0%	100%
	Synthetic insulation materials (e.g. polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), phenolic foam, expanded polystyrene (EPS))	1,000	t	5%	95%	0%	0%	100%
Fibre cement products	Fibre cement products (e.g. fibre cement slabs or slates)	1,000	t	100%	0%	0%	0%	25%
Areated/celluar concrete	Aerated autoclaved concrete (e.g. elements, blocks)	1,000	t	70%	0%	0%	20%	50%
Gypsum elements	Gypsum elements (e.g. gypsum blocks, gypsum (fibre/plaster)boards)	1,000	t	80%	0%	0%	20%	70%
Bitumen	Bitumen (e.g. bituminous roofing, vapour barrier, waterproofing membrane)	1,000	t	85%	5%	0%	10%	100%
Polyoelfins (PP,PE)	Polyolefins (PP, PE) (e.g. kraft paper or polyethylene (PE) vapour barrier, ducts), excluding packaging	1,000	t	10%	85%	0%	5%	100%
Elastomers	Elastomers (e.g. EPDM roofing)	1,000	t	90%	0%	0%	10%	100%
PVC	PVC cabling (e.g. electric cables and wire insulation)	1,000	t	10%	40%	0%	50%	100%
	PVC pipes (e.g. for sewerage)4	1,000	t	10%	30%	0%	50%	100%
	PVC profiles (e.g. window frames)	1,000	t	10%	45%	0%	45%	100%
	PVC sheets (e.g. PVC roofing, waterproofing membranes (like for swimming pools))	1,000	t	20%	65%	0%	15%	100%
Supple Flooring	Supple flooring (e.g. linoleum, fixed carpet, vinyl)	1,000	t	0%	95%	0%	5%	100%
Finishing Layers	Finishing layer fixed to stony waste (e.g. plaster (like gypsum plaster, calcareous plaster,loam plaster), paint, coatings, adhesives)	1,000	t	5%	0%	0%	95%	100%
	Finishing layer fixed to wood, plastic or metal (e.g. paint, coatings, adhesives)	1,000	t	0%	100%	0%	0%	100%
Remaining Waste	Combustible remaining waste	1,000	t	0%	100%	0%	0%	100%
	Non-combustible remaining waste	1,000	t	100%	0%	0%	0%	25%
Other hazardous waste	Aerosols and kits (e.g. PU foam, silicones)	1,000	t	0%	100%	0%	0%	0%
	Asbestos (bounded, unbounded)	1,000	t	100%	0%	0%	0%	0%
	Fluorescent lamps	1,000	t	30%	0%	0%	70%	0%
	Liquid construction site waste (e.g. paints, adhesives, resins, form mould oil, white spirit)	1,000	t	0%	75%	0%	25%	0%

Figure 0.2: Scenario LCS C2 Table - Part 1

sorted on collection point [%]	sorted on building site [%]	Means of transpor-tation	Average transport distance of transportation from						Total Transport	Unit
		Lorry 16-32 ton (Euro5)	demolition site to sorting facility/ collection point	Unit [km]	collection point/sorting facility to landfill	Unit [km]	collection point/sorting facility to incinerator	Unit [km]	[C2] Transport of Demolition Waste	[tkm]
25%	75%	100%	30	km	50	km	100	km	31,375	tkm
10%	90%	100%	30	km	50	km	100	km	31,150	tkm
25%	75%	100%	30	km	50	km	100	km	31,375	tkm
30%	70%	100%	30	km	50	km	100	km	31,450	tkm
25%	75%	100%	30	km	50	km	100	km	31,375	tkm
25%	75%	100%	30	km	50	km	100	km	34,125	tkm
60%	40%	100%	30	km	50	km	100	km	118,000	tkm
60%	40%	100%	30	km	50	km	100	km	113,600	tkm
60%	40%	100%	30	km	50	km	100	km	104,800	tkm
60%	40%	100%	30	km	50	km	100	km	52,000	tkm
15%	85%	100%	30	km	50	km	100	km	31,225	tkm
50%	50%	100%	30	km	50	km	100	km	59,000	tkm
50%	50%	100%	30	km	50	km	100	km	64,000	tkm
50%	50%	100%	30	km	50	km	100	km	34,250	tkm
50%	50%	100%	30	km	50	km	100	km	82,750	tkm
100%	0%	100%	30	km	50	km	100	km	105,000	tkm
100%	0%	100%	30	km	50	km	100	km	127,500	tkm
100%	0%	100%	30	km	50	km	100	km	127,500	tkm
25%	75%	100%	30	km	50	km	100	km	57,500	tkm
50%	50%	100%	30	km	50	km	100	km	51,500	tkm
70%	30%	100%	30	km	50	km	100	km	62,800	tkm
100%	0%	100%	30	km	50	km	100	km	77,500	tkm
100%	0%	100%	30	km	50	km	100	km	120,000	tkm
100%	0%	100%	30	km	50	km	100	km	75,000	tkm
100%	0%	100%	30	km	50	km	100	km	75,000	tkm
100%	0%	100%	30	km	50	km	100	km	62,000	tkm
100%	0%	100%	30	km	50	km	100	km	80,000	tkm
100%	0%	100%	30	km	50	km	100	km	105,000	tkm
100%	0%	100%	30	km	50	km	100	km	125,000	tkm
100%	0%	100%	30	km	50	km	100	km	32,500	tkm
100%	0%	100%	30	km	50	km	100	km	130,000	tkm
100%	0%	100%	30	km	50	km	100	km	130,000	tkm
25%	75%	100%	30	km	50	km	100	km	57,500	tkm
0%	100%	100%	30	km	50	km	100	km	100,000	tkm
0%	100%	100%	30	km	50	km	100	km	50,000	tkm
0%	100%	100%	30	km	50	km	100	km	36,000	tkm
0%	100%	100%	30	km	50	km	100	km	82,500	tkm

Figure 0.3: Scenario LCS C2 Table - Part 2

C Scenario LCS C2-C4: Framework Applied

Materials		Life Cycle Stage C2							
Materials (Revit)	choose product group/ waste	Description	Landfill [%]	Incineration [%]	Reuse [%]	Recycle [%]	EoL total	Distance [tkm]
Aluminium Alloy	Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Reinforced Concrete			#NV	#NV	#NV	#NV	#NV	#NV
Concrete	Stony & Glass	Concrete	5,00%	0,00%	0,00%	95,00%	100,00%	31,38
Reinforcement	Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Bitumen seal	Bitumen	Bitumen (e.g. bituminous roofing, vapour barrier, waterproofing membrane)	85,00%	5,00%	0,00%	10,00%	100,00%	77,50
Roof Tile	Stony & Glass	Bricks, roof tiles	5,00%	0,00%	0,00%	95,00%	100,00%	31,38
Double Glazing	Stony & Glass	Flat glass	5,00%	0,00%	0,00%	95,00%	100,00%	31,45
Triple Glazing	Stony & Glass	Flat glass	5,00%	0,00%	0,00%	95,00%	100,00%	31,45
Steel, chromium steel	Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Epoxy resin	Finishing Layers	Finishing layer fixed to stony waste (e.g. plaster (like gypsum plaster, calcareous plaster,loam plaster), paint, coatings, adhesives)	5,00%	0,00%	0,00%	95,00%	100,00%	32,50
Flat glass, coated	Stony & Glass	Flat glass	5,00%	0,00%	0,00%	95,00%	100,00%	31,45
Gravel, crushed	Stony & Glass	Bulk materials (e.g. sand, gravel, expanded clay grains)	5,00%	0,00%	95,00%	0,00%	100,00%	31,15
Hardwood	Wood	Surface treated, solid wood (e.g. painted or varnished (like window frames, solid parquet))	0,00%	85,00%	0,00%	15,00%	100,00%	104,80
Brickwork			#NV	#NV	#NV	#NV	#NV	#NV
Bricks	Stony & Glass	Bricks, roof tiles	5,00%	0,00%	0,00%	95,00%	100,00%	31,38
Mortar	Stony & Glass	Bulk materials (e.g. sand, gravel, expanded clay grains)	5,00%	0,00%	95,00%	0,00%	100,00%	31,15
Brass	Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Softwood	Wood	Untreated, uncontaminated wood (e.g. roofs, structures, formworks, auxiliary timber)	0,00%	25,00%	0,00%	75,00%	100,00%	52,00
PE foil	Polyoelfins (PP,PE)	Polyolefins (PP, PE) (e.g. kraft paper or polyethylene (PE) vapour barrier, ducts), excluding packaging	10,00%	85,00%	0,00%	5,00%	100,00%	120,00
Plaster	Stony & Glass	Bulk materials (e.g. sand, gravel, expanded clay grains)	5,00%	0,00%	95,00%	0,00%	100,00%	31,15
PVC, hard	PVC	PVC profiles (e.g. window frames)	10,00%	45,00%	0,00%	45,00%	100,00%	80,00
Steel, unalloyed	Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5,00%	0,00%	0,00%	95,00%	100,00%	31,23
Rock wool	Insulation Materials	Mineral insulation materials (e.g. stone wool, glass wool)	50,00%	50,00%	0,00%	0,00%	100,00%	105,00
Plasterboard	Gypsum elements	Gypsum elements (e.g. gypsum blocks, gypsum (fibre/plaster)boards)	80,00%	0,00%	0,00%	20,00%	100,00%	62,80
Polystyrene extruded (XPS)	Insulation Materials	Synthetic insulation materials (e.g. polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), phenolic foam, expanded polystyrene (EPS))	5,00%	95,00%	0,00%	0,00%	100,00%	127,50
Cement cast plaster floor	Stony & Glass	Concrete	5,00%	0,00%	0,00%	95,00%	100,00%	31,38

Figure 0.4: Scenario LCS C2-C4 Table - Framework Applied

D Selection of Environmental Data

By this point in the LCA, all the quantities and scenarios have been prepared in an Excel worksheet. So instead of typing in the all the data in an LCA software like SimaPro, it was much easier to do it the other way around and paste the environmental performance of 1 unit, e.g. m3, m2, or pcs, from SimaPro into the spreadsheet and perform the LCA there.

The EcoInvent 3.3 database was the source of all environmental data. The methods used were EF 1.0.3 and EPD 2017. Table 0.2 to table 0.7 show the selected environmental data per LCS. In the work process, the selected environmental data was marked with "***GN_*". The text following this mark is the name of the data as found in SimaPro.

Materials	Life Cycle Stages A1-A3
Materials (Revit)	SimaPro A1-A3 data sets
Aluminium Alloy	**GN_Aluminium alloy, AlMg3 {GLO}| market for | Alloc Def, U
Reinforced Concrete	
Concrete	**GN_Concrete, normal {CH}| market for | Alloc Def, U
Reinforcement	**GN_Reinforcing steel, at plant/RER U
Bitumen seal	**GN_Bitumen seal, V60 {RER}| production | Alloc Def, U
Roof Tile	**GN_Roof tile {RER}| production | Alloc Def, U
Double Glazing	**GN_Glazing, double, U<1.1 W/m2K {RER}| production | Alloc Def, U
Triple Glazing	**GN_Glazing, triple, U<0.5 W/m2K {RER}| production | Alloc Def, U
Steel, chromium steel	**GN_Steel, chromium steel 18/8, hot rolled {RER}| production | Alloc Def, U
Epoxy resin	**GN_Epoxy resin, liquid, at plant/RER U
Flat glass, coated	**GN_Flat glass, coated {RER}| production | Alloc Def, U
Gravel, crushed	**GN_Gravel, crushed {CH}| market for gravel, crushed | Alloc Def, U
Hardwood	**GN_Sawnwood, hardwood, dried (u=20%), planed {RER}| market for | Alloc Def, U
Brickwork	
Bricks	**GN_Brick, at plant/RER U
Mortar	**GN_Cement mortar {CH}| market for cement mortar | Alloc Def, U
Brass	**GN_Brass {CH}| market for brass | Alloc Def, U
Softwood	**GN_Sawnwood, softwood, dried (u=20%), planed {RER}| market for | Alloc Def, U
PE foil	**GN_Fleece, polyethylene {RER}| production | Alloc Def, U
Plaster	**GN_Base plaster, at plant/CH U
PVC, hard	**GN_Polyvinylchloride, at regional storage/RER U
Steel, unalloyed	**GN_Steel, unalloyed {RER}| steel production, converter, unalloyed | Alloc Def, U
Rock wool	**GN_Rock wool, packed, at plant/CH U
Plasterboard	**GN_Gypsum plasterboard, technology mix of plasterboard production, production mix at factory, 12.5 mm thick, 10kg/m2 EU-27
Polystyrene extruded (XPS)	**GN_Polystyrene, extruded (XPS), at plant/RER U
Cement cast plaster floor	**GN_Cement cast plaster floor, at plant/CH U

Table 0.2: Environmental Data for LCS A1-A3

"*Reinforced concrete*" and "*brickwork*" were modelled as composite materials, each consisting of the two materials below. To avoid double counting, the composite materials themselves were not further considered, therefore the gaps in table 0.2.

Table 0.3 shows the four datasets used for transport. These are the same for LCS A4 and LCS C2, even though the scenario of LCS C2 uses only one size of lorry.

Materials	Life Cycle Stages A4
Materials (Revit)	choose closest match
-	**GN_Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Alloc Def, U
-	**GN_Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Alloc Def, U
-	**GN_Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Def, U
-	**GN_Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Def, U

Table 0.3: Environmental Data for LCS A4 and C2

This would be the place for specific environmental datasets for LCS B4, but since this LCS consists of other LCS described here, no further environmental data is required.
Table 0.4 lists the datasets for LCS B6 (Operational Water Use) and LCS B7 (Operational Energy Use)

Life Cycle Stages B6-B7		
Description	SimaPro B6 and B7 dataset	RSP
Energy	**GN_Electricity, low voltage {AT}| market for | Alloc Def, U	50
Water	**GN_Tap water {CH}| market for | Alloc Def, U	

Table 0.4: Environmental Data for LCS B6 and LCS B7

Table 0.5 to 0.7 show the datasets used for the preliminary step for reuse and recycling (C3 - sorting) and the EoL of the product by incineration or landfill (C4). Since environmental data for this kind of detailed modelling was scarce, some changes and assumptions had to be made. These cases are emphasized by blue colour. Several times no accurate dataset was found. So, instead of using environmental data with significant deviation from the actual product, the framework of the EoL-scenarios was adapted. For example "*Bitumen seal*": since no specific environmental information could be found, the share of the product that is expected to be reused or recycled was allocated to C4 (landfill and incineration). This was done as a weighted allocation based on the shares of both, landfill and incineration. Such changes were marked with "*No data - allocate to C4*".
In other cases, a dataset was selected because it was the best option available but still not a very good match. These are "*Waste bricks*" for "*Roof tiles*", "*Used triple glazing*" for "*double glazing*", and "*Waste paint*" for "*Epoxy resin*" in LCS C3, and "*Scrap copper*" for "*Brass*" in LCS C4.

Materials	Life Cycle Stages C3	
Materials (Revit)	SimaPro C3 data sets sorting	Reuse + Recycling [%]
Aluminium Alloy	**GN_Aluminium scrap, post-consumer {RER}| treatment of, by collecting, sorting, cleaning, pressing | Alloc Def, U	95.00%
Reinforced Concrete		#NV
Concrete	**GN_Waste reinforced concrete {Europe without Switzerland}| treatment of waste reinforced concrete, sorting plant | Alloc Def, U	95.00%
Reinforcement	**GN_Waste reinforced concrete {Europe without Switzerland}| treatment of waste reinforced concrete, sorting plant | Alloc Def, U	95.00%
Bitumen seal	No data - allocate to C4	0.00%
Roof Tile	**GN_Waste brick {Europe without Switzerland}| treatment of waste brick, sorting plant | Alloc Def, U	95.00%
Double Glazing	**GN_Waste glass sheet {Europe without Switzerland}| treatment of waste glass sheet, sorting plant | Alloc Def, U	95.00%
Triple Glazing	**GN_Waste glass sheet {Europe without Switzerland}| treatment of waste glass sheet, sorting plant | Alloc Def, U	95.00%
Steel, chromium steel	**GN_Waste reinforcement steel {CH}| treatment of, sorting plant | Alloc Def, U	95.00%
Epoxy resin	No data - allocate to C4	0.00%
Flat glass, coated	**GN_Waste glass sheet {Europe without Switzerland}| treatment of waste glass sheet, sorting plant | Alloc Def, U	95.00%
Gravel, crushed	**GN_Waste concrete gravel {CH}| treatment of, sorting plant | Alloc Def, U	95.00%
Hardwood	No data - allocate to C4	0.00%
Brickwork		#NV
Bricks	**GN_Waste brick {Europe without Switzerland}| treatment of waste brick, sorting plant | Alloc Def, U	95.00%
Mortar	**GN_Waste cement in concrete and mortar {Europe without Switzerland}| treatment of waste cement in concrete and mortar, sorting plant | Alloc Def, U	95.00%
Brass	No data - allocate to C4	0.00%
Softwood	**GN_Waste wood, post-consumer {CH}| treatment of, sorting and shredding | Alloc Def, U	75.00%
PE foil	No data - allocate to C4	0.00%
Plaster	No data - allocate to C4	0.00%
PVC, hard	No data - allocate to C4	0.00%
Steel, unalloyed	**GN_Waste reinforcement steel {CH}| treatment of, sorting plant | Alloc Def, U	95.00%
Rock wool		0.00%
Plasterboard	No data - allocate to C4	0.00%
Polystyrene extruded (XPS)		0.00%
Cement cast plaster floor	**GN_Waste concrete, not reinforced {Europe without Switzerland}| treatment of waste concrete, not reinforced, sorting plant | Alloc Def, U	95.00%

Table 0.5: Environmental Data for LCS C3

Materials	Life Cycle Stages C4	
Materials (Revit)	SimaPro C4 data sets landfill	Landfill [%]
Aluminium Alloy	**GN_Waste aluminium {CH}| treatment of, sanitary landfill | Alloc Def, U	5,00%
Reinforced Concrete		#NV
Concrete	**GN_Waste concrete {Europe without Switzerland}| treatment of waste concrete, inert material landfill | Alloc Def, U	5,00%
Reinforcement	**GN_Waste concrete {Europe without Switzerland}| treatment of waste concrete, inert material landfill | Alloc Def, U	5,00%
Bitumen seal	**GN_Waste bitumen {Europe without Switzerland}| treatment of waste bitumen, sanitary landfill | Alloc Def, U	94,44%
Roof Tile	**GN_Waste brick {CH}| treatment of, collection for final disposal | Alloc Def, U	5,00%
Double Glazing	**GN_Used triple glazing, U<0.5W/m2K {CH}| treatment of used triple glazing, U<0.5W/m2K, collection for final disposal | Alloc Def, U	5,00%
Triple Glazing	**GN_Used triple glazing, U<0.5W/m2K {CH}| treatment of used triple glazing, U<0.5W/m2K, collection for final disposal | Alloc Def, U	5,00%
Steel, chromium steel	**GN_Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Alloc Def, U	5,00%
Epoxy resin	**GN_Waste paint {Europe without Switzerland}| treatment of waste paint, municipal incineration | Alloc Def, U	100,00%
Flat glass, coated	**GN_Waste glass sheet {Europe without Switzerland}| treatment of waste glass sheet, collection for final disposal | Alloc Def, U	5,00%
Gravel, crushed	**GN_Waste concrete gravel {CH}| treatment of, collection for final disposal | Alloc Def, U	5,00%
Hardwood	0	0,00%
Brickwork		#NV
Bricks	**GN_Waste brick {CH}| treatment of, collection for final disposal | Alloc Def, U	5,00%
Mortar	**GN_Waste concrete, not reinforced {Europe without Switzerland}| treatment of waste concrete, not reinforced, collection for final disposal | Alloc Def, U	5,00%
Brass	No data - allocate to Incineration	0,00%
Softwood		0,00%
PE foil	**GN_Waste polyethylene {Europe without Switzerland}| treatment of waste polyethylene, sanitary landfill | Alloc Def, U	10,53%
Plaster	**GN_Waste mineral plaster {CH}| treatment of, collection for final disposal | Alloc Def, U	100,00%
PVC, hard	**GN_Waste polyvinylchloride {Europe without Switzerland}| treatment of waste polyvinylchloride, sanitary landfill | Alloc Def, U	18,18%
Steel, unalloyed	**GN_Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | Alloc Def, U	5,00%
Rock wool	**GN_Waste mineral wool, for final disposal {Europe without Switzerland}| treatment of waste mineral wool, inert material landfill | Alloc Def, U	100,00%
Plasterboard	**GN_Waste gypsum {Europe without Switzerland}| treatment of waste gypsum, sanitary landfill | Alloc Def, U	100,00%
Polystyrene extruded (XPS)	**GN_Waste polystyrene {Europe without Switzerland}| treatment of waste polystyrene, sanitary landfill | Alloc Def, U	5,00%
Cement cast plaster floor	**GN_Waste concrete, not reinforced {Europe without Switzerland}| treatment of waste concrete, not reinforced, collection for final disposal | Alloc Def, U	5,00%

Table 0.6: Environmental Data for LCS C4 - Landfill

Materials	Life Cycle Stages C4	
Materials (Revit)	SimaPro C4 data sets incineration	Incineration [%]
Aluminium Alloy		0,00%
Reinforced Concrete		#NV
Concrete		0,00%
Reinforcement		0,00%
Bitumen seal	**GN_Waste bitumen sheet {CH}| treatment of, municipal incineration with fly ash extraction | Alloc Def, U	5,56%
Roof Tile		0,00%
Double Glazing		0,00%
Triple Glazing		0,00%
Steel, chromium steel		0,00%
Epoxy resin		0,00%
Flat glass, coated		0,00%
Gravel, crushed		0,00%
Hardwood	**GN_Waste building wood, chrome preserved {CH}| treatment of, municipal incineration with fly ash extraction | Alloc Def, U	100,00%
Brickwork		#NV
Bricks		0,00%
Mortar		0,00%
Brass	**GN_Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Alloc Def, U	100,00%
Softwood	**GN_Waste wood, untreated {CH}| treatment of, municipal incineration with fly ash extraction | Alloc Def, U	25,00%
PE foil	**GN_Waste sealing sheet, polyethylene {CH}| treatment of, municipal incineration with fly ash extraction | Alloc Def, U	89,47%
Plaster		0,00%
PVC, hard	**GN_Waste polyvinylchloride {Europe without Switzerland}| treatment of waste polyvinylchloride, municipal incineration | Alloc Def, U	48,68%
Steel, unalloyed		0,00%
Rock wool	No Data!	0,00%
Plasterboard		0,00%
Polystyrene extruded (XPS)	**GN_Waste polystyrene {Europe without Switzerland}| treatment of waste polystyrene, municipal incineration | Alloc Def, U	95,00%
Cement cast plaster floor		0,00%

Table 0.7: Environmental Data for LCS C4 - Incineration

E Investigation of the Models LOI

The non-geometrical information contained in the model elements, which is described by the LOI, has the following gaps:

- There is one occurrence of a flooring called "*Fußboden - Leer*" (german; translated: Flooring - empty). It is not clear what material and flooring structure this element represents. Thus, this element was not included in the scope.
- The LOI of this BIM Model does not match the LOG. The names of the materials are not sufficiently meaningful. For example, "*Autodesk Black 0-0-0*", "*Plastic - grey - 80-80-80*", and "*Textile - brown*" do not carry enough meaning to choose a fitting material for the LCA. Most of them belong to furnishing and other elements that are not part of the scope, like a writing on the front of the building. A complete list of the materials in the BIM model can be found in Appendix 1. The rest of the materials were identified by their use in the BIM Model.
- The materials in the BIM model do not contain references to specific real materials. For properties like weight, assumptions were made, depending on the name, building element, and use of the material.

F Sankey Diagrams

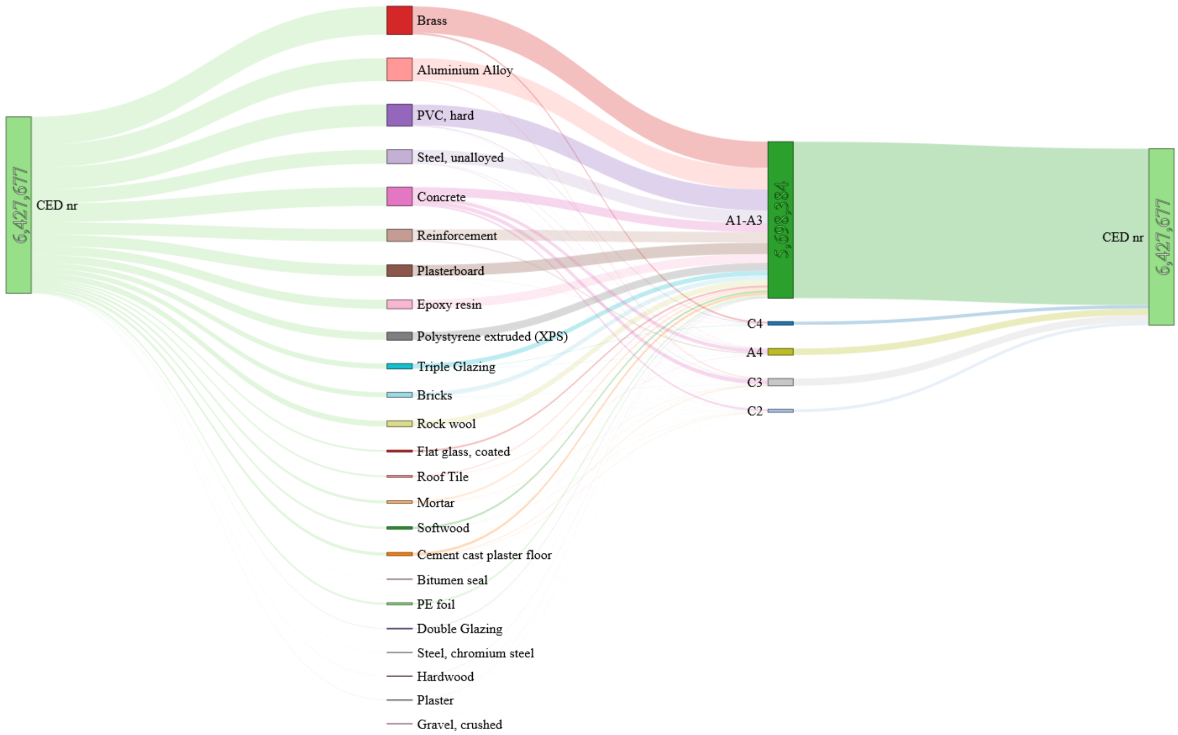


Figure 0.5: Sankey Diagram: CEDnr - Materials - LCS in MJ eq. for the Entire Building

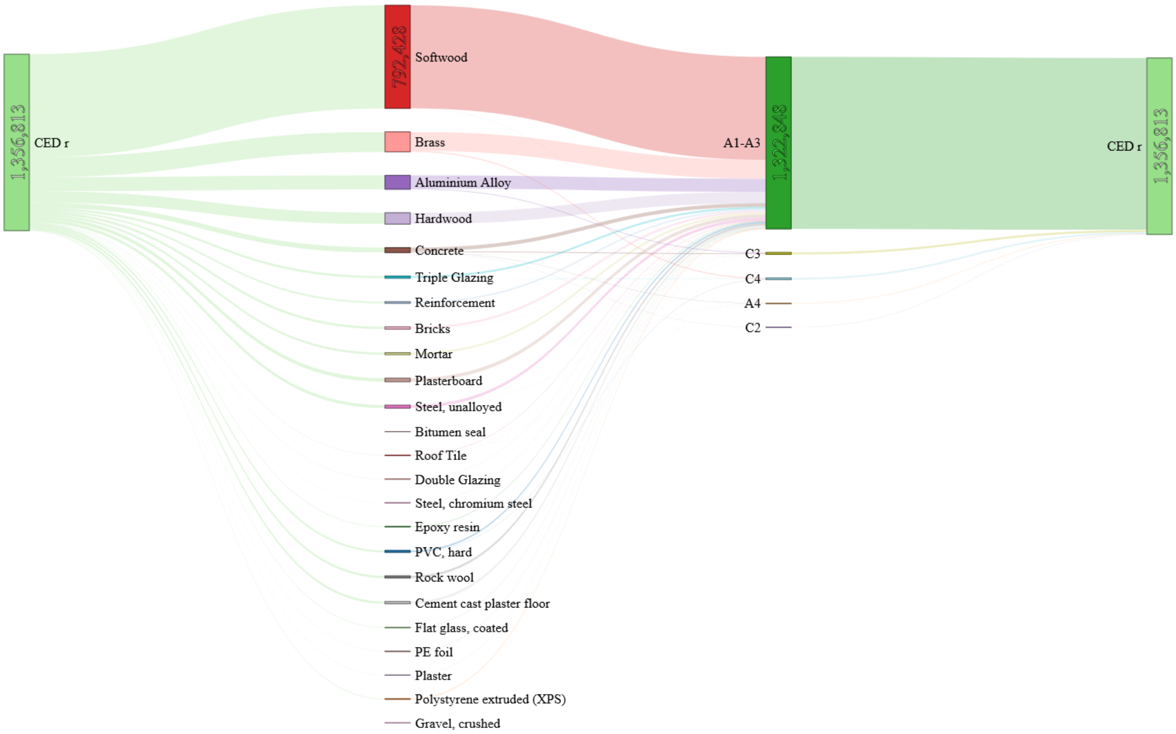


Figure 0.6: Sankey Diagram: CEDr - Materials - LCS in MJ eq. for the Entire Building

G Sensitivity Analysis

In the course of the LCA, information from different sources was merged and many assumption had to be made, e.g. in the definition of the scenarios. In order to confirm the results of the LCA, these assumptions and decisions were analysed for their impact on the overall results.
Figure 0.7 illustrates the most important steps of this LCA.

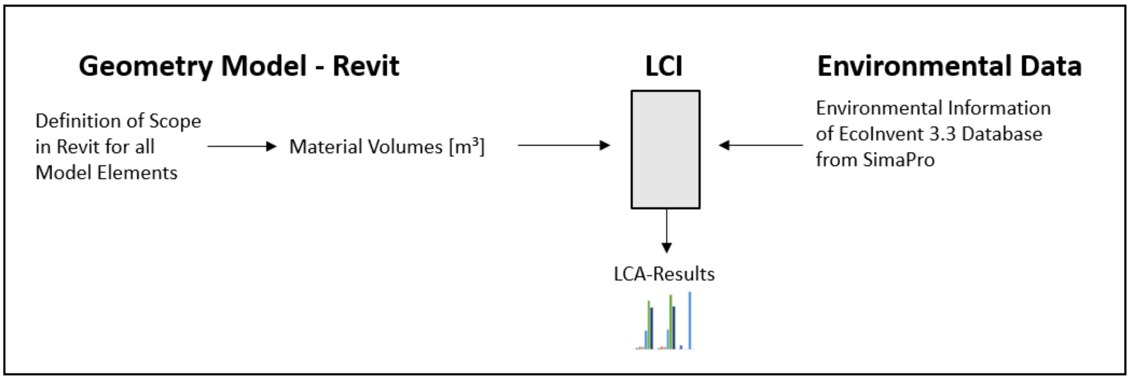


Figure 0.7: Overview of LCA - Case A

The LCA starts with the definition of the scope. The scope, however, is a set boundary condition of this LCA and not to be changed.
In line with the scope, the material quantities were extracted from the BIM Model and slightly transformed to match the choice of environmental information available. Both, the material quantities and the environmental information, have great impact on the LCA results and are therefore analysed more closely. So, these are the parameters that were tested for their influence. The composed materials of reinforced concrete and brickwork were investigated both, as a whole and broken down in their constituents.
In order to get the influence on the final LCA results, the values of these parameters were increased by 20% and the change of the LCA results was noted in percent. The results were collected in table 0.8
First, all of the material quantities were increased by 20%, giving the expected result of an total increase of LCA results by an equal amount. Then, the weights were tested, and finally, all of the materials were tested one by one.
The same approach was applied to the environmental data. Starting with an increase of all data, followed by an individual examination of the single LCS'.

Inputs increased by 20%	Global warming (GWP100a) [kg CO2 eq]	CED non-renewable, excl. raw materials [MJ eq]	CED renewable, excl. raw materials [MJ eq]
Original (Embodied Impacts excl. B4)	528.275,71	6.413.707,25	1.354.975,83
Quantities [m² and m³]	20,00%	20,00%	20,00%
Specific Weights [kg/m³]	17,12%	18,14%	6,39%
Aluminium Alloy	2,14%	2,58%	1,57%
Reinforced Concrete	4,05%	3,48%	0,74%
Concrete	2,86%	2,11%	0,56%
Reinforcement	1,19%	1,37%	0,18%
Bitumen seal	0,00%	0,01%	0,00%
Roof Tile	0,21%	0,20%	0,03%
Double Glazing	0,08%	0,07%	0,02%
Triple Glazing	0,66%	0,60%	0,24%
Steel, chromium steel	0,01%	0,01%	0,02%
Epoxy resin	0,90%	1,01%	0,06%
Flat glass, coated	0,22%	0,20%	0,05%
Gravel, crushed	0,00%	0,01%	0,00%
Hardwood	0,02%	0,03%	1,29%
Brickwork	1,12%	0,84%	0,49%
Bricks	0,64%	0,56%	0,26%
Mortar	0,48%	0,29%	0,23%
Brass	2,47%	3,19%	2,26%
Softwood	0,23%	0,25%	11,68%
PE foil	0,16%	0,23%	0,02%
Plaster	0,06%	0,04%	0,02%
PVC, hard	1,58%	2,47%	0,22%
Steel, unalloyed	2,21%	1,59%	0,33%
Rock wool	0,49%	0,66%	0,24%
Plasterboard	1,11%	1,30%	0,39%
Polystyrene extruded (XPS)	1,58%	0,89%	0,06%
Cement cast plaster floor	0,67%	0,35%	0,25%
Environmental Data (Embodied Impacts)	20,00%	20,00%	20,00%
Environmental Data (A1-A3)	16,98%	17,73%	19,50%
Environmental Data (A4)	0,61%	0,74%	0,06%
Environmental Data (C2)	0,26%	0,33%	0,02%
Environmental Data (C3)	0,66%	0,82%	0,23%
Environmental Data (C4)	1,49%	0,37%	0,19%

Table 0.8: Sensitivtiy Analysis - Increase of 20%

There are several points worth of note:

- The parameters have varying influence on the different impact indicators. GWP and CEDnr have a similar profile in this analysis but CEDr is significantly influenced by the amount of wood and less so by the quantities of reinforcement and concrete.
- The increase of the environmental data of LCS A1-A3 leads to an almost equal increase in CEDr. The sum of the other LCS of the embodied impact make up hardly more than one half percent in this analysis.
- In GWP and CEDnr reinforced concrete is the biggest influence, followed by the metals of brass, aluminium alloy, and unalloyed steel.

The LCA results are influenced the most by changes of the amount of reinforced concrete and metals, or wood, depending on the impact category regarded. In all three impact categories analysed, changes in the production stage (A1-A3) make up the major share of influences by environmental data.

H Illustration of Correction Factors

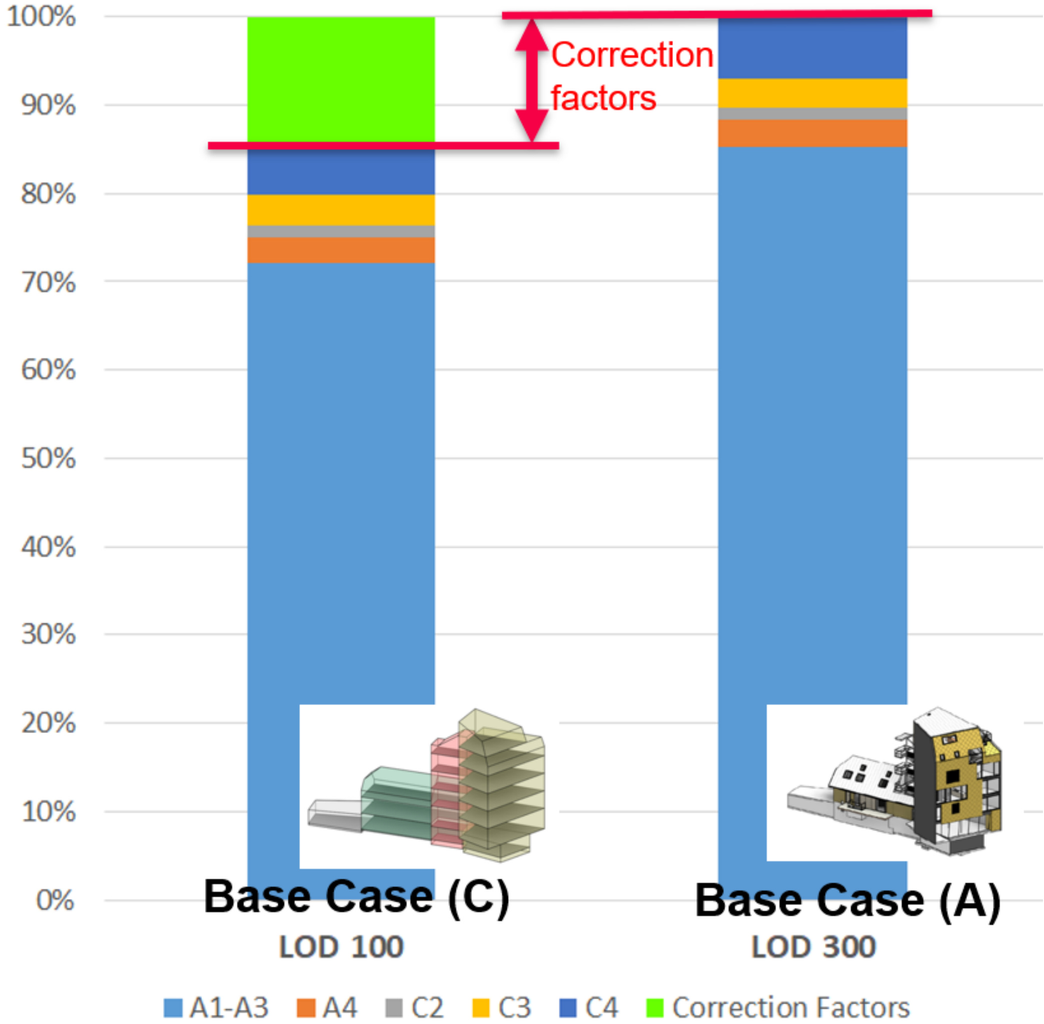
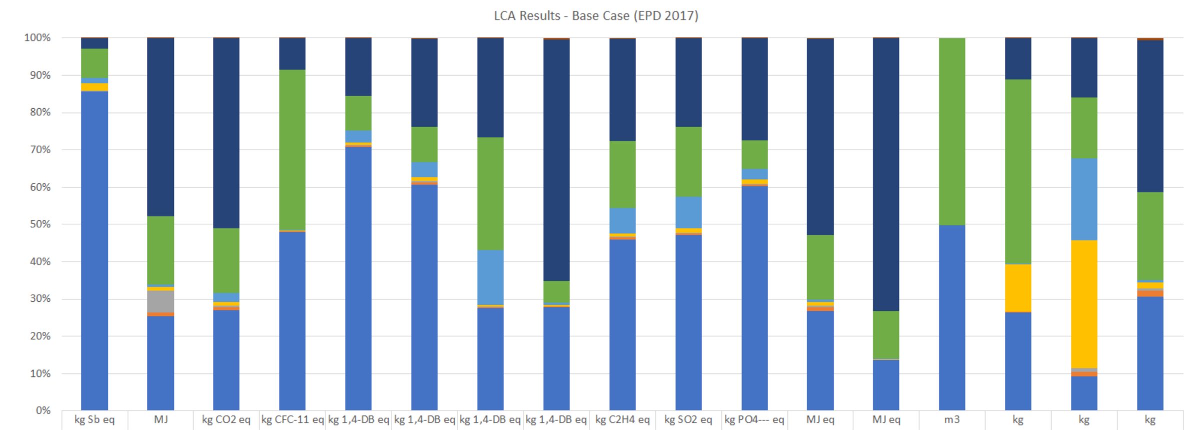


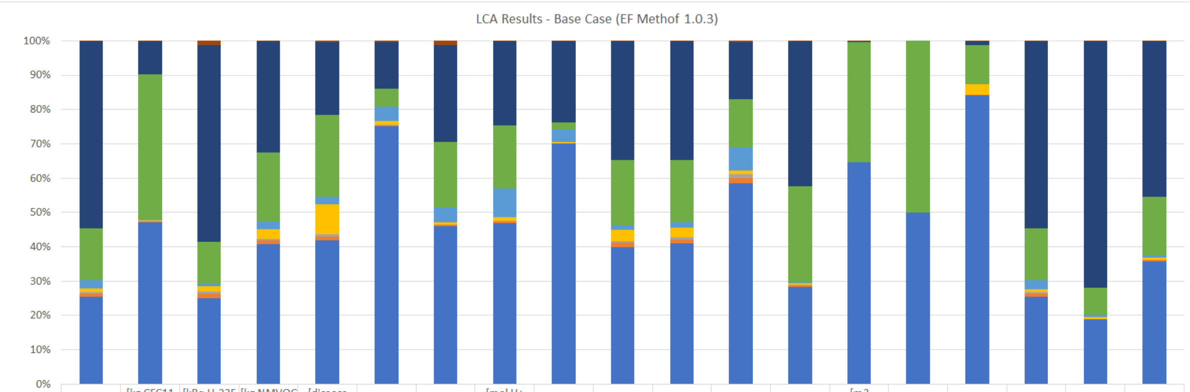
Figure 0.8: Correction Factors

I LCA Results: Case B



	kg Sb eq Abiotic depletion	MJ Abiotic depletion (fossil fuels)	kg CO2 eq Global warming (GWP100a)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity	kg 1,4-DB eq Fresh water aquatic ecotox.	kg 1,4-DB eq Marine aquatic ecotoxicity	kg 1,4-DB eq Terrestrial ecotoxicity	kg C2H4 eq Photochemical oxidation	kg SO2 eq Acidification	kg PO4--- eq Eutrophication	MJ eq CED non-renewable, excl. raw materials	MJ eq CED renewable, excl. raw materials	m3 Use of net fresh water	kg Hazardous waste disposed	kg Non hazardous waste disposed	kg Radioactive waste disposed
B7	0,0159	27.317,0479	2.347,0551	0,0006	833,0514	28,4781	1.054.116,3	50,3775	0,9403	10,9025	1,4120	67.460,1528	11.289,9175	0,0000	0,1188	731,3025	1,3192
B6	1,5138	11.592.927,	969.868,782	0,1147	136.112,118	4.828,6991	453.566.322	8.686,8500	158,1135	2.690,2891	549,7470	13.454.638,	7.931.830,7	0,0000	32,0791	96.814,1210	86,3292
B4	4,4488	4.451.579,1	329.952,216	0,5834	81.835,2891	1.917,5596	514.145.155	803,8042	104,1201	2.097,0919	151,3543	4.435.587,2	1.370.147,5	625,0310	144,2128	99.270,1932	49,7942
C4	0,6888	138.860,694	45.454,9478	0,0017	28.389,5394	854,1454	249.808.045	67,9349	39,5120	975,3530	56,2690	151.628,286	16.563,6537	0,0000	0,2175	132.907,773	1,2274
C3	1,2043	257.474,348	17.743,6642	0,0028	4.822,4638	176,5217	6.702.124,0	57,8802	4,4139	121,4534	24,0039	267.014,708	15.834,0127	0,0000	37,3525	209.469,147	3,1847
C2	0,0208	1.434.806,9	7.581,4786	0,0014	2.132,7824	78,0990	1.168.160,5	10,3816	1,2372	24,4153	3,9899	116.779,464	1.645,2903	0,0000	0,0628	5.511,2078	1,6309
A4	0,0796	253.444,389	16.435,4737	0,0029	3.814,5956	142,7393	3.513.988,2	24,8910	2,8454	52,5750	8,0808	244.161,212	4.047,3959	0,0000	0,1758	7.537,8733	3,2762
A1-A3	47,3905	6.140.342,2	512.550,616	0,6495	624.205,592	12.354,9270	470.226.275	3.719,9821	265,2600	5.322,5984	1.208,1313	6.847.309,4	1.485.850,7	621,5612	76,9155	56.125,8992	64,6547

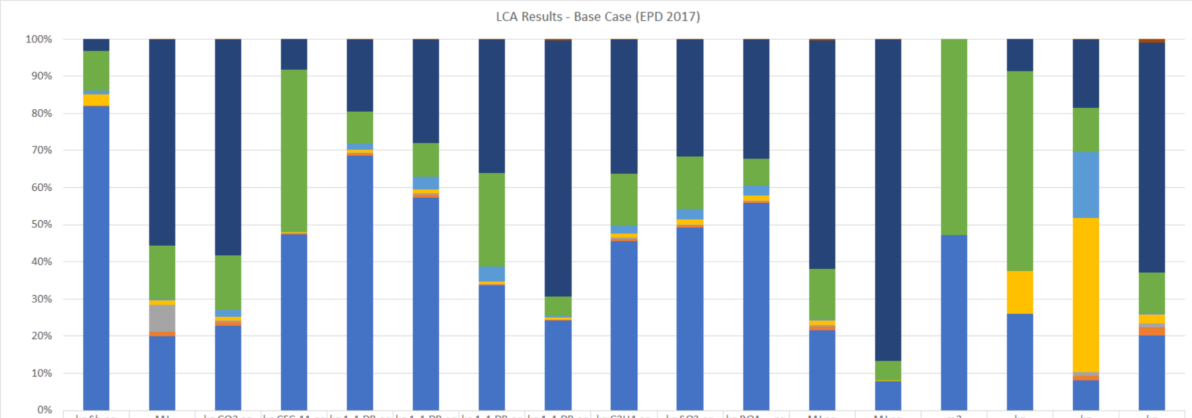
Figure 0.9: LCA Results Case B - EPD Method



	[kg CO2 eq] Climate change	[kg CFC11 eq] Ozone depletion	[kBq U-235 eq] Ionising radiation, HH	[kg NMVOC eq] Photochemical ozone formation, HH	[disease inc.] Respiratory inorganics	[CTUh] Non-cancer human health effects	[CTUh] Cancer human health effects	[mol H+ eq] Acidification terrestrial and freshwater	[kg P eq] Eutrophication freshwater	[kg N eq] Eutrophication marine	[mol N eq] Eutrophication terrestrial	[CTUe] Ecotoxicity freshwater	[Pt] Land use	[m3 depriv.] Water scarcity	[MJ] Resource use, energy carriers	[kg Sb eq] Resource use, mineral and metals	[kg CO2 eq] Climate change - fossil	[kg CO2 eq] Climate change - biogenic	[kg CO2 eq] Climate change - land use and transform.
B7	2.428,434	0,0004	1.074,524	9,1414	0,0002	0,0018	0,0005	13,1970	0,1523	2,3804	26,4699	6.023,563	23.031,05	17.802,76	0,0000	0,0120	2.388,617	7,6711	3,7465
B6	994.227,1	0,1091	47.408,34	1.774,954	0,0174	0,0901	0,0118	3.251,903	105,9049	512,4425	6.116,388	278.219,5	26.748.94	28.855,46	0,0000	0,3738	987.436,9	3.666,544	1.148,467
B4	277.152,3	0,4780	10.183,43	1.112,270	0,0195	0,0352	0,0080	2.448,758	9,2532	279,6186	3.206,976	235.973,4	17.603.01	4.517.959	888.600,4	3,7834	275.635,7	397,5738	428,5916
C4	45.797,38	0,0017	591,6627	122,5300	0,0018	0,0264	0,0018	1.077,546	15,7128	20,3357	245,8740	114.389,2	212.061,4	331,4650	0,0000	0,0195	45.690,28	30,0218	19,2645
C3	18.033,68	0,0033	1.257,034	147,9113	0,0073	0,0082	0,0002	157,3870	2,1789	47,9046	532,4055	17.399,09	332.650,0	307,6700	0,0000	1,0102	17.908,90	36,6343	16,1188
C2	7.661,361	0,0018	536,0395	30,4649	0,0005	0,0011	0,0001	31,2272	0,1039	8,9696	98,9850	18.868,20	118.932,0	26,9074	0,0000	0,0138	7.633,099	1,4915	2,7191
A4	16.626,39	0,0036	1.074,710	58,1611	0,0009	0,0020	0,0002	66,0964	0,3492	16,8347	186,7796	27.290,05	173.900,5	66,6435	0,0000	0,0526	16.558,17	4,2449	9,1238
A1-A3	465.976,5	0,5307	20.720,09	2.240,328	0,0342	0,4960	0,0192	6.205,871	312,6605	591,6276	7.250,774	982.861,5	17.914.78	8.352.746	888.600,4	27,9787	461.171,0	957,8396	904,6756

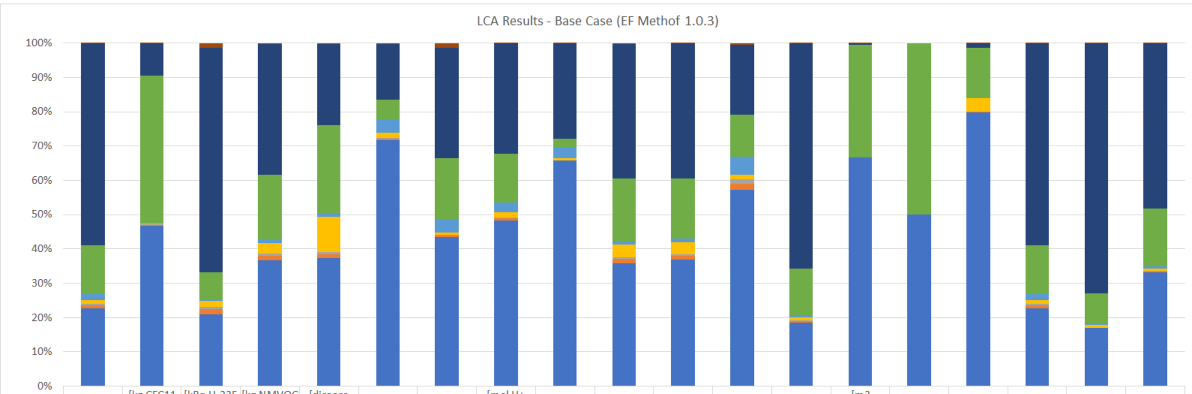
Figure 0.10: LCA Results Case B - EF Method

J LCA Results: Case C



	kg Sb eq Abiotic depletion	MJ Abiotic depletion (fossil fuels)	kg CO2 eq Global warming (GWP100a)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity	kg 1,4-DB eq Fresh water aquatic ecotox.	kg 1,4-DB eq Marine aquatic ecotoxicity	kg 1,4-DB eq Terrestrial ecotoxicity	kg C2H4 eq Photochemical oxidation	kg SO2 eq Acidification	kg PO4--- eq Eutrophication	MJ eq CED non-renewable, excl. raw materials	MJ eq CED renewable, excl. raw materials	m3 Use of net fresh water	kg Hazardous waste disposed	kg Non hazardous waste disposed	kg Radioactive waste disposed
B7	0,0159	27.317,0479	2.347,0551	0,0006	833,0514	28,4781	1.054.116,3	50,3775	0,9403	10,9025	1,4120	67.460,1528	11.289,9175	0,0000	0,1188	731,3025	1,3192
B6	1,5138	11.592.927,	969.868,782	0,1147	136.112,118	4.828,6991	453.566.322	8.686,8500	158,1135	2.690,2891	549,7470	13.454.638,	7.931.830,7	0,0000	32,0791	96.814,1210	86,3292
B4	5,0037	2.972.750,6	243.844,890	0,6041	61.836,9785	1.571,7908	315.223.010	674,1806	60,6077	1.196,7315	125,8133	2.918.192,6	474.545,251	269,3834	198,2449	63.293,9102	15,0725
C4	0,5411	85.823,4665	30.391,6317	0,0009	11.274,4323	600,7503	52.348.582,	43,1395	9,8535	243,2343	43,3754	95.862,5131	11.079,2169	0,0000	0,1111	93.739,1101	0,7150
C3	1,3750	257.980,892	17.928,8861	0,0028	5.162,0410	188,2520	7.185.141,8	62,5929	4,5393	122,5826	24,2985	268.381,480	16.719,8429	0,0000	42,6718	219.628,340	3,1557
C2	0,0195	1.536.485,6	7.102,5857	0,0013	1.998,0627	73,1658	1.094.372,3	9,7258	1,1591	22,8731	3,7378	109.402,954	1.541,3637	0,0000	0,0588	5.163,0860	1,5279
A4	0,0743	235.354,995	15.267,2150	0,0027	3.536,1576	132,3544	3.273.643,0	23,1452	2,6450	48,8367	7,5011	226.727,490	3.763,6782	0,0000	0,1637	6.953,6179	3,0410
A1-A3	38,8094	4.166.059,7	381.170,907	0,6573	483.003,984	9.950,9294	423.507.059	3.053,3941	199,5869	4.192,0955	957,2875	4.695.107,9	716.563,190	240,3830	95,7263	42.678,9687	28,1109

Figure 0.11: LCA Results Case C - EPD Method

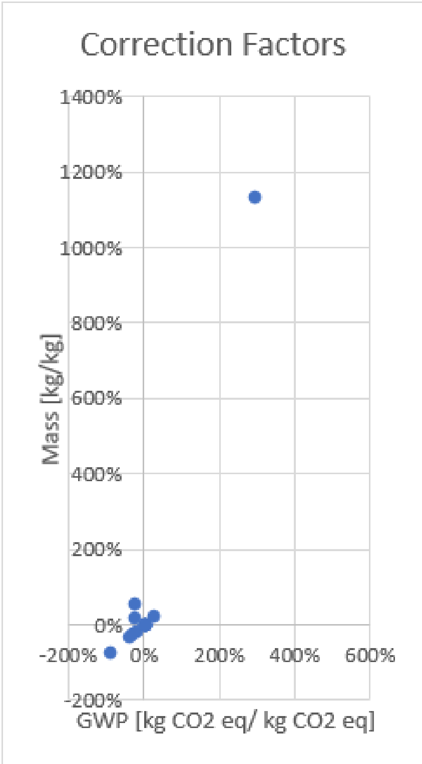


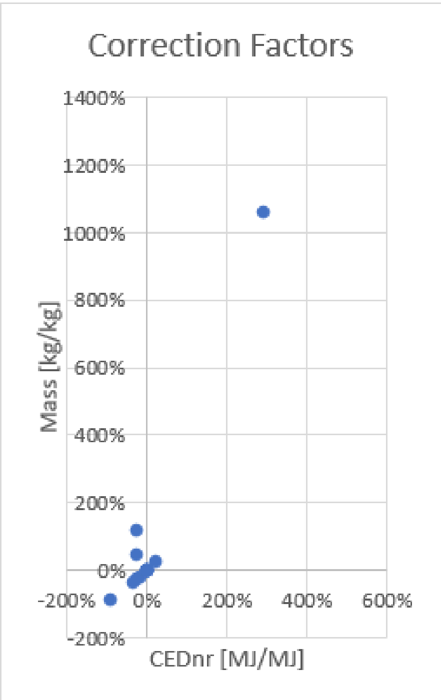
	[kg CO2 eq] Climate change	[kg CFC11 eq] Ozone depletion	[kBq U-235 eq] Ionising radiation, HH	[kg NMVOC eq] Photochemical ozone formation, HH	[disease inc.] Respiratory inorganics	[CTUh] Non-cancer human health effects	[CTUh] Cancer human health effects	[mol H+ eq] Acidification terrestrial and freshwater	[kg P eq] Eutrophication freshwater	[kg N eq] Eutrophication marine	[mol N eq] Eutrophication terrestrial	[CTUe] Ecotoxicity freshwater	[Pt] Land use	[m3 depriv.] Water scarcity	[MJ] Resource use, energy carriers	[kg Sb eq] Resource use, mineral and metals	[kg CO2 eq] Climate change - fossil	[kg CO2 eq] Climate change - biogenic	[kg CO2 eq] Climate change - land use and transform.
B7	2.428,434	0,0004	1.074,524	9,1414	0,0002	0,0018	0,0005	13,1970	0,1523	2,3804	26,4699	6.023,563	23.031,05	17.802,76	0,0000	0,0120	2.388,617	7,6711	3,7465
B6	994.227,1	0,1091	47.408,34	1.774,954	0,0174	0,0901	0,0118	3.251,903	105,9049	512,4425	6.116,388	278.219,5	26.748.94	28.855,46	0,0000	0,3738	987.436,9	3.666,544	1.148,467
B4	241.472,3	0,4937	5.777,520	871,2350	0,0187	0,0327	0,0065	1.438,535	8,7728	239,1804	2.717,324	167.155,0	5.576.947	3.846.440	173.335,7	4,2784	239.990,1	453,6878	405,8979
C4	30.586,15	0,0009	364,9019	53,6068	0,0009	0,0203	0,0014	274,2629	12,4422	13,4570	165,7576	71.511,57	135.300,1	233,1465	0,0000	0,0105	30.533,02	11,3782	13,2237
C3	18.225,73	0,0033	1.255,640	143,7501	0,0075	0,0093	0,0002	157,9714	2,4329	46,4279	517,0395	18.979,88	351.382,4	319,6912	0,0000	1,1538	18.097,99	39,7556	16,9253
C2	7.177,423	0,0017	502,1800	28,5405	0,0005	0,0010	0,0001	29,2547	0,0973	8,4030	92,7325	17.676,37	111.419,5	25,2078	0,0000	0,0129	7.150,945	1,3973	2,5474
A4	15.444,72	0,0034	997,4845	53,9524	0,0008	0,0019	0,0002	61,3858	0,3256	15,6143	173,2493	25.225,86	160.611,6	61,9790	0,0000	0,0491	15.381,26	3,9527	8,5061
A1-A3	382.792,8	0,5365	15.240,49	1.707,421	0,0274	0,4000	0,0159	4.886,296	249,8282	467,4197	5.715,931	780.120,8	7.555.101	7.775.812	173.335,7	23,2038	379.130,4	850,8136	791,7763

Figure 0.12: LCA Results Case C - EF Method

K Correction Factors by Levels

Level(s)	Correction Factors			
	Mass	GWP	CEDnr	CEDr
112	-18.80%	-18.80%	-18.80%	-18.80%
121	0.00%	0.00%	0.00%	0.00%
122	-26.65%	-26.05%	-26.09%	-26.23%
123	-26.16%	18.21%	123.52%	819.69%
124	0.00%	0.00%	0.00%	0.00%
131	0.00%	0.00%	0.00%	0.00%
132	0.00%	0.00%	0.00%	0.00%
133	0.00%	0.00%	0.00%	0.00%
141	-36.79%	-31.89%	-38.01%	-29.83%
142	0.00%	0.00%	0.00%	0.00%
151	292.87%	1136.33%	1059.73%	1083.80%
152	-91.66%	-73.44%	-90.24%	-93.63%
213	0.00%	0.00%	0.00%	0.00%
214	24.66%	23.74%	24.02%	24.05%
215	-24.61%	56.27%	46.79%	90.52%
261	0.00%	0.00%	0.00%	0.00%





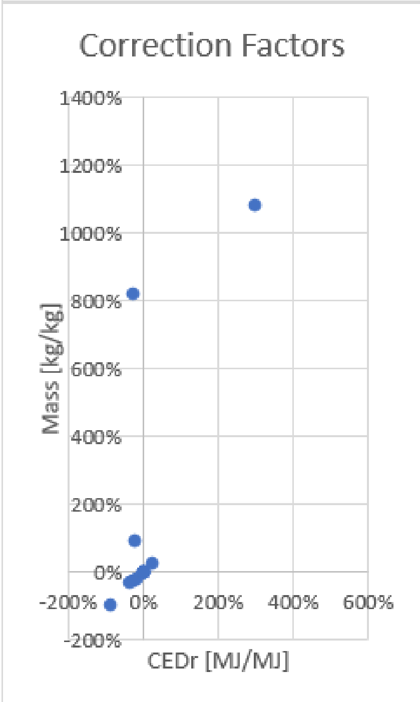


Figure 0.13: Correlation of Quantities and Impact Categories in Correction Factors (Levels)

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Glossary

AIA	American Institute of Architects
API	Application Programming Interface
BEPS	Building Energy Performance Simulation
BIM	Building Information Modelling
CEDnr	Cumulative Energy Demand - Non-Renewable
CEDr	Cumulative Energy Demand - Renewable
EBC	Energy in Buildings and Communities Programme
ER	Exchange Requirements
ESL	Expected Service Life
gbXML	Green Building XML Schema
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
IDM	Information Delivery Manual
IEA	International Energy Agency
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCS	Life Cycle Stage
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
MEP	Mechanical, Electrical, Plumbing
MVD	Model View Definition
NBIMS	American National BIM Standard
NIBS	American National Institute of Building Sciences
ODP	Depletion Potential of Stratospheric Ozone Layer
PCRs	Austrian Product Category Rules
RQ	Research Question
RSL	Reference Service Life
RSP	Reference Study Period
UN	United Nations
VPL	Visual Programming Language
WCED	World Commission on Environment and Development