



IFC-based variant analysis considering multicriterial sustainability analysis of buildings

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Abstract

The process of shifting the construction industry to a more sustainable future demands for easy and reliable ways, to rate the sustainability impacts of building projects. In the optimal case, before the moment to choose the right alternative is gone. Life Cycle Costings (LCCs) and Life Cycle Assessments (LCAs) are long established tools, to estimate the cost and environmental impact of building projects and their methods are therefore mature. Combining these proofed techniques with the new possibilities of Building Information Modeling (BIM) and the chances of early design stages, an automated, multicriterial sustainability analysis will be possible. Benefiting from the circumstance that BIM-enabled building models already encompass a relatively detailed design stage during these early phases, the possibility to make detailed alternative comparisons can be used. Therefore, planners will still be able to contribute the learning to the construction process without the high resistance to changes that are typical for later design phases. By combining the BIM model output and several databases for LCCs and LCAs, construction alternatives can be compared without the need for manual information gathering. This is possible, because the information included in an early phase building model is used to the full extent and only crucial, missing data is supplemented. An automatic calculation with the help of a component catalog is possible, in most cases, without adding any material information to the BIM model. A calculation without external component templates is possible if layer information is included in the model as well. Since the early phase models are not set on specific components, a variant comparison with the help of possible component templates is the best solution for building models during the early design stages. The methodology for a holistic simulation approach for multi-criteria sustainability analyses on the basis of early design phase BIM models is discussed as well.

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Abbreviations

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
API	Application Programming Interface
B/Q	Bill of Quantities
BIM	Building Information Modeling
BKI	Baukosteninformationszentrum Deutscher Architektenkammern
BNB	Bewertungssystem Nachhaltiges Bauen
CEN	European Committee for Standardization
CO₂-equi.	CO ₂ -equivalent
DB	Database
DBD	Dynamische Baudaten
DBMS	Database Management System
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
EPD	Environmental Product Declaration
GWP	Global Warming Potential
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
ISO	International Organisation for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LOD	Level of Development
PE	Primary Energy
PENRT	Total Non-Renewable Primary Energy
PERT	Total Renewable Primary Energy
SQL	Structured Query Language

1 Introduction

1.1 Setting

As the impacts of climate change become more visible around the world, the tone of public debate is changing. Politicians are coming under pressure and are passing this on to the major energy consumers and emitters of CO₂. The building sector is, including the manufacturing, transportation and use of construction materials, accountable for 38% of the global CO₂ emissions. This is the highest total level ever recorded, even though the share dropped from 39% in 2018 due to even higher increases in the sectors of transportation and other industries (UNITED NATIONS ENVIRONMENT PROGRAMME, 2020). If it is due to moral reasons or further legislation, the building sector has to make the shift towards a more sustainable future. Already, new regulations to address the mentioned problems are coming into effect. The new CO₂/t pricing in Germany is one example (UMWELTBUNDESAMT, 2020). Even though it is only aimed at the transportation sector and operational energy as of now, similar regulations for all CO₂ emitting businesses are considered. These events are pressuring the building sector to prepare for higher restrictions and also avoid costs through the possibility of emission pricing in the future. With these requirements, the bar is set high to retain profitable and environmental compatible construction.

Another development are certifications to assess the sustainability of buildings, which are gaining popularity (ZIMMERMANN et al., 2019). These certifications try to cover multiple criteria of sustainability, but also refer to long established sustainability analyses, like LCA and LCC. On the one hand, builders themselves use their influence to make projects more sustainable, and on the other hand, the public image of companies can be influenced positively by positive certification results. The reason to make building more sustainable are therefore manifold.

Simultaneously, the construction industry is currently undertaking a digitization, like so many other branches of the economy do as well, and therefore new possibilities regarding automation and digital planning are available. Especially the topics of BIM and climate change are strongly represented in publications (SINGH, 2019). No wonder, many researchers are coupling digital building models and environmental assessments. While nearly all recent researches

have only coupled one sustainability criteria, new possibilities allow to process multi-criteria analyses with the help of BIM building models (FORTH et al., 2021).

1.2 Motivation

This leads to the goal of creating a design decision support tool, which takes all available sustainability criteria into account. Several requirements show promising value to this kind of tool. The benefits of aiming for special circumstances are therefore shortly explained.

1.2.1 Multi Sustainability Criteria

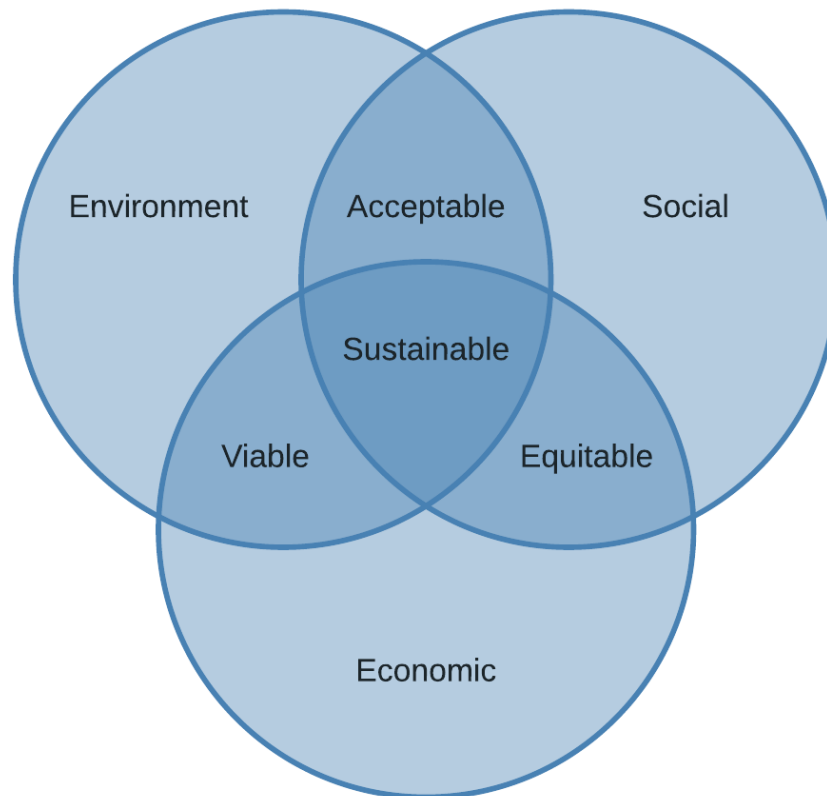


Figure 1.1: Three pillars of sustainability with their intersections (based on TEDESCHI et al., 2015).

The three pillars of sustainability, which are displayed in Figure 1.1, are ecology, economy and social factors. To make construction more sustainable, in the best case, all three aspects should be considered, since often times, one is traded off for the other. Especially the intersections between the pillars are valuable

to fulfill. To eliminate the contrasts between the main aspects of sustainability, multi-criteria assessments can be utilized. The optimal result would be to meet all three sustainability requirements by combining several criteria in one calculation.

Life Cycle Social Assessment (S-LCA/LCSA)

Having covered two of three pillars of sustainability with LCA and LCC, the remaining factor is the social impact. A coherent method was introduced by the United Nations Environment Program in 2009 (ANDREWS et al., 2009). It is derived from the method of LCAs, "because it is holistic, systemic and rigorous" (ANDREWS et al., 2009). But instead of analyzing the environmental impact of a product or process, it includes social and socio-economic factors. The impact categories include, among others, human rights, working conditions and governances.

LLATAS et al. (2020) reviews literature with the BIM-integrated Life Cycle Sustainability Assessment (LCSA) approach. It includes S-LCAs as well as LCAs and LCCs, and can therefore be used to get an overview of reference projects. In 36 investigated publications which refer to BIM-integrated LCA case studies, none investigated the social impact assessment S-LCA. Therefore, the method is established, but not investigated yet. Further developments will proof, if the social pillar of sustainability can be assessed through this process or if other solutions have to be found.

1.2.2 BIM

As already mentioned, the building sector is transforming itself into a more digital branch. Therefore, new possibilities through technology are opened up. One of those is BIM. The technology has evolved over the last decades from paper drawings, the first use of CAD-programs in the 1990s to openBIM today, which is representing an accessible and collective system for several parties to work on at the same time (SACKS et al., 2018). Through optimizing the whole process, increasing complexity, faster development and more efficient operation and maintenance of bigger projects is feasible. Furthermore, the collaboration between different disciplines in design and construction and automatic error diagnosis will become feasible.

These benefits lead to the fact, that a huge amount of information are stored within the building model. Therefore, the extraction of cost estimates and im-

Improvements in energy efficiency and sustainability through planning alternatives is an arising possibility. As the use of BIM is predicted to be very common for future building projects, automated assessments based on the information of a BIM model can present a huge chance (SACKS et al., 2018). Especially to make sustainability analyses more accessible, which can help to find a good balance, comparing the different pillars of sustainability.

1.2.3 Early Planning Phases

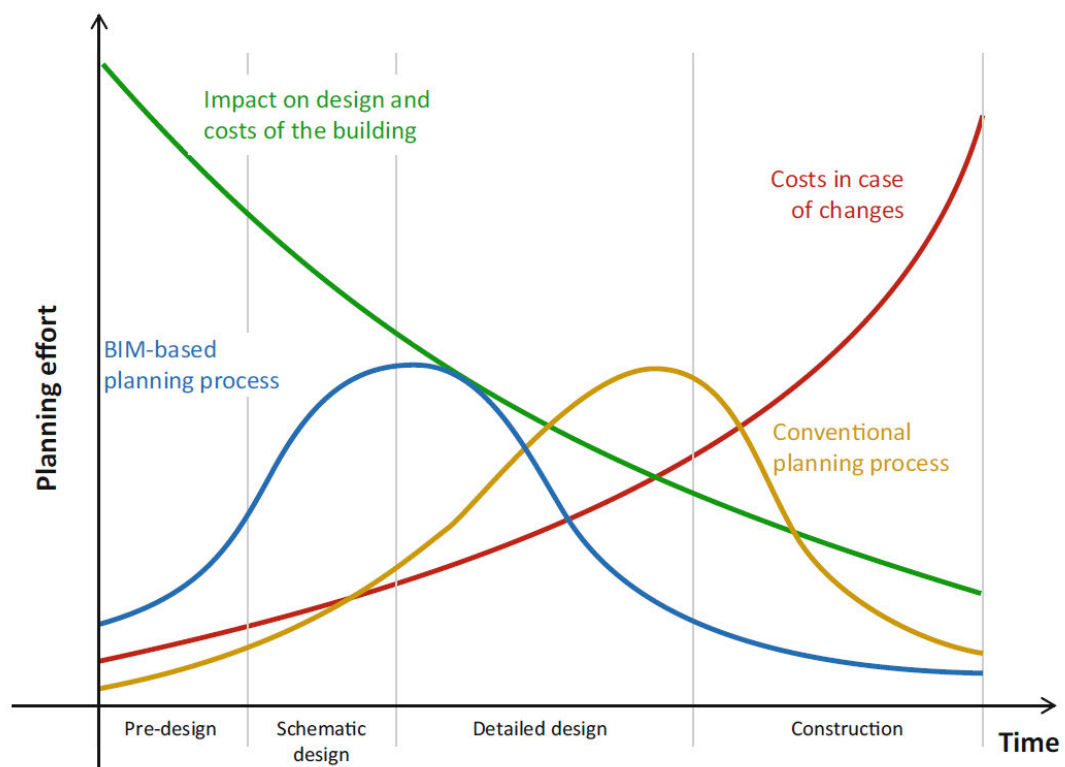


Figure 1.2: Correlation between progress in design and costs of changes (BORRMANN, KÖNIG, et al., 2018).

By using BIM as a planning tool, the early-design stages gather a new importance. If the whole building process is accompanied by a detailed model, the design decisions that would normally occur in later phases are now shifted to the early planning stages (BORRMANN, KÖNIG, et al., 2018). In Figure 1.2, the impact of BIM regarding the different phases of building projects is represented. Obviously, the earlier important changes are made, the better. Additionally, changes further along the line will become more expensive and harder to perform. This leads to the conclusion, that assessments regarding building performance have the best impact when executed during the early design stages.

On the contrary to the benefits of an earlier analysis, the level of information is lower and possibly more vague (BASBAGILL et al., 2013). Therefore, it is necessary to detect the crucial information and possibly enrich the data source.

1.3 Scope and Goal

1.3.1 Project Frame

All mentioned methods and techniques are already established or used on a regular basis. What does not yet exist, is a program or method to combine all of the stated requirements and perform a fully automated analysis for building projects in the early phase of planning.

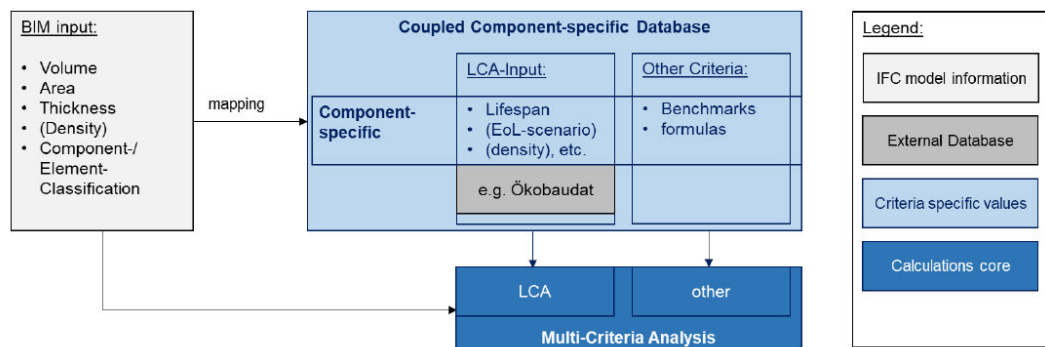


Figure 1.3: "General Strategy for a standard component database for multi-criterial variant analysis" by FORTH et al. (2021).

Figure 1.3 is displaying the project strategy followed by FORTH et al.(2021). The first part is the establishment of a BIM model, which has to fulfill all needed requirements for the chosen use-case and is exported via the Industry Foundation Classes (IFC) format. The exported data will then be used to simulate one or more chosen use-cases, f. e. through a LCA. The last step incorporates a tool for the design decision process. The project matches the requirements already described.

This thesis concerns itself with the sub-task of combining different data sources in a specific database and investigating the interface between BIM-based planning and environmental assessments. To grasp a scientific approach and identify problems, research guidelines will be established and the resulting process is tested in a case study.

1.3.2 Research Goal

The research goal will be framed through several research questions, which will be investigated through the project. Divided to sub-parts, the thesis spans the selection of databases for environmental and economic factors as well as the potential integration of further criteria. Furthermore, the arrangement of different data to be used in the same process, preparing the building model to incorporate all the important information and lastly accessing the data through a reasonable method. Considering the challenges of combining data and preparing the BIM building model, four fundamental questions can be formulated to lead through the thesis.

Research Questions:

1. How can data regarding multicriterial properties of materials be combined in a single database to provide a basis for comprehensive analysis methods?
2. How can different design and component alternatives be implemented in a database to enable an optimization through analyzing different variants?
3. Which information for an automated, multi-criteria building analysis is already contained in an early phase BIM model?
4. Which information is typically missing an early stage BIM model and which can be complemented?

2 State of the Art

2.1 Literature Review

Sustainability analyses and BIM-based modeling are not new approaches. Already, many researches are attributing to a combined approach to create reliable and fast assessment tools. An overview of the current research is given through the literature review made by FORTH et al. (2021). The aim of analyzed research encompasses the topics BIM, BIM-LCA integration and LCA. Additionally, the BIM-integrated LCC approach is investigated through the review by SANTOS et al. (2019).

The list of suitable researches can be limited to the specific topics. Therefore, approaches using the detailed design stages are excluded. For the access to BIM-based building information, an exchange format has to be identified. Several approaches are common, with IFC being the most adopted technology for open BIM applications. Also, to base LCAs on model information, open and closed solutions are available. The open ones using a Bill of Quantities (B/Q) or the IFC format, closed approaches mainly focus on software specific Application Programming Interfaces (APIs). (FORTH et al., 2021)

The literature review by SANTOS et al. (2019) is concerning integration of several sustainability criteria, like the methods of LCA and LCC. The most recent methods include interfaces between BIM through a quantity takeoff or IFC export. The later uses assessment data included directly in the BIM model. Different sustainability criteria are established via a combined database, with the possibility of including analysis relevant information directly in the BIM model as well. Analyzed by SANTOS et al., the remaining challenges for these kind of integration lie in interfaces and licenses for different programs and databases. Additionally, the possibility to combine external and internal information is important for many use cases.

The mentioned methods for integrating BIM and sustainability assessments and combining different analysis criteria are investigated during the thesis. The most recent publications feature the use of IFC as the data interface and either combined database or enrichment of the BIM model.

2.2 Early Design Stages

2.2.1 Design Stage Allocation Systems

To aim at the early design stages for this project, the overall concept has to be explored. Several systems to allocate projects to phases or stages are available and in use. A selection of systems, for example from the UK and Germany, are given in Figure 2.1. The illustration makes it obvious that the design stages vary wildly between each other and enables the user to roughly match different phases to each other.

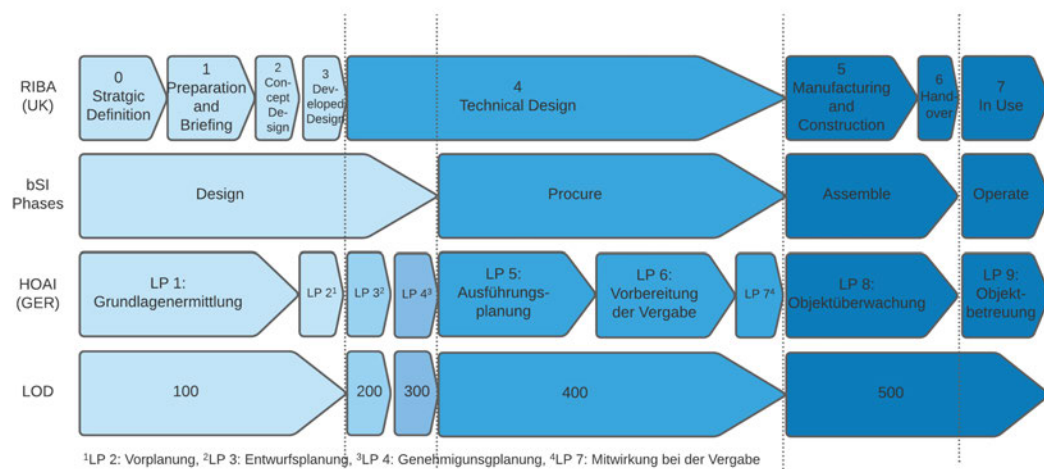


Figure 2.1: Project stages of the systems RIBA, bSI, HOAI and LOD (based on BUILDINGSMART, 2019).

van BERLO et al. (2014) give an overview over the different developments for some Level of Detail and Level of Information concepts. In 2006, the concept of Danish Information Levels was developed. It is specialized on 3d modeling and focuses on evolving the detail, while differentiating between geometric and non-geometric information.

In the UK, the BSI has introduced two standards, the level of model detail (LOD) and the level of model information (LOI). The first refers only to geometric, the second to semantic information.

These Systems are either aimed at organizing building project phases (RIBA, UK) or defining fees (HOAI, GER), however the design process is always very linear, without enabling iterations for changes early into the project (SCHNEIDER-MARIN and ABUALDENIEN, 2019).

In 2008, several committees of the American Institute of Architects (AIA) have adopted the concept of Level of Detail, and developed it further into Level of

Development. Therefore, the geometric detail was extended with non-geometric information. The same standard was taken over by the BIMForum in 2013. The LOD working group was formed under the new standard patron.

van BERLO et al., 2014 states, that publishers agree, that a pure development of detail is not enough to describe BIM models. Through the AIA, the concept of Level of Development (LOD) was widely spread, which is one reason why several committees recommend it as a guideline. This statement is also supported by SCHNEIDER-MARIN and ABUALDENIEN (2019).

2.2.2 Level of Development

The BIMForum, developer of the LOD standard, is an organization, which investigates the possibilities of further BIM-based use cases and strives to retrieve the most out of the technology (BIMFORUM, 2020). The standard itself consists of five basic LODs, from Level 100 to 500. Additionally, the step 350 was added as an extra subdivision. According to SCHNEIDER-MARIN and ABUALDENIEN (2019) the early design stages are defined as the phases from the pre-draft or preparation to the first design draft. Comparing this with the Figure 2.1, the intersection of the different systems aims at LOD 200. However, the definition varies between an early LOD 200 and the LOD 300. In the coherent figure, the area is marked by the first and second separation line.

The information definition by BIMFORUM (2020) concerning the latest LOD standard is rather vague. Geometric information for LOD 200 is defined as "a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation." For LOD 300, it is defined as a specific system and specific information. Both levels may have non-graphical information attached.

Despite being vague in an overall description of LODs, the standard defines precisely what information is included for the different object types, e.g. external wall, door etc., during the LODs. This will be referred to in the later process.

2.3 Building Information Modeling

2.3.1 Definition

Defining BIM with one sentence alone is not possible, because it consists of several tools, libraries, interfaces and elements, which form a system together. The Bavarian Architectural Association (2021) is defining its core as follows: "The core of BIM is a smart, three dimensional building model, which contains further digital information as a base for planning, constructing, operation, upkeeping and eventually even demolition[.].".

To describe the whole BIM environment, further information is necessary. SACKS et al., 2018 have published the third version of the "BIM Handbook", which incorporates all available topics concerning the system of BIM. One of the authors, Charles Eastman, is an early adapter of digital building models and has accompanied the development process of BIM from the start. Therefore, fundamental information to define BIM can be retrieved from the book. The parts described are displayed in Figure 2.2.

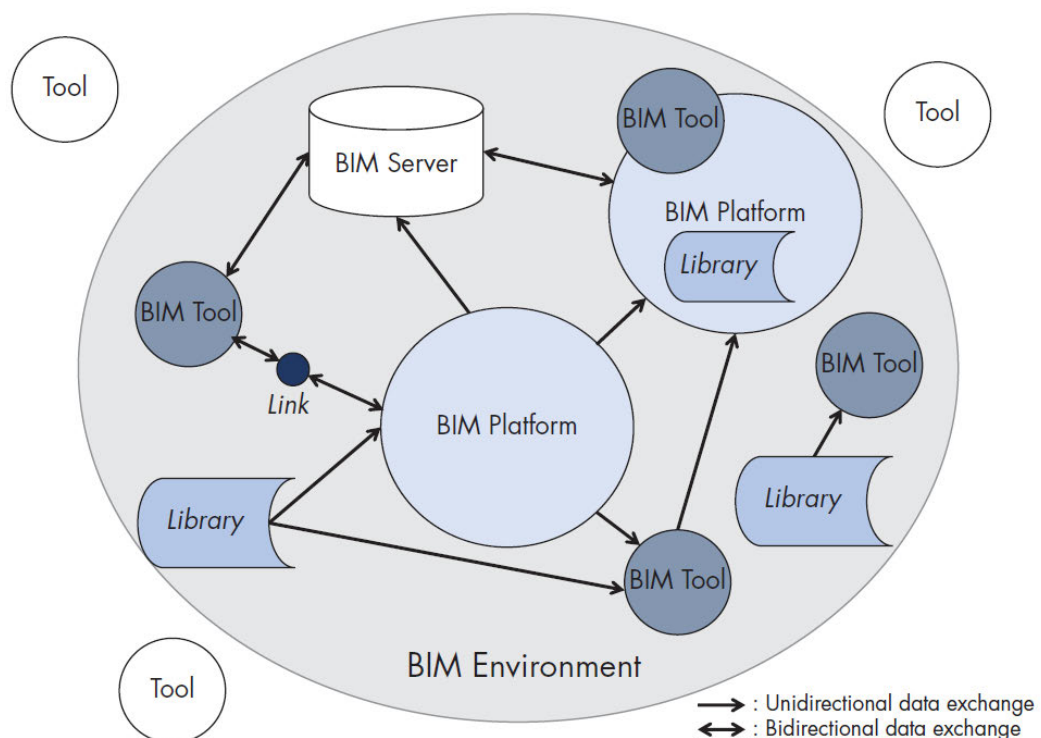


Figure 2.2: Different components of the BIM environment (SACKS et al., 2018).

The complete system is described as the BIM environment. It consists of one or more BIM platforms, additional tools and libraries as well as an optional

server. The BIM platform is the core of the system. It handles the BIM building model and combines information from different interfaces. Another part of the BIM platform is the authoring tool, which handles the information integrity through different project stages and data transformations. Most platforms also incorporate several BIM tools. Examples are software like Revit and Allplan, which include rendering and drawing tools as well as libraries and interfaces.

Additionally to the platform, different external libraries and tools can be integrated to extend the functionality of the system. Also, with the process of clouds and server-based applications, a BIM server can provide an interface between different users. Therefore, models can be assessed from anywhere, without the need to transfer files between different users.

Often, with referring to BIM, the actual building model is addressed. This wording is problematic, since the BIM environment encompasses much more. Therefore, the model itself is referred to as a BIM model.

2.3.2 Dimensions of BIM

The transition that is made in many businesses right now is not easy. To jump from conventional paper or 2d digital drawings to a BIM-based workflow, which is connected to the models of other project participants, is not really feasible. Often, these transitions are adopted through several steps. These can be distinguished with the terms closed and open BIM as well as little and big BIM. These represent two considerations to differentiate between the levels of implementation. The context is displayed in Figure 2.3.

closed vs. open BIM

Closed BIM is describing the use of software which is only provided by one vendor. Therefore the software and data exchange is closed and other programs cannot access it, because of limited data formats and interfaces. Open BIM, on the other hand, represents the method of neutral exchange formats and interfaces. This leads to a completely free choice in software and the project can be accessed by everyone who can operate compatible software. Therefore, additional value is added to the process of BIM by moving to the top of Figure 2.3.

Little vs. big BIM

The term little BIM describes the use of BIM in limited use cases and a specific field, as well as single life cycles. Therefore, each company or discipline is using a different digital model, specifically designed to one project phase. With these circumstances, producing a BIM model for such a small use case is very time consuming and expensive in comparison to the benefits achieved. By moving from left to right in Figure 2.3, more disciplines and life cycles are combined in the same model, with the goal of describing the complete building project with a single BIM model. Therefore, the efforts per use case are shrinking.

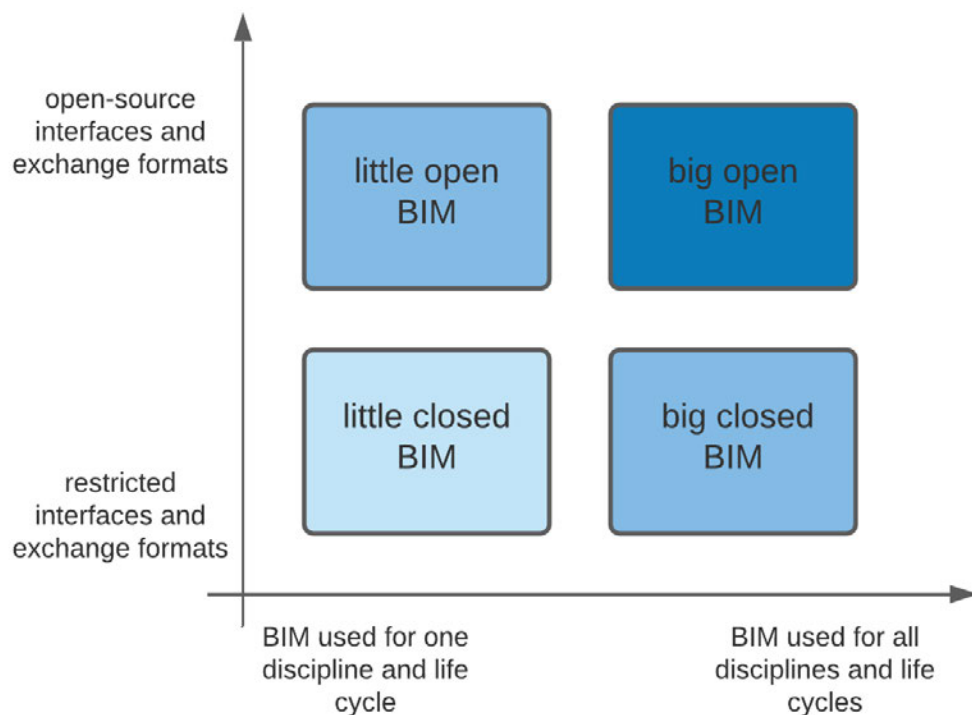


Figure 2.3: Comparison of closed to open and little to big BIM (based on T. LIEBICH et al., 2011).

When these two terms are combined, it should be aimed for big open BIM, to optimally exploit the technology.

2.3.3 Data Exchange

The data exchange between BIM projects and other programs, like third party calculation tools, can basically be divided in three different methods which are described by SACKS et al. (2018).

The first is a direct link approach. It is most common, in the case that one business is providing software for the digital model and also for further calculations or data usage. It is also possible that different businesses have joined forces to provide a seamless interface between their products. These links are mostly put into execution through APIs and therefore another program or extension is necessary to transfer data from the BIM model to consecutive applications. The first method falls within the scope of closed BIM.

The second solution is a file-based data-exchange. Data is written to a file by the software that is managing the BIM-model. That file is then read by the subsequent tool. This has certain requirements for the file-format. It needs to be defined, which information is included and in what matter, which is mostly controlled by standards. If this file format is open source, big open BIM can be realized through the second solution.

The last and most modern approach is the data exchange through a Database Management System (DBMS). With this method, the model is saved in a space that is accessible everywhere for all participants and can be modified by several editors at the same time. Mostly, these are cloud systems that merge all the data from different participants and can provide detailed registers for materials, construction parts or physical properties if included. Additionally to functioning as a data exchange format, a DBMS has some benefits during the project development phase which are described by LOGOTHETIS et al. (2018). Especially avoiding inconsistencies in the model is to be highlighted here. Because no separate models are generated for local work, no inconsistent changes can be made while the DBMS is checking for errors. The third solution requires an open BIM approach and the integration of developed solutions into the existing BIM environment.

Bill of Quantities

"Bill of quantities (B/Qs) is an essential document in a construction project which provides the detail of the contract amount" (RAZALI et al., 2014). It therefore represents a data exchange format referring to the first solution. Through this document, a service provider can easily communicate which costs are to be expected at which point. A semi- or fully automated creation is thus a logical step towards full BIM use. As a drawback, RAZALI et al. states already in 2014 that the use of B/Qs is decreasing, because new methods are replacing it. These include new tools for cost estimation, which replace the time consuming step of manually establishing a B/Q.

2.3.4 Industry Foundation Classes

For the second and third methods of data exchange within a construction project, an open exchange format is needed. Through the literature review, the IFC is recognized as the most common used format for this method. It is therefore investigated in more detail. IFC as a format is evolving since 1994 until today. Before that, there were several attempts by different smaller collaborations to define unified exchange formats. Nevertheless, IFC was the project with the biggest adaption rates (BORRMANN, BEETZ, et al., 2018). It originated from a joint effort by several US-based companies, notably Autodesk is one of them, to create a new standard for open exchange between digital models.



Figure 2.4: IFC Releases since 1995 (Based on BUILDINGSMART, 2021 and D. T. LIEBICH and WEISE, 2017)

They formed an alliance with the name International Alliance for Interoperability (IAI) and the official start for development was in 1995. In January 1997, the first version (IFC 1.0) was released which only covered very limited functions mostly referring to the architectural sector. With consecutive versions, the function range constantly rose. In 2006, the consortium behind the standard changed its name from IAI to buildingSMART and is since then operating under this name.

In 2007 IFC 2x3 TC1, a further addition to the latest version, was released and is still listed as an official Version. Additionally, IFC4 was released first in 2012 with the latest issue in 2017 (BUILDINGSMART, 2021). Therefore, software still supports IFC 2x3 TC1 and IFC 4 ADD2 TC1. The most recent version is used by many public authorities since it was established as an ISO standard and is even obligatory to use in many private projects (BORRMANN, BEETZ, et al., 2018).

Technical Implementation

Figure 2.5 displays the typical object structure of a building model. The first layer incorporates the building site, which is one per BIM model in the most cases. The second layer includes the building itself, the storeys and places. In this layer,

every location inside the model is defined. The third layer then describes the different products, which consist of objects. The objects incorporate additional geometric and non-geometric information.

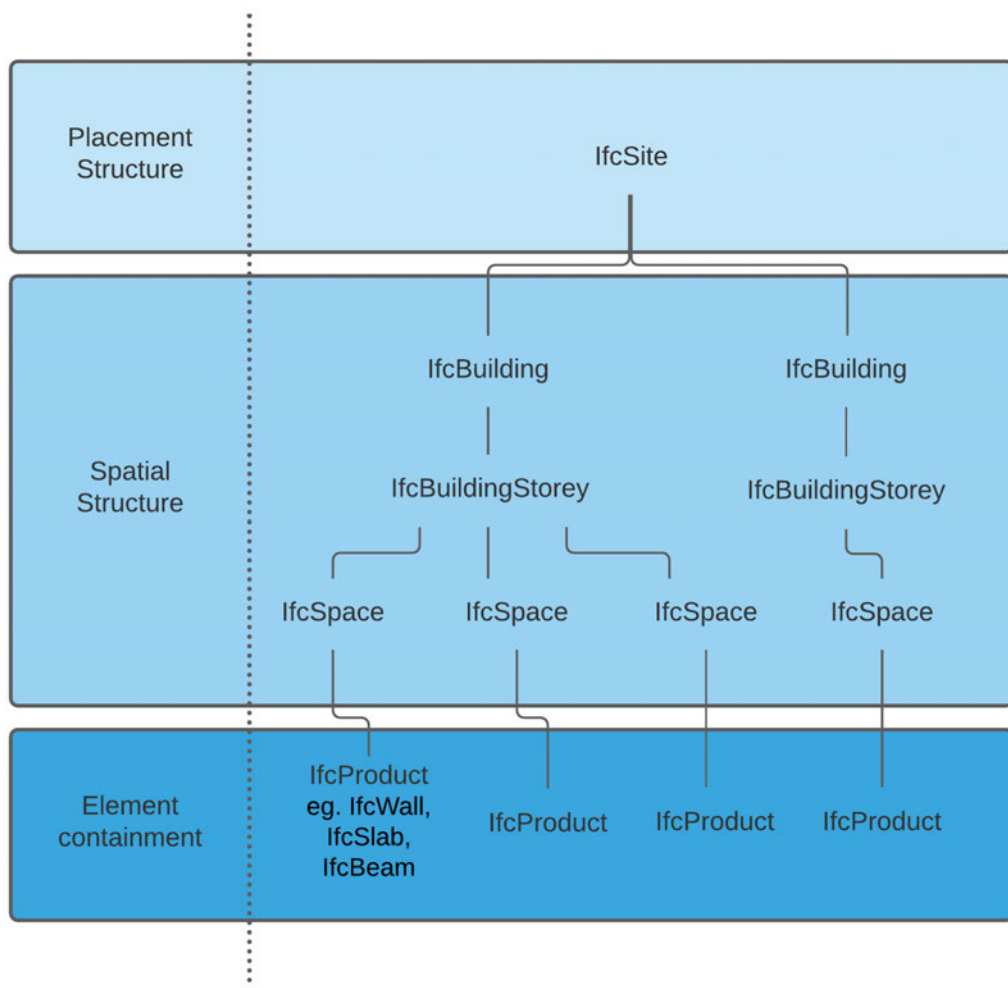


Figure 2.5: Hierarchical illustration of IFC Objects (Based on ZIMA, 2017)

Besides the structure depicted in Figure 2.5, the object-oriented implementation of IFC is described by BORRMANN, BEETZ, et al. (2018). On the data model level, the higher layers can reference lower ones. The core layer incorporates basic classes, which can be individualized by higher layers, and the core kernel. Through the kernel classes, like `IfcObject`, `IfcRoot` and `IfcActor`, three core extensions are derived. Those are Control Extension, Product Extension and Process Extension. Figure 2.6 depicts the structure of the IFC data model.

Directly above the core layer is the interoperability layer. It represents an interface between the core and domain layers. The later depicts the top layer, which defines different domains. Through the top to bottom hierarchy, every class of one of the lower layers has to be assigned to one of the domains. The

classes defined in the top layer resemble the different disciplines of construction, eg. the architecture domain, building controls domain, hvac domain and construction management domain. Some typical disciplines are further divided into sub-disciplines, which are then represented by a domain.

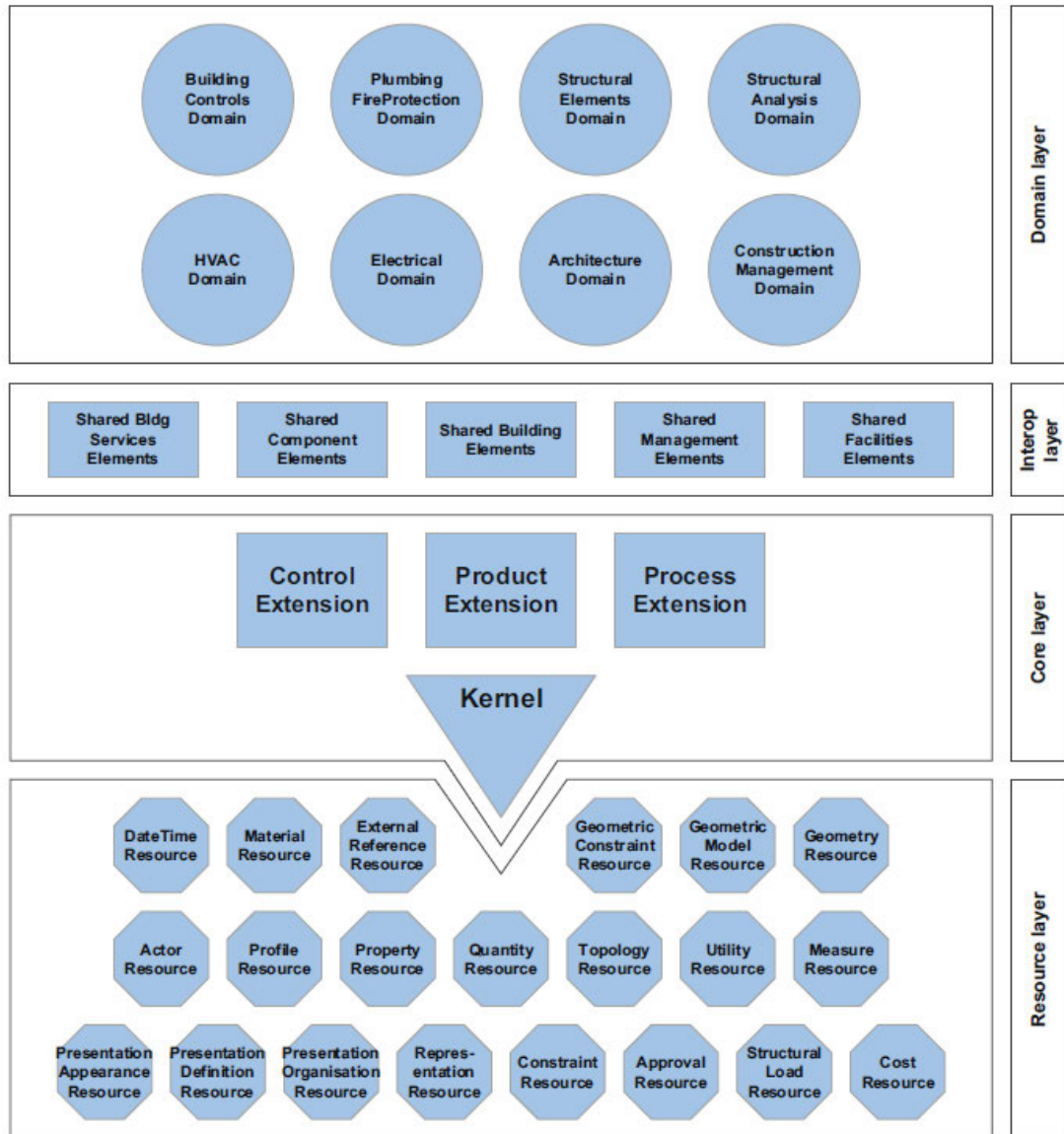


Figure 2.6: Data model structure of IFC (BORRMANN, BEETZ, et al., 2018)

The lowest layer represents classes that cannot exist without being referenced to one of the classes above. They incorporate basic geometrical, material or topology information.

Due to this structure, the IFC data format is extremely flexible. More data can always be added to the objects in hindsight, which enables the enrichment of the model during the planning process. Therefore, it is important to use a defined level of information, like the LOD. (BORRMANN, BEETZ, et al., 2018)

IFC and LOD

In Figure 2.7, an example for the technical implementation is given over the different LODs by SCHNEIDER-MARIN and ABUALDENIEN (2019). As information in the model is enriched during the progressing development process, IFC objects might be divided to several others or extended. In the example, only the geometric information changes from LOD 100 to 120. In the next step, from 120 to 200, material group information is added to the semantic part and the geometric object is again extended with outer measurements. In LOD 250, the opening with geometric measures is included, in 300, layers are differentiated and instead of a material group, the specific material is defined. Additionally, the geometric information now corresponds to a geometric volume.

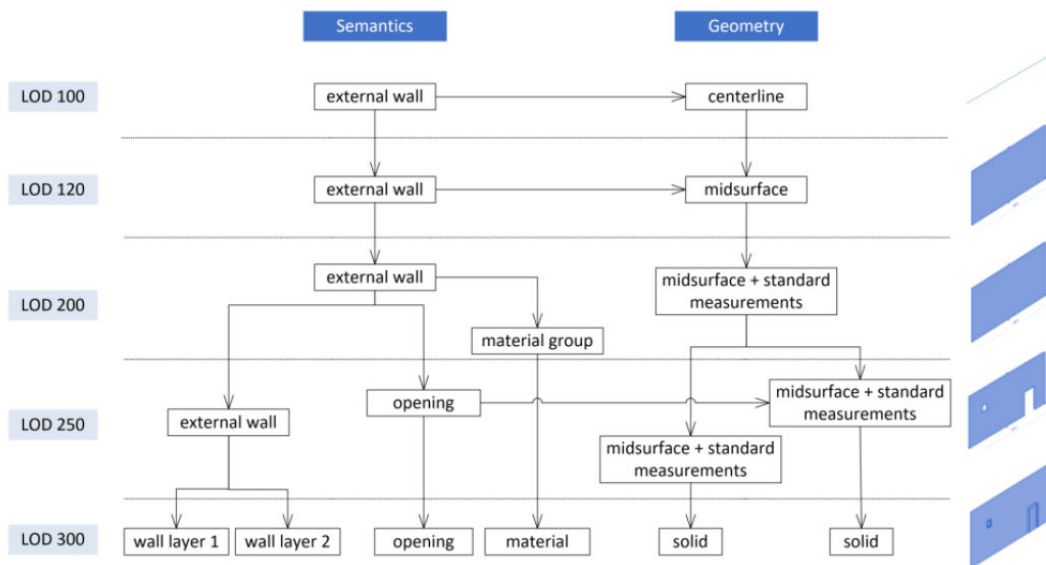


Figure 2.7: Information included for an external wall in different LODs (SCHNEIDER-MARIN and ABUALDENIEN, 2019)

The distinction between semantic and geometric information is specifically highlighted. According to the definition of BIMFORUM (2020), semantic information may be included in LOD 200 and 300. In the example, this corresponds only to the material and material group, but can also include cost or other information relevant to sustainability analyses.

2.4 Life Cycle Assessment

To calculate environmental assessments of buildings, construction projects and the phase of life of a building, the life cycle assessment is the method of choice. Over the last decades, LCAs have become the norm for the purpose of calculating environmental impacts of products and building projects. "A LCA refers to environmental aspects and potential environmental impacts over the course of a product lifetime from the production of raw materials over production of the product, usage, waste processing, recycling to the final disposal (namely from cradle to grave)" (DIN EN ISO 14040, 2021) This definition given through the International Organisation for Standardization (ISO) and adopted through the DIN:EN ISO 14040 and 14044 by the German Institute of Norming, leads to a holistic analysis of all environmental aspects of a product or building project.

In 1997, the first standard for calculating a LCA was released and since 2003, ISO and European Committee for Standardization (CEN) are releasing separate standards for the construction sector. The most recent version is the DIN EN ISO 14040 (2021, February), with additions from 2020. (BUYLE et al., 2013)

2.4.1 Methodology

General Framework

The approach for LCAs consists of four steps which are represented in Figure 2.8. The first is a goal and scope definition. As the name suggests, the objective of the analysis and a framework for the process needs to be established. "The scope of the study should be sufficiently well defined to ensure that the breadth, depth, and detail of the study are consistent and sufficient for the stated objective" (DIN EN ISO 14040, 2021).

The second step is an inventory analysis, which is defined as a Life Cycle Inventory (LCI). This incorporates analyzing all in- and outputs of the product or building during its lifetime. It leads to unprocessed data which will be handled in the next step. Certain prerequisites have to be considered for data sources and handling. "Data quality should be defined by certain characteristics describing both quantitative and qualitative aspects, as well as the procedures for collecting and using these data" (DIN EN ISO 14044, 2021, transl.). Derived from this statement is the necessity, that the data source has to be valid and inconsistencies have to be observed. Missing datasets, for example, have to be explained through a justified "non-null value", a "null value" if reasonably

explained or a calculated replacement value, that relies on a similar estimation process (DIN EN ISO 14044, 2021).

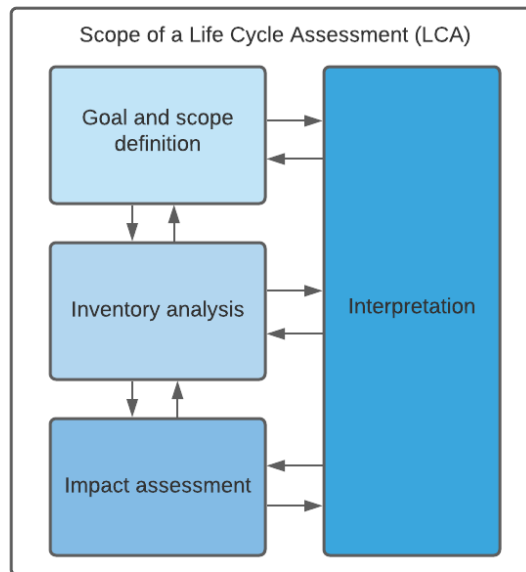


Figure 2.8: Standard Methodology of a LCA according to DIN EN ISO 14040.

The third analysis step is called the impact assessment or Life Cycle Impact Assessment (LCIA) and consists of using the raw data and data from environmental databases as, for example, the Ökobaudat in Germany or the international ecoinvent. Both are multiplied to result in a value for the environmental impact. A certain amount of concrete can therefore be quantified. The result is, for the example of using the Global Warming Potential (GWP) as an indicator, expressed as kg CO₂-equivalent (CO₂-equi.).

In the fourth LCA step, these results will be interpreted and compared to other similar products or construction projects, as well as to the established scope and goal. "The evaluation phase may address the iterative process of reviewing and revising the LCA study framework, as well as the nature and quality of the data compiled in a manner that meets the established objective."(DIN EN ISO 14040, 2021, transl.) Differences and similarities can then be used to explain the positive and negative properties of the project, or adjust the scope and goal for a better result. (DIN EN ISO 14040, 2021)

Life Cycle Phases or Modules

The environmental data, which is multiplied with the raw masses of a building, is divided into several modules. Figure 2.9 is showing the separation of building life cycles according to DIN EN 15978:2012.

The modules A1-A3 represent the production phase, from sourcing the materials, transportation to the factory and production of the building material. Modules C3 and C4 refer to the waste treatment and disposal. The modules A4-A5 and C1-C2 are referring to the on-site construction and demolition process. All modules encompassed in B refer to the use-phase of the building. This includes repairs, replacements and also operational energy and water use. Module D crosses the system boundaries and represents calculated values of waste material in the case of "reuse- recovery- and recycling potential"(transl.). (DIN EN 15978:2012, 2012)

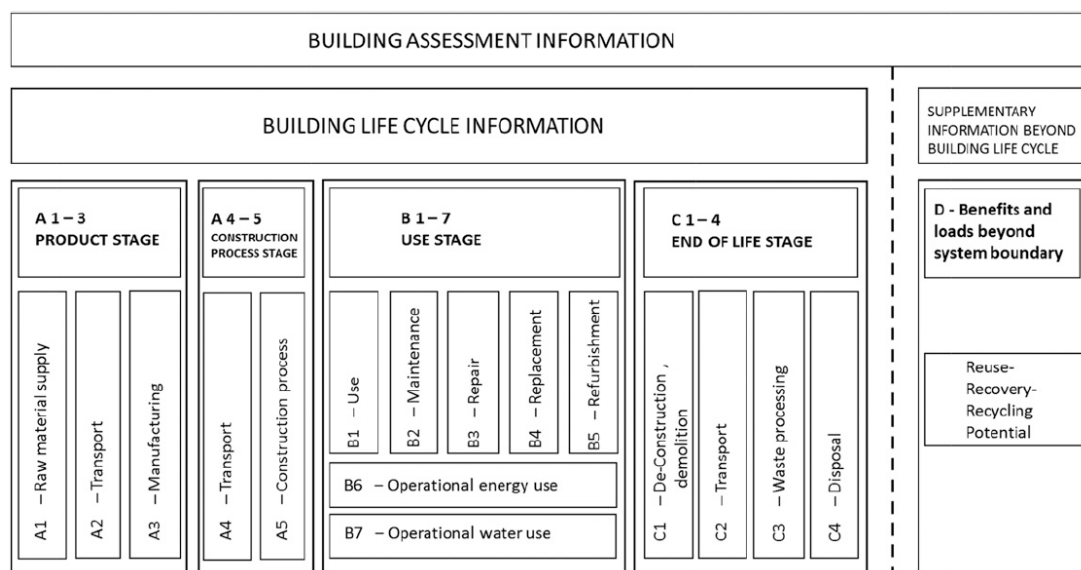


Figure 2.9: Modular information for the different stages in life cycle assessment according to DIN EN 15978:2012, 2012

The modules referring to on-site processes (A4-A5 and C1-C2) and module D are questionable in their accuracy. For the first, processing on-site underlies many fluctuations between different building sites and data gathering is hard during the construction process. Therefore, many datasets are missing both values or databases are not at all considering them in the first place (KBOB, 2016 and ecoinvent ASSOCIATION, 2021). The potential of module D can, at the earliest, be exploited after the whole life cycle of 50 years or more. Due to this long lifespan, recycling methods of the future would need to be taken into account. (HAFNER and RÜTER, 2018)

Indicators

Environmental indicators are values, which are assigned to the material datasets. As described in the General Framework of LCAs, these indicators are multiplied with the gathered data of the building.

The Table 2.1 gives an overview of recommended indicators for different sources. The first document, the "*Kriterienkatalog Gebäude Neubau*" is published by the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) and serves as a guidance document for the DGNB building certification. The "*Bilanzierungsregeln für die Erstellung von Ökobilanzen*" by Bewertungssystem Nachhaltiges Bauen (BNB) is published by a German ministry and serves as a guidance document for all LCAs made for the German region. The "AIA Guide to Building Life Cycle Assessment in Practice" document by the AIA serves the same benefit for the North American region. All three are recommending a similar set of indicators with a few differences.

Table 2.1: Environmental indicators referred to different LCA recommendations (DGNB, 2018 and BMU, 2015 and AIA, 2016)

Environmental Indicators	Environmenta I Reference	DGNB	BNB	AIA
GWP – Global warmen potential	kg CO ₂ -equi.	x	x	x
ODP – Ozone (layer) depletion potential	kg CFC ₁₁ - equi.	x	x	x
POCP – Photochemical ozone creation potential	kg C ₂ H ₄ -equi.	x	x	
POFP – Photochemical oxidant formation potential	kg NMVOC-equi.			x
AP – Acidification potential	kg SO ₂ -equi.	x	x	x
EP – Eutrophication potential	kg H ₃ PO ₄ - equi.	x	x	x
ADPE – Abiotic resource (fossil fuel) depletion potential	kg Sb equi	x		x
Ecological Toxicity	g 2, 4-D-equi.			x
FW – Fresh water	m ³	x		x
PE – Primary energy	MJ/kWh	x	x	
PENRT – Total primary energy non renewable	MJ/kWh	x	x	
PERT – Total primary energy renewable	MJ/kWh	x	x	

Each indicator has a reference unit, which standardizes multiple calculated values to one. For example the GWP is stated as kg CO₂-equi.. In the process of standardization, all emitted gasses that have an influence on the GWP are normalized to CO₂. This includes, for example, methane, which is quantified by 28, since 1kg of methane has the same estimated influence on global warming as 28kg of CO₂. (EPA, 2021) Another factor that has influence on the selected

indicators are the databases, which might not represent all the recommended. This will be investigated in Section 2.5.1

Challenges

Following the standards DIN EN ISO 14040 and DIN EN ISO 14044, the methodology of a LCA analysis is strict but also adaptable at the same time. The bigger framework is very clearly defined, the details are subject to a scope of interpretation which lies in the execution. Here, transparency is important to keep the ability to compare different analysis from each other.

Another problem refers to databases, which often have varying consistency over many datasets. Therefore the set of modules used in an analysis has to be limited or the empty datasets need to be replaced through external Environmental Product Declarations (EPDs). EPDs are provided mostly by manufacturers or institutions to define the environmental impacts of one specific product and typically comprise the usually used modules. They are standardized under the norms ISO 14025, ISO 14040 and DIN EN 15978. This leads to the fact, that the information is reliable and transparent, even though it is provided by manufacturers themselves. Since EPDs are defined, among others, by the same standards as LCAs, the same indicators are represented. (MORO, 2019)

Additionally to this difficulty, HOLLBERG (2016) mentions more critical points. Many problems occur because of the long life cycle of buildings. In most cases the moment of the analysis lies ahead of the construction as well as the living phase of the planned building. Therefore, not the actual product can be assessed, but rather the future plans. When the planners represented the possibilities well and the adaptations remain little, the result is still valuable, otherwise adaptations in the analysis have to be made as well.

2.4.2 Environmental Databases

Several environmental databases are available, to derive the different material datasets from. In Germany, the best known is the Ökobaudat, since it is published by a Germany ministry and freely available (BMI, 2021). The database can be searched online for individual datasets or downloaded as a whole as a .csv table. Therefore, it can be sequentially read by a software. The Ökobaudat includes all datasets which were recommended by the DGNB and BNB documents. All previously described modules are included in the

Ökobaudat, however, the modules A1-A3 and C3-C4 are represented with the most consistency. (BMI, 2021)

The Ecoinvent represents "the world's most consistent and transparent life cycle inventory database" (ecoinvent ASSOCIATION, 2021). It can only be accessed with a corresponding license and is available in the ecospold2 format. This format was exclusively developed for the Ecoinvent. The database can also be derived from other sources, for example the openLCA Nexus (openLCA NEXUS, 2021), where it is prepared and transformed to be used with different software.

It includes by far the most environmental indicators of the investigated databases. For example are all indicators described in Table 2.1 available in several versions, referring to different time spans, for example the GWP referred to 20 and 100 years. When a prepared version is available, the data can as well be read by a dedicated software and therefore imported to a database. The life cycle modules in the Ecoinvent are represented as activities. This means, that each dataset has a description in its name, which refers to an activity. These are, for example, production of concrete, market for concrete or waste treatment of concrete. (ecoinvent ASSOCIATION, 2021)

The third featured database is the "*Ökobilanzdaten im Baubereich*" provided by KBOB (2016). In the further thesis, it is referred to as the KBOB databases or KBOB. It includes the GWP, Primary Energy (PE) and a third indicator, which is exclusively used in Switzerland. It was introduced by a ministry of the Swiss government and uses several ecological factors standardized to one value (BAFU, 2014). The KBOB provides datasets for around 280 materials in the construction category, as well as some other categories which represent different topics of buildings. These are, for example, building equipment, transportation or energy. The modules represented in the KBOB are fabrication and elimination, which refer to A1-A3 and C3-C4. The database is freely downloadable in the .csv format, which can be read by software. (KBOB, 2016)

2.5 Life Cycle Costing

Additionally to the environmental assessment, sustainability includes the ecological properties of products. To address this aspect, LCCs are the established method. PLINKE and UTZIG (2020) define it as "Life Cycle Costing (LCC)[, which] identifies as a set of methods for the ecological planning, regulation and control of objects across their entire life cycle." Furthermore it is stated, that the first LCCs were used in the 1930s by the military for huge provisioning projects. Therefore, the method is already much older than the first LCAs. Later in time, the method was transferred to other major projects and used to optimize the ecological features. These include, for example, monitoring maintenance and energy costs and foreseeing necessary replacements and refurbishments, to budget them. (PLINKE and UTZIG, 2020)

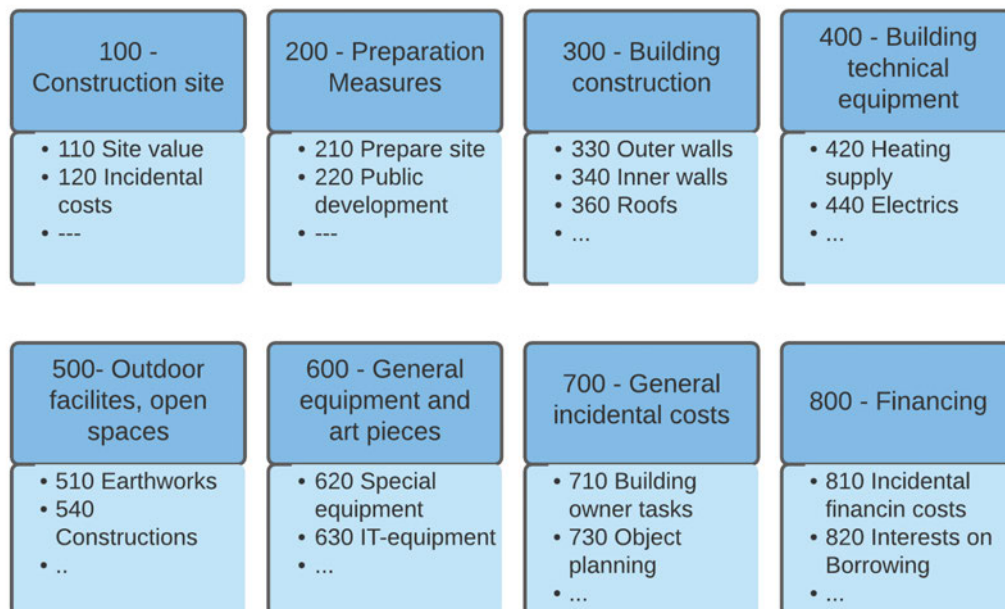


Figure 2.10: "Summary of cost types defined through DIN 276. Not all subitems are represented"(DIN 276, 2018)

The process itself has many similarities with a LCA when considering the framework. Today it is standardized through the DIN 276 (2018), DIN 18960 (2020) in Germany and ISO 15686-5 (ISO 15686-5, 2017) internationally. It is similarly to the LCA divided by the same module system shown in Figure 2.9. For modules A and C, the calculation is related. It is defined through the DIN 276, which focuses on the construction and demolition phases. DIN 276 also defines different cost types for different parts of the building. These cost types range from 100, construction site, over 300 and 400, building and its technical equipment, to 800, financing. Therefore, all costs can be described through a

type. An overview over the cost types can be extracted from figure 2.10. Here, masses or part counts are multiplied with standard prices to receive a total cost value. The costs are either retrieved through a database or directly from the supplier. ISO 15686-5 is specifying, among other things, the running costs of a building, namely module B. Additionally to the ISO norm, the DIN 18960 gives a specific definition of the submodels incorporated in B. (MORO, 2019)

The general framework of a LCC is established in the beginning of the process. Here, options are between a limited or holistic analysis. The first includes all important factors of costs like the construction, demolition and the use phase. A holistic analysis includes revenues as well. The time frame which is assessed is often a dedicated span, because LCCs can easily surpass the life span of a building, which by itself is too long of a time period for many clients. Even with the narrower assessment, the use phase is often hard to predict because it is dependent on many factors like users, long term changes in weather etc. Limiting the fluctuations of an unpredictably long life cycle is another reason for a fixed time period. As well as the methodology, also the difficulties occurring in LCCs are similar to the ones in LCAs. For once, it is fixed in time and viewpoint. Developments which will inevitably happen in the future cannot be taken into account today. It is also possible that demolition and recycling will become a lot cheaper with the progress of robotics. (PLINKE and UTZIG, 2020)

2.5.1 Cost Databases

Other difficulties concern the availability of data. Software for this case is supplied by a few businesses, which includes databases for regional and component based costs. Examples for this are "*Dynamische Baudaten*" by the f:data GmbH (DBD, 2021) and "*BKI Kostenplaner*" by the Baukosteninformationszentrum Deutscher Architektenkammer GmbH (BKI, 2021). They will be addressed as DBD and BKI databases in further chapters. Both are used with a demo access, therefore, only manual extraction of datasets is possible. f:data GmbH has noted on request that an API access is possible, to develop a software that uses the cost database. However, the license must be purchased together with the software by each user.

Both databases include a catalog of building components as well as individual materials. As already mentioned in the previous section, the data for a LCA is coherent to the different materials. In many cases, cost data is linked to building components. The reason for this is the big share of personnel costs included,

whereas the environmental impacts are mostly dedicated to production and disposal.

2.6 Database

2.6.1 Fundamentals

Since digital data has become available through the invention of computers, the need of digital storage was created as well. Small or seldom accessed amounts of data can be stored on hard drives, floppy disks, compact discs or analog tapes before that and then be put away in a closet until they are needed again. Huge amounts of data on the other hand, which not only need to be stored but also re-accessed or manipulated for further work steps cannot be handled by hand. The solution to this are structured databases, which are already in use for some decades. (BEGG and CONNOLLY, 2014)

Even though the IT-industry is one of the fastest changing industries we have, some principles seem to be made to stay. Examples are the PC architecture, some programming languages invented in the 70s, f. e. C, and the relational model, on which most databases are still build today. The relational model was as well invented in the 70s and is based on tables, which contain information, and relations between those tables to give the data a structure. To handle this framework, Structured Query Language (SQL) was invented shortly after the concept of relational databases. SQL is still the most important concept regarding databases today, even though non-relational ideas have evolved over the time of decades and are now summarized under the term NoSQL. The latter are mostly developed to counter the weaknesses of traditional SQL databases and experience a huge growth over the last decade. (GERKEN, 2018)

2.6.2 SQL vs. NoSQL

The concept of SQL is, compared to other information technology, rather inflexible. Information is always stored in tables, which are linked through key attributes. To manipulate the data, SQL was added as sort of a programming language. Benefits of this system are especially the ease of use. Even though queries stay mostly simple, a huge amount of information can be accessed in the form of tables or sets. The straight forward form can even enable humans to read the database without a special system, which makes relational

databases easy to understand, even though the concept was expanded since its introduction. (KLEINSCHMIDT and RANK, 2005)

This was necessary to keep up with the fast development, which has happened over the last decades and is still gaining even more momentum as new technologies are explored every year. Additions are more complex data management systems and new versions of SQL-based programs. These sometimes introduce new commands or just a more versatile application interface for faster handling. Still, the relational model is not able to fulfill all the needs of some applications. (MEIER and KAUFMANN, 2019)

Here, NoSQL has emerged to fill the gap. The concepts developed under this name are not bound to the relational model, tables and links between those, but can take a huge variety of forms, e.g. graph-, document- or key-value-based. This enables non-relational databases to be very flexible regarding the variants and velocity of data that is stored. Two important points concerning the advancement of Big Data, which is further described in Section 2.6.3. (GERKEN, 2018)

2.6.3 Big Data

Big Data is a commonly known term, which is located not only in specialized articles any more, but also in general publications. One reason for this is the huge hype the expression has experienced. But the definition of Big Data itself is not as easy as one might think. It relies on a minimum of three criteria, also called the three V's (GHAVAMI, 2021).

Those are volume, velocity and variety and each is on its own surpassing the boundaries of traditional databases. They are illustrated with an explanation in Figure 2.11. With the internet and especially everybody connected to it at all times, the amount of data that can be gathered by big companies is multiple times higher in comparison to last decade. And even the 2000s have experienced far more data availability than the 90s. Therefore, the volume big companies are storing is in the magnitude of petabytes. In contrast, a major building project has only taken about 3 Gigabyte of scanned drawings (SACKS et al., 2018).

Additionally, the data is gathered all the time and can change at every second and has therefore to be processed at real time, which represents the second V. With mobile phones and even smaller devices connected to the internet, which often monitor not only our location but also body functions and personal

communication, the availability of real time data is given anytime. The third V is represented by the type of data. In its beginnings, the internet mostly consisted of pure text in only a hand full of formats. An example for big data gathering are social networks, where thousands of words, pictures, voice messages and more are transferred every second. (FASEL and MEIER, 2016)

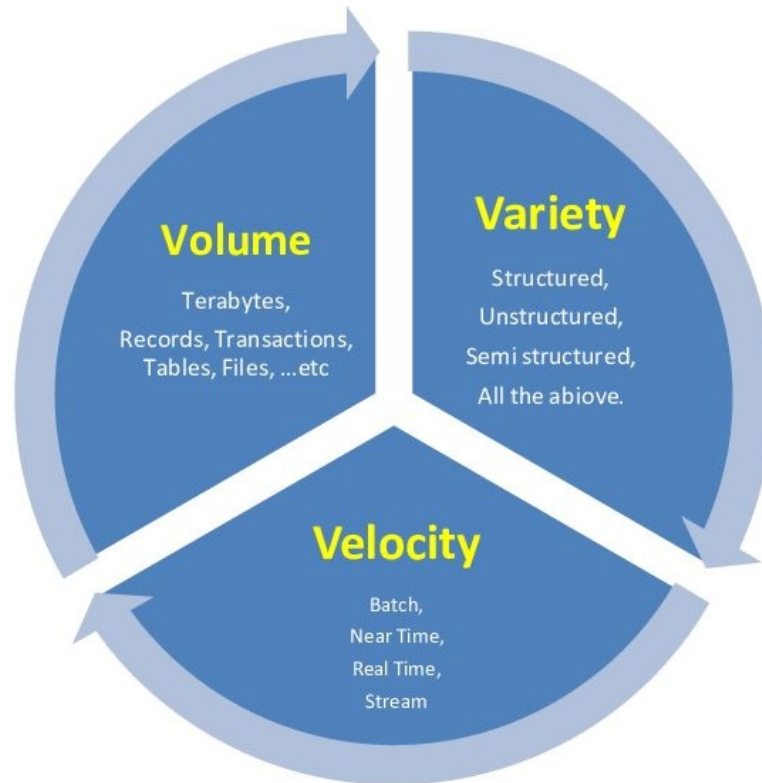


Figure 2.11: Visualization of the three V's of Big Data. (AL-BARHAMTOSHY and EASSA, 2014)

3 Methodology

3.1 General Framework

3.1.1 Hypotheses

The goals of this thesis are clearly defined by the research questions in Section 1.3.2. The four established questions can be distinguished thematically. Question 1 and 2 correspond to combining data from different sources in a database framework. Questions 3 and 4 correspond to the possible environmental analyses with a BIM model from different LODs and what data can be supplemented to the model for more refined analysis processes. Each question will subsequently be investigated and for each a hypothesis is established.

Research Question 1:

- How can data regarding multicriterial properties of materials be combined in a database framework to provide a basis for comprehensive analysis methods?

The aim resulting from the first, is to create a joint database for sustainability assessments, focusing on LCA and LCC. The factors of sustainability usually include the ecological, economic and social. For the first two of these drivers, there are already established methods for studying buildings. Although the third, the social aspect, has not appeared in many studies so far, it is nevertheless getting more and more attention in the debates, as pointed out by LLATAS et al. (2020). For these reasons, the first hypothesis is limited to the cost and environmental impact of building projects. Nevertheless, the possibility of including other factors at a later stage should be kept open.

Hypothesis 1:

- With the appropriate database design, various criteria can be included in the automated calculation of a construction project's sustainability impacts.

Research Question 2:

- How can different design and component alternatives be implemented in a database to enable an optimization through analyzing different variants?

The second research question regarding sustainability analyses relates to the comparison of variants in the early design phases. These offer the advantage of enormous flexibility in terms of materials, building designs and architecture.

Hypothesis 2:

- The comparison of variants, materials and designs of a building project in automated calculations is possible in the early design phases if appropriate interfaces and data structures are considered in the execution.

Research Question 3:

- Which information for an automated, multi-criteria building analysis is already contained in an early phase BIM model?

The third and fourth question relate to the information content of an early design BIM model. However, the third alludes to the fact that the necessary information may already be available in the usual model. It is important here, to distinguish how far the automation of the process should be taken. Presumably, different users also have different requirements for the building model, or for the information in the calculation that is to be influenced. Furthermore there are big differences between different LODs, even if they are adapted to the early design phases. Thus, for each LOD, and for interim steps between the levels as well, there should be a detail grade of analysis possible with the information included. The hypothesis is elaborated from these prerequisites.

Hypothesis 3:

- The minimal information for different levels of automated sustainability calculation is known and therefore, information requirements for the BIM model can be established.

Research Question 4:

- Which information is typically missing an early stage BIM model and which can be complemented?

The fourth question refers to the opposite direction of possibilities. The study starts with the required calculations and then analyzes what information would be needed for this in an early-phase BIM model. Here, too, the requirements of the user and the LOD of the model are very important. Thus, different possibilities for the project calculation require different details of information included in the model.

Hypothesis 4:

- For multi-criteria sustainable building analyses, all necessary information can be obtained from an early-phase BIM model or added to the model early on, according to the requirements of the analysis.

The following project will investigate these four hypotheses and, in the best case, prove them to be true.

3.1.2 Approach

To fulfill these hypotheses, the following methodology is developed. It is depicted in Figure 3.1, where the two project aspects, "Sustainability Database" and "BIM Model and Interface" are labeled as part 1 and 2. The red frame encloses the elements that are performed within the project scope and therefore shows the outer boundary. Outside areas represent input databases (cost and environmental databases) and processes that are necessary to get an automated result, but are not part of this work (calculations and mapping).

Part one is about creating a database. It has to connect data inputs for cost and environmental data. It involves converting established environmental databases into a format which suits the analyses methods and ensures that the possible sources are not limited, which is accomplished by using a standardized data format. For LCA and LCC, price or environmental impact per volume or area is common. Furthermore, the cost data from special databases is imported and stored accordingly linked to the environmental data. This also means finding a common point for the disparate data. The possibility to import other data forms should be preserved (e.g. social factors). For further LCA and LCC calculations, data is then exported in a suitable format. Which data has to

be exported depends on the information accessible in the BIM model. This is geometric information as a minimum and specific material layer information with the highest LOD from the early design stages.

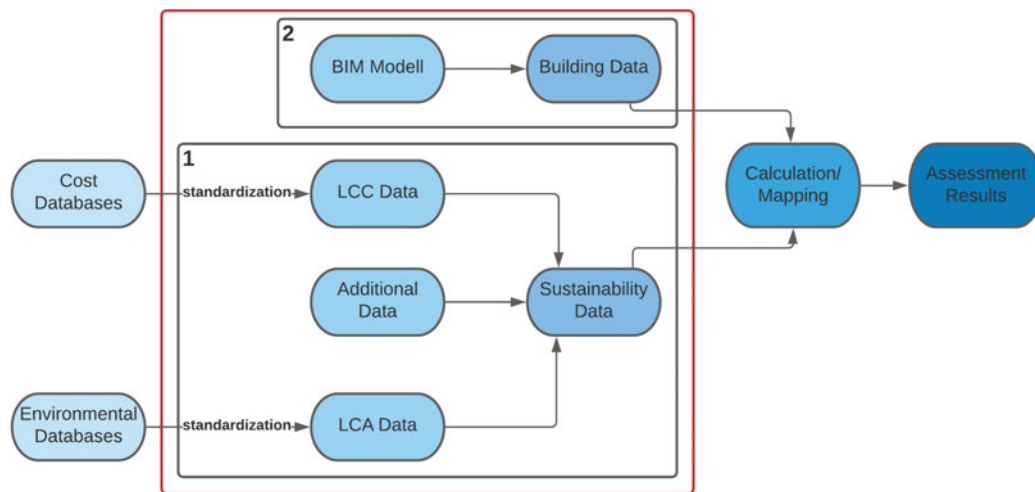


Figure 3.1: General framework represented as a flow chart, including the project boundary and the separation for first and second part.

The second part inside the red frame, the export of a BIM model, consists of reviewing the available data and export possibilities. Here it is to be determined which data is indispensable for the calculation, which is already stored in an early phase BIM model and which absolutely has to be entered manually. Because these requirements are very dependent on how the resulting method is to be used and which data is to be flexibly selected later, there are several possibilities for the interface between BIM model and the sustainability database. These are providing all material and layer information through the 3D model, adding all but geometric information through separate input methods or a mixed approach of both. For each of these possibilities, the necessary input and output parameters vary, which is why they must be considered separately.

In order to clarify this at an example, the use of different components can be consulted. In this example, an architect is developing a new building. The client wants to compare environmental impacts and cost for different variants. A huge building company may have a standard catalog for their projects, which can be provided through a template catalog. On the other hand, if components are established from scratch for a single project, the information can as well be included directly in the building model, since it is very individual. The architect could therefore either use a provided catalog from the construction company or establish several templates in the modeling software, regarding individual requirements. For both methods, the information requirements for the model are different.

For the case study, the automated calculation and manual mapping is established, to prove that part 1 and 2 are functioning properly. Mapping methods are important when investigating different LODs and the resulting possibilities for the project. These include different levels of automated mapping. Therefore, mapping processes will be discussed as well, but not investigated in detail.

After retrieving building data from the model and linking it with sustainability data, an example calculation is performed, with automated exports and manual mapping, in order to validate the project. A completely automated calculation is the logical next step, but lays beyond the scope of this thesis.

3.1.3 Prototypical implementation

Database

The prototypical implementation for this thesis uses several software products. The first part is creating a database for which the free program "MySQL Workbench" was chosen. The reasons for choosing this system are its open-source availability and data access possibilities with a relation SQL-based exchange. According to KAMARUZZAMAN (2021), MySQL is the most popular free-to-use database system in the world. This ensures that other users have already solved many typically occurring problems and that sufficient documentation is available. In addition, with the "Workbench" a program for easy administration of the database via an user interface is available and the possibility to host a local server is given. Through a connection to the server, other programs are enabled to access the database. With the availability of the professional version of the software, the database could be upgraded if the project needs more features in the future.

BIM Modeling

For the second part of the project, a digital example model is created, from which an IFC file is exported. An automated solution is then used to extract information from this export. On the buildingSmart website (2021) there is an overview of which programs are certified to export IFC files according to the latest exchange standards. Among them is Revit, of which the 2021 Version is used. The certification of buildingSmart concerns the export settings and ensures that the corresponding file contains the necessary minimum information. There are several certifications, including one architecture-related and one engineering-

related. The Revit modeling environment enables the user to create models in various levels of detail with prefabricated components (AUTODESK, 2021).

Data Processing Language

For a processing language to handle the database and IFC export, Python was chosen. The main actions performed automatically consist of merging, transforming, or retrieving data from different sources. Python is known to be particularly well suited for these commands, as it specializes in data handling (GALLINELLI, 2021). JetBrains' PyCharm was chosen as the development environment because researchers can use a professional license. The program comes with GIT connectivity and other valuable features for writing code (S.R.O., 2021).

The database connection to Python is established by "MySQL Connector", an extension that allows easy access to the database. Through a so-called connector, SQL commands can be executed directly from the running code on the database. Thus, the writing and reading of data is possible.

For an interface between the IFC model and Python, the IFCOpenShell Package is used. It is a software library, which is specialized on the IFC format (IFCOPENSHELL, 2020). It provides functions to import files in the IFC format, which can subsequently be read through Python code.

Another source used is the published code for the quantity takeoff of eLCA (BBSR, 2021). It is open source and consists of a function, that can extract selected information from an IFC file. It scans the file for keywords and creates an object for each building component. Then, information is extracted from the file and added to the established objects. This includes geometric and semantic information like area, thickness and materials.

3.2 Sustainability Database

3.2.1 Specific Database Framework

The database, which results from the first part of the methodology, has to fulfil certain requirements. These specify that different types of data, such as costs and environmental impacts, should be linked in one database. More precisely, data regarding LCA and LCC. The export must therefore be unified, and the structure must take all units into account. For this, it is necessary to find an overlap to match both datasets. Other requirements, on the other hand, refer to different data sets within the same calculation method. In order to be flexible expandable in the future, the possibility to connect additional data sources should be possible. This hurdle concerns several levels of the database framework.

First, it should be possible to connect other environmental databases, as there are significant regional differences. Material sources and production processes can deviate with different regions, let alone different transportation distances, which depend highly on the location of the building site. All databases used, environmental and costs, contain data related to a specific region. In some cases, e.g. in ÖkobaDat, there are also global values, but these are primarily average values from different regional data sets. If a similar method is to be used in several regions of the world, a specific database must therefore be imported.

Second, there may soon be greater interest in including social factors in existing calculations. As described in section 1.2.1, sustainability relates to this factor in the same way as to ecologic and economic concerns. If new results on this or other aspects to assess are reached soon, corresponding data can be appended to the original structure, hopefully with minor adjustments. Again, an integration point has to be found as an interface for different datasets.

Traditional or Big Data

The three V's of big data must be reviewed to determine which database system is suitable (FASEL and MEIER, 2016). The known and used data sources, like the ÖkobaDat, DBD cost database and IFC exchange format, refer to static tables or text documents. Many of the included data sets are based on a single source, and the type of data is relatively standardized. Environmental databases, for example, differ somewhat in the different columns that are necessary to use the

complete information. However, they all contain one value per environmental indicator and module. These values are always related to the functional units, such as material's mass, volume or area, and can therefore be used with a manageable number of different calculations. The selection of indicators can also vary, depending on the database. The most critical indicators, especially GWP, Total Renewable Primary Energy (PERT) and Total Non-Renewable Primary Energy (PENRT), are stored in each of the databases used, such as Ökobaudat, KBOB and ecoinvent.

The volume of information, the first V of big data, is especially growing during the use phase of building. The reasons are explained in Section 2.6.3 For the sustainability simulations, this condition plays a minor role since the focus lies mainly on the production and disposal of the building. Although the use phase is also an essential factor for the environmental impact and costs, it's excluded from the scope for this thesis. Therefore, the volume of data for this project cannot be expected to explode, and the requirements for the first V are not met.

This fact leads to a database that has to function with a limited range of data types and relatively static data. Therefore, high velocity as well as variety of data, the second and third V's, are not given regarding LCA and LCC data as of now. In addition, the information that can be exported from an IFC model remains remarkably consistent over several versions. Although new minor releases and addendum are regularly made by buildingSMART, these often improve details instead of changing the existing structure of the format (BUILDINGSMART, 2021)

The database, therefore, only needs to be adjusted in the event of major version changes. The data from the IFC-model is not even incorporated directly into the database structure but used in the mapping process. That leads to the necessity of only changing the data interface, which handles the exchange of masses and areas. Hence, an application suitable to process traditionally shaped data will be sufficient in this case.

Consecutively, a SQL-based storage of data can be used to combine cost and environmental information. As described in Chapter 2, SQL-based databases consist of several interlinked tables (MEIER and KAUFMANN, 2019). Thus, the underlying information is split to be able to represent all circumstances only through these tables. In the case of mapping components, however, this is very helpful, as different levels can be mapped as detail levels, providing a simple overview and a detailed storage option. Each table needs unique keys to guarantee the definite assignment of the various tables to each other. The architecture in detail is explained in the following Section 3.2.2.

3.2.2 DB Architecture

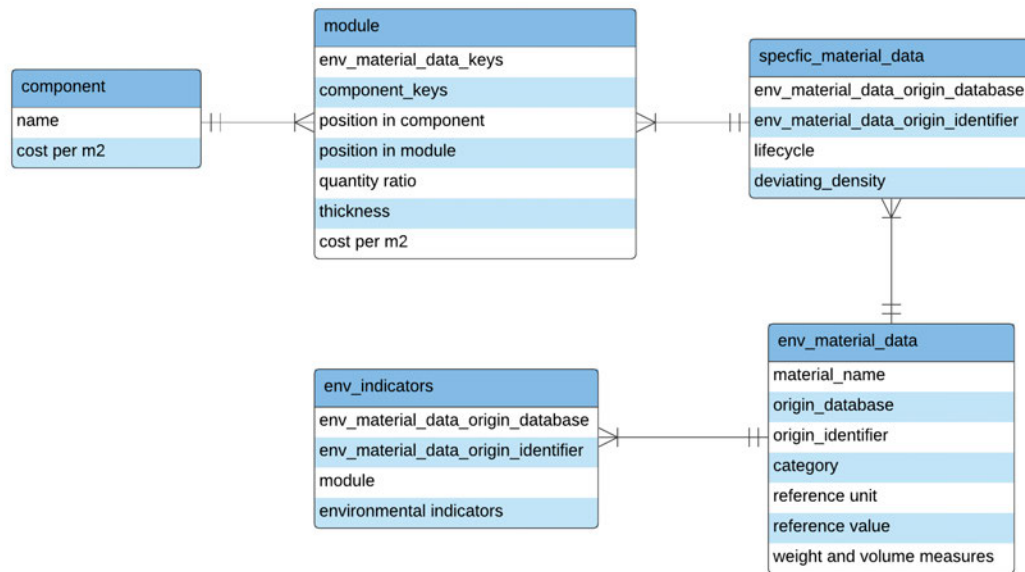


Figure 3.2: Class diagram illustrating the schematic database architecture.

Materials

The resulting database structure is depicted in Figure 3.2. The schema can be considered from the individual material to the component. The main material datasets are represented in the "env_material_data" table. In this table, the imported materials are stored with all relevant information. Essential information is that which is indispensable for the later calculations. Further information concerning the materials can be omitted because the reference to the original data source is ensured. Responsible for this are the two keys, the origin database and the associated identifier. Both are necessary to ensure the uniqueness of each entry.

Further crucial information at this point includes the density and other volumetric measures as well as the reference unit and value. These are later used to assign the material indicators to the quantity take-off of the BIM-based model.

Furthermore, the table "specific_material_data" provides additional information about the service life and a deviating density. These variables allow creating further variations from limited material data sets. For example, a material can consist of the same primary environmental dataset but include different life cycle periods, or a variation of the same dataset with a different density.

Further Material Information

Two connections emerge from the main material table. In "env_indicators", as the name suggests, the related environmental indicators are imported. The separation to the material table was done because of the different modules also known as life cycle phases of materials. In the Ökobaumat database, as described in Section 2.4.1, the indicators are assigned to different modules. Therefore, one entry in the material data table is linked to several entries in the indicator table. Datasets have an entry for production and further entries for the following cycle phases, such as the use and end-of-life phases. These phases correspond to modules A, B, C and D in the Ökobaumat, but are described as different processes in the ecoinvent. Consequently, each database has several entries per material, one for each life cycle phase. These cycles correspond to each other but are not identical, because the underlying life cycle structure for each database is different. This is one significant difference among the original environmental data sources and has to be considered in the structure of the database. In Ökobaumat, the production and assembly process is represented by module A. In KBOB and ecoinvent, one value per material is assigned to the production process. Therefore, the values need to be transferred to the module system of Ökobaumat, to be stored similar in the database, either by mapping the environmental factors to each other or transforming the units if not matching. All information on the material level is dedicated to calculating the LCA.

The second connection to the basic material table is to "specific_material_data". Here, the life cycle period of materials is added and, if needed, a deviating density can be stored as well. The function of this table for the calculation of LCAs will be explained in more detail in the corresponding section.

At this point or also at a later point in time, there could still be a need to store different indicators for materials already entered or further materials with indicators, e.g., from EPDs. This might be necessary if very special materials are to be included in the calculations or a company has calculated their own materials already, and wants to use these results for further assessments. A function could be appended to the python code for this purpose to import the additional information from another table, or the information is manually added to the structure of one of the used environmental databases.

Components

In the table "module", a link between materials and components is made so that both can be flexible connected. By using a table in between material data and

modules, the cardinality from components to materials can be a n:m relationship. In addition to keys and other necessary or helpful variables for working with the data sets, the thickness variable is recorded here. It is later needed for calculating the volume or the area of a module if the reference unit differs from the target unit $1/m^2$. Depending on the quantity of layers, modules represent one or several materials.

In the case that one module layer consists of more than one material, a ratio is used to express the proportion of the respective material in the layer. A good example is reinforced concrete, since the concrete and steel parts share the same layer and can be described with a volume percentage. In this case, the value of "position in module" is the same for two different materials. The costs can be inserted from the described programs in Section 2.5.1 directly per module. The price is linked either to modules consisting of one material or several layers in the cost databases. Therefore, the same structure is applied to the different modules. Components form the last table of the database. They provide an overview of the elements to be examined and the respective costs per component. At the same time, they serve as an interface to the user. By selecting different components, a completely different calculation can be made by making a few changes. This modification works to select other components, resulting in entirely different modules and materials being called up during the calculation.

One problem that remains is, that through the calculation structure in python, when the same material gets used twice in one module, it is only considered once. This is due to the fact that during the gathering of indicator values coherent to the modules, some lines can occur multiple times. To prevent the results from representing too much information, duplicates are dropped during the process. A workaround is to use thicknesses or ratios for identical layers in the component templates. For example can a wall paint be used on both sides of the wall. Then, the ratio can be set to two, instead of adding the layer twice.

3.2.3 Environmental Data Sources

There are several options when it comes to data for calculating LCAs. An overview has already been given in the section 2.4.2. Multiple different data sets are not necessary to do consistent analyses of buildings, since many sources have done so with only limited data. However, the goal of this thesis is not to make a LCA, but rather to prove that different data sources can be

integrated in the proposed framework. Therefore, several databases will be used to prove the hypotheses.

Ökobaodat provides one of the most used environmental databases in Germany. Therefore, it has been selected as the primary data source for environmentally related data. It is specifically designed for the construction industry and is publicly available. It also offers the possibility of automatically importing all data sets through the option of a data download as a .csv file. The disadvantages are partially incomplete data sets and different sources, which may not all be of the same quality. Since Ökobaodat was chosen as the primary source of environmental data, the database structure is based on it. The different life cycle phases are indicated with the modules A-D, and the most important indicators were chosen according to the criteria from section 2.4.1. The database could easily contain more indicators, but this would not add any value to this thesis' research questions.

Other database sources used are KBOB and ecoinvent. Ecoinvent is the most extensive database for environmental data worldwide (ecoinvent ASSOCIATION, 2021). It was possible to use an older version of the database for research purposes. The current version was not available for download in a suitable format, and in some cases, individual data sets could be retrieved. However, since the goal is to automatically process and use the data, it was decided to use rather older data in the correct format than current data without formatting.

Regarding the life cycle of a building, Ökobaodat offers a straightforward assignment to different modules. All available data is imported and stored separated by those modules, although the data for the modules for the use phase as well as the recycling phase is often not available. Only the most common materials have consistent data over all indicators and life cycle phases regarding the Ökobaodat. A solution to this was investigated by STENZEL (2020). Materials are grouped to categories and mean values are calculated for each environmental indicator. Therefore, missing values are represented by similar materials. Additionally, end-of-life scenarios from the Ökobaodat were mapped to matching materials.

With KBOB, this division is only made for two different cycles. The production phase and the disposal phase. This separation allows data from KBOB to be assigned to modules A1-A3 and C3-C4. Ecoinvent does not assign the data sets to a fixed system but each data set is called an activity (ecoinvent ASSOCIATION, 2021). This division means that the materials' life cycle phase is not directly indicated, but a description is included in the name. An assignment was made by recognition of the words "production" and "waste". However, this

only works for some products in the construction industry and serves more as a demonstration that the data structures are compatible other than a real life solution. Other data sets include the same keywords in their names as well. For example, one activity can refer to constructing a complete production facility rather than producing a single material.

In terms of the environmental indicators used, the two other databases, KBOB and ecoinvent, diverge widely. While KBOB only contains three values, UDP, GWP and PE, ecoinvent offers a bigger selection than even Ökobaudat. Additional to all environmental indicators presented in Section 2.4.1, ecoinvent includes gradations for each, considering also a time period. The intersection of the available indicators was selected to compensate for these differences. Therefore, the maximum number of indicators is used without the need to fill in data manually. The selected indicators are GWP and PE. The energy is represented by sub-indicators PERT and PENRT. From ecoinvent, the data set with the mean period of years was selected in each case. It would also be possible to average all or select another single value, but this will not make any difference for the execution of the project because the same values will be chosen for validation.

In addition to importing via the environmental databases, it is possible to add supplementary values for individual materials. This can be used, for example, if information for calculating the environmental impact per square meter is missing. It also offers the possibility to import from other sources to achieve a more accurate calculation. A second input table besides the example components table, contains the materials involved, the source table, the field to be changed, and the new value.

Consistency

For Ökobaudat, this problem concerns mostly missing environmental indicator values. Even though the database provides many life cycle modules, most material datasets are missing at least some values for the living phases of the building. Since other databases seldom provide such a variety of life cycle modules but are mostly limited to a production and an end of life value, a compromise is only to use these modules. Then, Ökobaudat only has very few blank spaces concerning the additional material data.

The available version of KBOB provided nearly all promised data very consistently. Only some end of life values were missing. No additional information had

to be added during the calculation process, but the small selection of datasets would make it difficult to find a complete calculation only on this source.

Even though the available version of ecoinvent is very consistent for all the included datasets and indicator values, additional material information, specifically density or areal weight, was completely missing. Also, the assignment of activities to life cycle modules is not very transparent and differs a lot compared to Ökobaudat and KBOB, which share the mentioned modules. Some additional material information had to be added to the used datasets. The abundance and consistency of different environmental indicators, on the other hand, is far superior to other sources.

3.2.4 Cost Data Sources

However, to prove the first hypotheses, more than just environmental data is to be assessed. An important role is direct comparison of costs and environmental impacts. Also, the component templates, needed for the example project, have to be established. Both can be retrieved from the cost databases since these are designed to calculate authentic components as best as possible. For this purpose, the databases of Dynamische Baudaten (DBD) and Baukosteninformationszentrum Deutscher Architektenkammern (BKI) were used. Each can be accessed with a proprietary software.

It was not possible to get database access through an API. Hence, the individual data sets were read by hand and stored together with components in a table for later import. However, upon request, DBD confirmed that it is possible to integrate the data into a process through the course of software development if the data license is coupled to the software license. Thus, it would be possible to use an API to retrieve costs and building components automatically.

For testing the calculation, it has to be sufficient to transfer the cost data manually. Values for individual layers or entire modules have been added to the example components table. Most of the materials and modules have more than one corresponding cost value assigned. Where this is the case, an average value of the costs is formed. The table 3.1 demonstrates that there are only minor differences in most of the cases. In some cases, the descriptions and costs stored in the databases differ significantly from one another. The selection was then limited to the source with the smallest differences to the environmental datasets.

Data transformations are not necessary for the cost data, since both tables refer to the reference unit €/m².. The frame of the tested LCC will be limited to the modules A1-A3 and C3-C4 for this thesis. The reasons are the different calculation methods and estimations that are necessary to calculate the use phase of a building. To compare different variants, the modules B1, B2, B6 and B7 would also be very interesting. Nevertheless, the calculation methods for running costs differ from those for construction, demolition and replacement. Therefore, these phases are excluded from the frame of the project.

Table 3.1: Components and adhering costs examples from BKI and DBD databases.

Component Name	BKI Cost	DBD Cost	Cost mean
Interior plaster	28,74 €	27.31 €	28.03 €
Brickwall, 24cm	85.10 €	86.81 €	85.96 €
EPS rigid foam insulation ~60mm, prefabricated part	38.83 €	37.42 €	38.13 €
Reinforced concrete slab, C30/37, 20cm	-	40.95 €	40.95 €
Prefabricated Wall, wood, ~40cm	187.29 €	-	187.29 €
Thermal insulated composite system	102.53 €	115.98 €	109.26 €

3.2.5 Database Component Import

After the sample components, including their costs, have been extracted from the databases, corresponding templates can be created. Additionally to cost and structure, the component table links different modules together. It is hence possible to create components that incorporate datasets from different sources as well as combine different components in one building model. Instead of creating component templates in an excel table, an automatic mapping of material data incorporated in the model would be a clean solution. The advantages of both alternatives are investigated.

3.3 BIM Model and Export

3.3.1 Requirements

The database described in the previous chapter will provide the necessary background information on materials and components. The BIM-based model provides the remaining information to make a functional calculation process. The BIM-based information consists primarily of geometric but also material-specific data, depending on the requirements. However, some prerequisites must also be considered for a meaningful implementation.

The goal is to develop a method that is able to function primarily with open BIM. Therefore, the end result must meet the corresponding conditions. Open BIM has the prerequisite of being available to all stakeholders of BIM workflow, and can be used with all open BIM compatible programs. This means that generally known exchange formats must be used to which all software manufacturers have access. The exchange format must be able to take into consideration different disciplines to achieve the requirements of big BIM as well. This allows the prototypical implementation be used for higher LOD-models as the construction project progresses. Big BIM means the model is enriched with much additional information concerning different disciplines of construction. Therefore, the exchange format must be suitable for this circumstance.

3.3.2 Level of Development

The hypotheses from Section 3.1.1 includes the investigation during the early design stages. This can be addressed by using different LODs, which define the detailing of information in both geometric and semantic information.

The early phases were determined in Section 2.2 as LOD 200 and 300, because they do resemble the end of the schematic design and the beginning of the technical. A lower LOD would only result in a rough sketch of the building, and the subsequent planning phase already deals with details of the building equipment and is too inflexible.

From the definitions of the corresponding LODs, it follows that the model at level 200 may only contain rough geometric shapes and no material-specific information. The related materials are stored in level 300, but the components are shown without containing very fine details. For LOD 200, this means that no material-specific information can be extracted from the BIM-based model.

The thickness of the superstructure could indicate the composition of the layers. However, load-bearing or insulating layers have specific requirements and, therefore, similar wall types have similar thicknesses, regardless of the materials. With the level of detail contained in LOD 300, the additional information encompasses the components through material information. This would enable a different mapping method than LOD 200.

3.3.3 Exchange Format

The goal of this thesis is a method that can combine BIM and several analysis methods. Besides specific formats which were developed for independent software, the IFC format has become the obligatory data format for BIM and the construction sector in general. It is developed under the ISO 16739 standardization norm as an open source format (SACKS et al., 2018). The version IFC 4 is the most current one. It supports open BIM through being open source and interfaces for programming languages are already build.

Theoretical Extraction

To extract the data for LCA and LCC, the chosen method is reading the IFC File directly and output a B/Q with the selected information. The file is opened with the according function of the IFCOpenShell package. With the eLCA code, all building objects stored in the IFC file are created in Python with their coherent information. A selection of objects and attached data is then exported for further use.

The information, which is essential for the calculation of LCA and LCC, contains the area and a possibility to map the components. The structure of information favors that the components are divided into groups at the upper level of architecture. For example, this level separates walls from horizontal structures and wall openings. Horizontal structures are subsequently divided into floors, ceilings, and other subtypes on the next level. However, a prerequisite for the chosen method is that the components already contain information about the type. Which object class a component corresponds to is very clear, because this information is already included in a BIM-based model with the LOD 100. If part of this information is missing, it may have to be added to the used building templates. Through the different types of parts in IFC, the building components can be assigned to a cost group. The cost types described in Section 2.5 provide a clear definition for that. Geometric and semantic information is coupled to each item. The area is subsequently extracted and all crucial information

for further calculations is written to a table. Materials are also specified in the example IFC model, but are not used for the method, because the simplest early stage model would not contain those and material information is provided through the external component catalog.

Technical Extraction

```
#1184= IFCQUANTITYAREA('GrossFootprintArea',$, $, 2.595000000000002, $);
#1185= IFCQUANTITYVOLUME('GrossVolume', $, $, 15.0510000000001, $);
#1186= IFCQUANTITYAREA('GrossSideArea', $, $, 50.1700000000002, $);
#1187= IFCQUANTITYAREA('NetSideArea', $, $, 45.9268000000004, $);
#1188= IFCQUANTITYVOLUME('NetVolume', $, $, 13.7277839999995, $);
#1189= IFCELEMENTQUANTITY('170L4J7OTC7QFsbAjXCY7o', #42, 'Qto WallBaseQuantities', $, $, (#1181, #1182, #1183, #1184, #1185, #1186, #1187, #1188));
#1191= IFCREDEFINESBYPROPERTIES('21iAR06af4Ju8hU6FQ6Q23', #42, $, $, (#1178), #1189);
#1195= IFCWALLTYPE('3JvYgcleD0UfhWUIkIAPBr', #42, 'Basiswand: Au\X2\00DF\X0\enwand tragend 300', $, $, (#1197), $, '2483079', $, .STANDARD.);
#1196= IFCPROPERTYSET('3JvYgcleD0UfhWUIkIAPBr', #42, 'Pset_WallCommon', $, $, (#1196));
#1197= IFCPROPERTYSET('3JvYgcleD0UfhWUIkIAPBr', #42, 'Pset_WallCommon', $, $, (#1196));
#1202= IFCPROPERTYSET('2wbbyh_pndKPihs5Sp4syh', #42, 'Pset_EnvironmentalImpactIndicators', $, $, (#1202));
#1203= IFCPROPERTYSET('2wbbyh_pndKPihs5Sp4syh', #42, 'Pset_EnvironmentalImpactIndicators', $, $, (#1202));
#1206= IFCPROPERTYSET('30FXcBjFL4aQmVDGGKONPN', #42, 'Pset_ReinforcementBarPitchOfWall', $, $, (#1206));
#1207= IFCPROPERTYSET('30FXcBjFL4aQmVDGGKONPN', #42, 'Pset_ReinforcementBarPitchOfWall', $, $, (#1206));
#1210= IFCPROPERTYSET('2WPQqIxxvDFWkkaCDKPCy', #42, 'Pset_WallCommon', $, $, (#359, #360, #1196, #1202));
#1212= IFCREDEFINESBYPROPERTIES('2e2SR8kSD6BRSted5LUH40', #42, $, $, (#1178), #1203);
#1215= IFCREDEFINESBYPROPERTIES('02AvuALjn3V00zOfu0LrtB', #42, $, $, (#1178), #1207);
#1218= IFCREDEFINESBYPROPERTIES('1rsMYsa5f3zh6_FDR7cmv9', #42, $, $, (#1178), #1210);
#1221= IFCARTESIANPOINT((2.93971631466817, 3.45298461281562, -3.));
#1223= IFCAXIS2PLACEMENT3D(#1221, $, $);
#1224= IFCLOCALPLACEMENT(#139, #1223);
#1225= IFCARTESIANPOINTLIST3D((-2.51959612059274E-16, 0., 0.), (7.7, 0., 0.));
#1229= IFCINDEXEDPOLYCURVE(#1225, $, .F.);
```

Figure 3.3: Clipping of an IFC document opened with a text viewer. Keywords marked.

Figure 3.3 is displaying a clipping from an IFC file, read by a text editor. Red frames are marking important keywords for the extraction of a B/Q. The code by eLCA is recognizing the different objects contained in the file. Each object represents a component from the BIM-based building model.

Because lines are linked to the object with ID's, certain information can be found by keywords, and their values can be extracted. Since these keywords are different depending on the exporting software, they must also be adapted accordingly in the code. In the download package by eLCA (2021), besides the script for retrieving the information from an IFC file, details of suitable character sets are stored. These can be deposited in the modeling software, or the appropriate keywords are added to the script. For this project, the second method is used because only one model is examined. When executed with a Python compiler, the eLCA function creates an object from each IFC file element and then retrieves various information about each object found. Additionally, the mapping from cost type to building component is stored in another table. Here, the different alternatives can be switched up by changing the building component's names. Theoretically, all found information, or, in this case, only a necessary selection, can be passed to a table. The result is then used together with information from the database to calculate LCA and LCC.

3.4 Prototypical implementation

3.4.1 Interfaces

In order to make a meaningful calculation, data must be connected through a mapping process. The developed hypotheses must also be considered to find a suitable solution for matching the different datasets. As shown in Figure 3.1, the mapping module is the only connection between building model data and the database. However, since the mapping process is out of scope, workarounds were used for each handled interface. The first is the mapping of building components created with the BIM-based model to component templates. The second is concerned with linking material datasets from the environmental databases to the created building components, which would be an optional mapping step to simplify working with the program.

The characteristic values of the individual components from the IFC Model are the component type, cost group, thickness, and material information. In an automated process, templates with a similar material composition could be assigned to the components. Although, since one goal of this project is to use the LODs 200 and 300, it is not always guaranteed that all necessary material information is stored. Another goal concerns the comparison of variants in early phases. This entails making several calculations for one model or creating one model for each alternative. Therefore, the mapping per cost group and component type was preferred, instead of including the material layer information in the model as well. Using different variants and a component catalog as an input is a more reasonable way than to create a different building model for each simulated alternative. Both methods, an external component catalog or several component families in Revit, must be created, since the mapping process is not establishing component templates. The possibility to enrich the BIM-based model with material layer information does not offer any added value for comparing different variants. One possibility to reduce the manual effort would be, to include several simulation variants in one Revit template or family. This option is further discussed in the Outlook in Section 5.4.

Mapping layers to materials from the environmental databases was also manually done by hand for this project. The automated assembly of components brings some exciting possibilities and will be considered in the Outlook. In this case, as mentioned earlier, the mapping processes were out of scope. Searching the environmental databases by hand to find the best matching dataset forms a laborious task. It is potentially error-prone, if no profound environmental

database experience exists, because a lot of similar datasets exist. However, this problem does not affect the case study, because only the calculation process is validated, not the quality of sustainability input information. Therefore, if faulty datasets are used during the calculation, they are as well used for the validation calculation.

3.4.2 Importing to the SQL Server

Once imported, it is possible to store the environment, cost, and component data on the SQL server. However, due to the trial and error process, minor changes were also often made to the database, so the mentioned data is re-imported each time the code is run. The `setup_db.py` function is executed to import the environmental data from Ökobaudat, KBOB, andecoinvent. The procedure for importing environmental data is called once per line of the corresponding table. This procedure stores the general material information in "env_material_data" and the module-specific information in "env_material_indicator". Also, the additional table with supplementary material information is read, and the affected fields are updated. More Materials, f. e. from EPDs, can be added by appending the information to one of the environmental databases. Hence, it is also read during the initial commit. Another option would be to create a suitable interface especially for EPDs.

The component table is also imported to PyCharm using a Python script, similar to the environmental databases. First, a script is executed for components, then for modules, and finally for the material connection. During the import, data is transferred to the corresponding fields of the database. The connections between the different objects, such as components and modules, are established. This process is implemented by procedures created in MySQL Workbench. It is designed to prevent duplicate entries and call additional procedures if exceptional cases occur. These exceptions include, for example, importing another indicator for the same material. In this case, the change in "env_material_data" is skipped, and another line is created in "env_material_indicators". Once the set-up-script is executed, all the required data is stored in the database.

3.4.3 Calculation Process

After importing the materials and variants, the corresponding information is retrieved from the database. Figure 3.4 displays an overview of the executed steps. First, the extracted B/Q is analyzed. The given code by the eLCA

was modified to output the components together with their cost groups, type designation, and area. The resulting table is then compressed by summing the area for objects of the same cost type and class. Therefore, each component type, for example external load-bearing wall, occurs once and is indicated with its quantity and the summed area. In addition, the selection of the corresponding building templates for the chosen variant is attached here. Subsequently, a dataframe of the component categories, the used templates, and the related costs per m² is created in PyCharm.

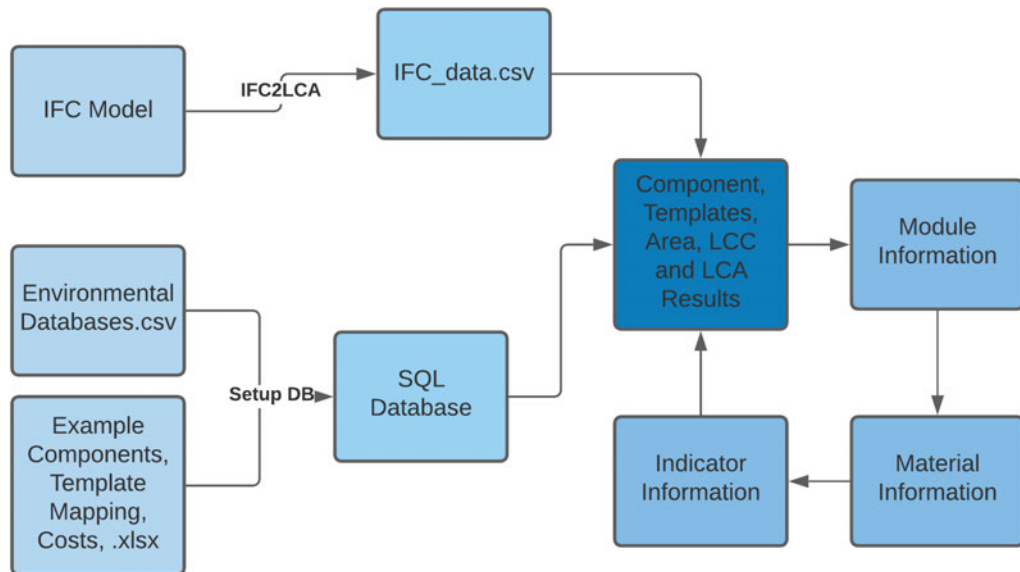


Figure 3.4: Calculation process of LCA and LCC step-by-step.

This table combines almost all higher-level information. In several queries, all information down to the environmental indicators can be retrieved. During the process, the results are summed up several times. First, the sustainability indicators are summed up per module, and subsequently, the values are calculated per component by summarizing all underlying modules. The result is one value per indicator and template. It is then multiplied by the area or the number of components. Further conversions, depending on the reference unit, take place to unify the values to m². For example are indicator values referring to m³ multiplied with the layer thickness, represent a value per m². In addition, the ratio of mixed layers and the total thickness of a component are taken into account. Finally, the areas are multiplied with costs and the environmental indicator values to receive LCA and LCC results.

4 Case Study and Validation

To validate the proposed methodology and the implemented mapping and calculation processes, a case study is simulated. In the following sections, the execution and results will be described

4.1 Case Study

4.1.1 BIM Model of Case Study

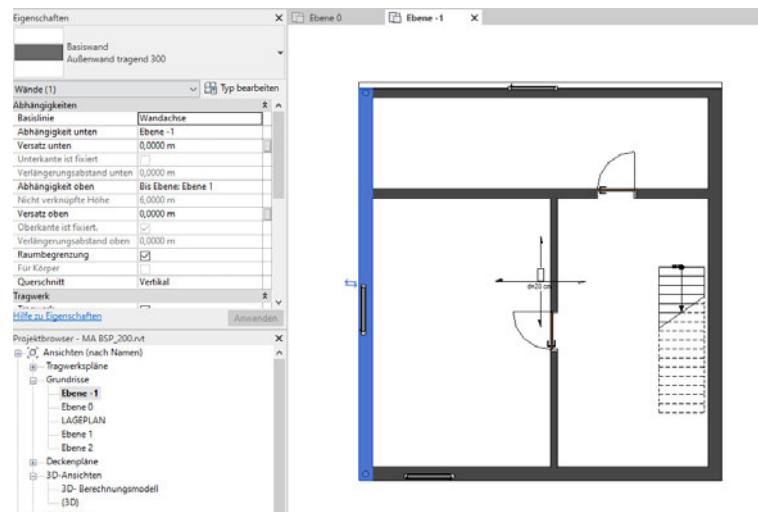


Figure 4.1: Ground plan of the example model in Revit. Screenshot of the basement level (-1) with one outer wall selected.

The BIM model for the case study is created in Revit. The typical modeling process includes already established walls from templates. An example for the selection of a wall type is given in Figure 4.1. A drop-down menu is visible on the left side of the image, which states "Basiswand" (engl.: "basic wall"). In Revit, modeled parts need to have a template assigned. Therefore, one possibility to establish a model corresponding to LOD 200 is to create templates or families without material information. The other option is to create a model using the standard templates and not use the included material information for further calculations. The second method was chosen because all basic templates already have material information included, and it would only represent another manual process to define templates with less information.

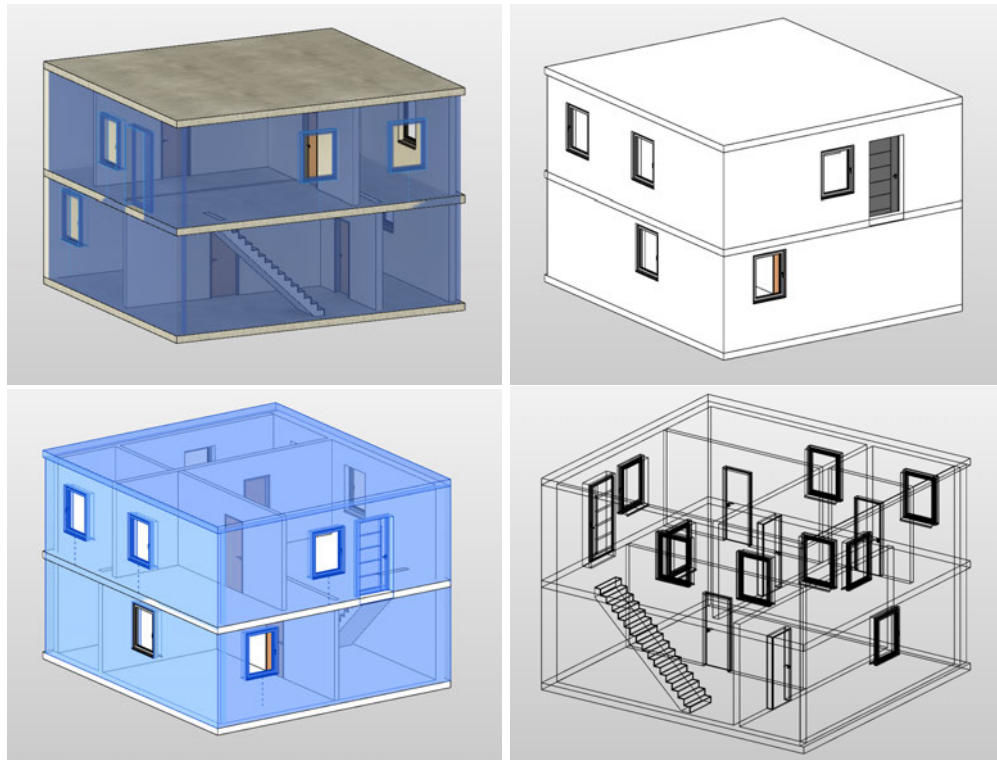


Figure 4.2: Different views from Revit, displaying the example model. (1) Rendered view with transparent outer walls. (2) Shaded view. (3) Shaded view with transparent roof and outer walls. (4) Wire model view.

Figure 4.2 shows four screenshots from Revit, which display all the included components. The model consists of two floors, one of which represents a basement. The following component types are represented: load bearing and non-load bearing inner and outer walls as well as windows, inner doors, and one outer door on the ground floor. Windows and doors are essential for the example calculation because the LCC calculation is based on a different reference unit. Walls, floors, ceilings, and roofs are calculated by area, whereas the reference unit of windows and doors is by piece. The size of windows and doors contributes to a high price fluctuation. Therefore, price is calculated per quantity, while environmental indicators are calculated per m^2 . With the method of using the already established templates, the model represents a higher LOD than 200. Additionally to the information incorporated in LOD 200, materials and thicknesses are included in the objects. For example, the detailed material information and frame to glass ratio for windows. Those are typically not present in an early-phase model. Therefore, not all available information will be used for further mapping and calculations since the details are not yet decided in LOD 200 and 300, but rather options are investigated.

Extracted from this model is a list of all building components, their associated component type, cost group and the area, displayed in Table 4.1. With this

selection exported, the BIM model provides the reference unit square meters, which is needed for the cost and environmental data. Since additionally a catalog of component templates is included, other crucial information is derived from it. This includes the thickness of different layers, which is necessary if the reference unit is not m². Regarding to this method only the object type and area are needed for further calculations. Here, also the quantity for windows and doors is included. The quantity is not directly stored in the IFC file but is calculated by counting the corresponding objects. With this method, only three load-bearing outer walls are listed because they were modeled from the bottom floor to the model's top. Inner walls are represented per floor, and therefore, two load-bearing inner walls are counted, one for each floor.

Table 4.1: Quantity takeoff for the example model.

Component Name/Class, Type	Cost type	Quantity	Area [m ²]
Outer wall, load bearing	331	3	130.6
Outer wall, non-load bearing	332	1	40.1
Inner wall, load bearing	341	2	39.1
Inner wall, non-load bearing	342	3	34.4
Ground slab, floor	351	3	210.75
Window	334	9	22.3
Outer door	334	1	2.8
Inner door	334	5	10.2
Flights, straight	351	1	3.2

Other reference units can be used by selecting different output parameters for the B/Q by eLCA. This possibility is helpful if the LOD of the model changes. For example, thickness or other material information could be included, and therefore the pre-established template would not need to include this information separately. In another case, the material ratio for mixed layers was used as a workaround. Since ecoinvent incorporated only datasets with single glass panes, the ratio for the 3-pane window is multiplied by three. It has the same effect on the environmental values as representing the same dataset three times during the calculation.

4.1.2 Component Templates of the Case Study

Components

Table 4.2: Example for components used as templates for the project.

Nr.	Component Description	Pos.	Module Name	Thickness [mm]
07	Reinforced concrete, insulated composite system *	1	Reinforced concrete C20/25	200
		2	EPS composite system	180
08	Solid wood construction, insulated composite system *	1	Prefabricated wall construction	395
09	Reinforced concrete flooring, floor screed	1	Reinforced concrete C30/37	200
		2	Floor screed	50
*	Plastered and painted	1	Plaster	10
		2	Paint	1

For each of the component types included in the model, several example components are established. Components from the cost databases are used as templates, from which several alternatives are created. Care was taken to use several materials as the core layer. Wooden, concrete and brick walls are represented. A selection of three templates is presented in Table 4.2. From the typical construction types, which include brick, concrete, and wood, some variations were created for the different wall types. For example, a thinner version of a load-bearing outer wall is used as a non-load bearing wall. Also, templates with plain walls are established with and without dampening to differentiate between primary and advanced building styles. As slabs, ceiling flat roof templates are created. The established templates for flat roofs incorporate a gravel layer. Since it was not uncommon to install a fill-layer in floors in the last century, these ceiling templates can also be used as floors. An overview of the components is included in Appendix A 2. The 20 components consist of 29 different environmental datasets, which are attached in Appendix A 1. To each environmental dataset, the source Database (DB) is indicated. The majority of material datasets is derived from Ökobaudat, with a few representing KBOB and ecoinvent. Datasets from different sources are not combined to represent a single value, but modules can contain materials from different databases. This enables to choose from a wider variety of datasets.

Materials

The different databases which are taken into account include different environmental indicators and general material information as well as different levels of consistency. Ecoinvent presents by far the most consistent environmental values while also representing the most different indicators. These observations only concern the available version for this project. Only very few values are missing for most datasets, with only around 200 from 12.000 datasets completely missing all values. Since none of the faulty datasets were used for the example components, the empty lines could be skipped during the data import. However, no general material information, such as density or basis weight, was available. To ensure a working calculation process, this information had to be added to the used datasets. Otherwise, the datasets could not be transformed to the needed reference unit. This concerns the "concrete, 20MPa" and "flat glass, coated" since the reference units, m³ for concrete and kg for flat glass, did not correspond to the needed format.

The available version of KBOB includes a little under 300 material datasets with the focus on building materials and processes. Additionally, it includes more datasets for other sectors, such as building equipment and transportation. Although it encompasses only three different indicators, the available data is consistent. The usual information, the reference unit, density or weight per area and the modules A1-A3 are always included. For over 80% of the datasets, modules C3 and C4 are included as the end-of-life scenario. The others are processes, like establishing a construction pit, or steel based materials. Since the generic material information is very consistent, no additional data had to be added to the KBOB datasets.

Table 4.3: Additional Material Data that was added to the existing datasets.

Table	Identifier 1	Identifier 2	Datafield	Value
env_material_data	Oekobaudat	35be6146-5a80-4a9e-a32d-5d05c03a8d5c	weight_areal	0.32
env_material_data	Ecoinvent	concrete, 20MPa//[GLO] market for concrete, 20MPa	density_raw	2400
env_material_data	Ecoinvent	flat glass, coated//[GLO] market for flat glass, coated	weight_areal	30

The current version of Ökobaudat, 2021-II, includes 7000-8000 datasets specifically for the Architecture, Engineering and Construction (AEC) industry. A few datasets encompass information for all the available life cycle modules as well as general material information. However, the majority only includes

modules A1-A3 and C3-C4. Even though many materials for the case study were derived from Ökobaumat, only once had additional data to be added for the selection. The modified datasets are displayed in Table 4.3 through their corresponding identifiers. Possibly, by choosing material datasets with missing values in mind, this problem can be avoided. However, for the calculation of the case study, these circumstances were not considered. For the calculation of a real construction project, these material datasets would either be filled with external data or replaced with similar, complete datasets. However, complete datasets are not crucial to fulfilling the developed hypotheses as long as all calculation information is given. This aspect will be taken up again during the case study validation in the Section 4.2.1.

Multi-layer Modules

During the import of templates, the selected materials are linked to modules. These include modules with one to four materials per layer for the case study. The multi-layered modules are shown in table 4.4. Several assumptions have to be made to establish the modules. The ratios between different materials in a layer were approximated. An average volume ratio of 2% for steel in reinforced concrete can be assumed for smaller buildings. Only structural components with special static loads require a higher proportion (WEISS, 2010). These include f. e. concrete pillars. The proportion of frames in windows and beams in wood-frame constructions can also vary considerably. For the structure of window frames and wood beam constructions, 20% is assumed as an average value. This method can be used, when the window frame datasets are referred to m², which is the case for KBOB and ecoinvent window frames. Ökobaumat datasets refer to running meters. To calculate the running meters per window, the dimensions could be extracted from the IFC file.

The assumption of 20% can be checked by calculating with different frame and beam thicknesses. For windows, the frame proportion varies a lot with the overall size of the component. For example, a 10cm frame represents over 33% when the window is only one m² in total area. For a window with 4.00 m², the calculated ratio is under 20%. Therefore, for different components, different proportions are usual. Since this is an example calculation, mean values can be assumed without compromising the result.

Table 4.4: Modules containing more than one environmental dataset coupled with their environmental datasets.

Nr.	Name	Pos.	Material	Ratio
1	Reinforced concrete C20/25 2%	1	[GLO] market for concrete, 20MPa	0.98
		1	Bewehrungsstahl	0.02
2	Reinforced concrete C30/37 2%	1	Beton der Druckfestigkeitsklasse C30/37	0.98
		1	Bewehrungsstahl	0.02
3	Prefabricated wall construction, wood	1	Konstruktionsvollholz (Durchschnitt DE)	0.2
		1	Lose Zellulosedämmung	0.8
		2	Oriented Strand Board (Durchschnitt DE)	1
		3	Mitteldichte Faserplatte (Durchschnitt DE)	1
4	EPS composite system	1	WDVS mit EPS Dämmplatte geklebt	1
		2	Estrichmörtel-Zementestrich	1
5	Window, wood, 2-pane isolated glass	1	Fensterrahmen Holz	0.2
		2	Isolierverglasung 2-fach, Ug-Wert 1.1 W/m ² K, Dicke 18 mm	0.8
6	Window, wood and metal, 3- pane isolated glass	1	Window frame, wood-metal, U=1.6 W/m ² K	0.2
		2	Flat glass, coated (x3)	2.4

4.1.3 Calculated Variants

For the case study, three different variants are used with the same geometry of the BIM model. The chosen component templates are displayed in Table 4.5. Variant 1 features load bearing concrete and non-load bearing wood and brick walls. As slabs and stairs, reinforced concrete components are chosen. Variant 1 has the best insulation of the three variants, which is as well represented in the windows. The component has 3-panes of isolated glass and a wood-metal frame.

The approach for Variant 2 is much lighter, concerning the number of different layers and materials. All wall components consist of bricks without insulation. Also, the slabs, which represent the floor plate the ceiling and roof, are reinforced concrete without insulation. Using brick components for the walls and concrete

only for bigger slabs is the typical building style constructed in the second half of the last century (LOGA et al., 2015).

Table 4.5: Calculation variants 1, 2 and 3.

Component Name/Class, Type	Variant 1	Variant 2	Variant 3
Outer wall, load bearing	Reinforced concrete (20cm) C20/25, EPS composite system (18cm), plastered, painted	Bricks (24cm), plaster, painted	Reinforced concrete (20cm) C20/25, plastered, painted
Outer wall, non-load bearing	Solid wood wall (20cm), EPS composite system (18cm), painted	Bricks (17.5cm), plaster, painted	Reinforced concrete (12cm) C20/25, plastered, painted
Inner wall, load bearing	Reinforced concrete (20cm) C20/25, EPS dampening outside (6cm), plastered, painted	Bricks (17.5cm), plaster, painted	Reinforced concrete (20cm) C20/25, plastered, painted
Inner wall, non-load bearing	Bricks (17.5cm), plaster, painted	Bricks (17.5cm), plaster, painted	Reinforced concrete (12cm) C20/25, plastered, painted
Ground slab, floor	Reinforced concrete (20cm), C30/37, EPS dampening outside, plastered, painted	Reinforced concrete (20cm) C30/37, Cement screed above separation layer	Reinforced concrete ceiling (20cm) C30/37, sand pour, plastered, painted
Window	Window, wood and metal frame, 3-pane isolated glass	Window, wooden frame, 2-pane isolated glass	Window, wooden frame, 2-pane isolated glass
Outer door	Door, outside, wood and aluminium	Door, outside, glass insert	Door, outside, wood and aluminium
Inner door	Door, inside, wood and glass insert	Door, inside, wood	Door, inside, wood and glass insert
Flights, straight	Concrete stairs (30cm), 1m width	Concrete stairs (20cm), 1m width	Concrete stairs (30cm), 1m width

Variant 3 consists of reinforced concrete walls without insulation. The windows have 2 glass panes and the inner doors consist of wood with a glass insert, the outer door of wood and aluminum. Slabs and stairs consist of reinforced concrete. Variant 2 differs in the aspect, that bricks are used as the main load bearing material, whereas reinforced concrete and wood is used in Variants 1 and 3. Variant 1 is the only one featuring insulation in all building components.

Due to the structure of the established method, those different variants can be examined very easily. The templates are assigned to the corresponding types, as shown in the displayed table. The three chosen variants can be

compared to examine two different things. By comparing Variant 1 and 3, the difference between raw and well-insulated components is calculated. Especially when deciding the level of insulation or the quality of modules, these analyses can be beneficial. On the other hand, Variants 2 and 3 represent different structural materials, while keeping the same level of insulation. Here the price and environmental impacts of brick construction against reinforced concrete can be analyzed.

4.2 Sustainability Results

The calculations of sustainability indicators are executed for three different values, costs, GWP and PE, which are described in more detail in Section 3.2.3. Each of these results is then displayed as a total sum as well as per m² area. To calculate the gross floor area, the total area of the two floors was multiplied by 90%, resulting in roughly 126m². This method is an estimation, which takes floor area covered by walls into account. Also, openings for stairs etc. are usually not included in the gross floor area. The total results are then divided by this value to display a result per m² as well. This is a common way to compare different building plans. The model can be described as a standard building shell without a roof and additional windows and doors. The roof was substituted with a slab, like the ones for the floor plate and ceiling. The reasons to keep the model as simple as it is are already explained in Section 4.1.1.

4.2.1 Validation

Additionally to the automated calculation, the three variants are calculated manually with an excel sheet to validate the results. The areas for the second calculation are extracted directly from Revit. The components are established in a spread sheet which is linked to the environmental databases as .csv tables. The costs are added to the spread sheet manually from the cost databases.

Reaching similar outcomes in both procedures is a sign of a functioning calculation process. The reviewed manual method through the spread sheet can be checked for errors more efficiently, as all the steps are visible instead of consisting of several lines of code. Additionally, the python code has many intermediary steps because data is extracted from different sources and merged before a calculation is made.

Some minor deviations in the outcomes can be noticed. Two possible sources for the differences of results have been identified. The first deviation concerns the thickness of different materials in one layer. It is calculated as a total module thickness ratio. In the manual calculation, the value of 365mm for 92% of a 395mm thick module is used. The automatic calculation came to the value of 363,4mm. The second source for deviations is that values in the manual calculation are trimmed to two decimals on several occasions during the process, because the calculated numbers are too long to be presented in the spread sheet. Therefore, the additional decimals are lost to the subsequential process. Nevertheless, exact results are appended in Appendix A3.

Another possibility to check for consistency of the calculations is to compare the component structure to the results. The different variants deviate consistent from each other, considering the used materials. For example do the materials from Variant 3 to 1 only increase, but not decrease. This is the reason, why similar building components were chosen with and without insulation. A reasonable calculation result would therefore be, that costs and environmental indicators are higher in Variant 1.

Additionally, modules and materials can be directly checked for valid results. With the help of the manual calculation, environmental and cost values can be compared to the values in the database and to the values used during the automated calculation process. By stopping PyCharm at sensible points during the automated calculation, interim results can be compared, which helps to find calculation errors.

4.2.2 LCC Results

The first calculation, displayed in Figure 4.3, corresponds to the investment costs. Exact results are represented in Table 4.6. The assessment method of a LCC is used, but only the construction phase is considered. It is evident that Variant 1 has a higher price of nearly double the costs of Variant 2 and around one-third more than Variant 3. Per m^2 , this result is close to $1000\text{€}/m^2$ for Variant 1 and a little over $500\text{€}/m^2$ for Variant 2. Variant 3 lies in between with around $700\text{€}/m^2$. It is expected that variant 1 is more expensive than the other two since it encompasses more layers and higher quality materials. Also, components are generally thicker than those of the other two variants. The difference between Variants 2 and 3 are not minor, even though only the type of main material deviates. Since concrete components can be thinner

and still fulfill the needed static restrictions, Variant 3 consists of less material concerning the volume but is still more expensive than Variant 2.



Figure 4.3: LCC calculation results for variant 1 and 2. (1) Total and (2) per m² net gross area. Graphs are displayed in full size in Appendix 3 + 4.

Table 4.6: Calculation results concerning costs.

Price [€]	Variant 1		Variant 2		Variant 3	
	Automatic	Manual	Automatic	Manual	Automatic	Manual
total	121,717.00 €	122,375.45 €	65,493.00 €	65,880.67 €	88,313.00 €	88,797.24 €
1/m²	966.01 €	971.23 €	519.79 €	522.86 €	700.90 €	704.74 €

4.2.3 LCA Results

The considered indicators for the sustainability analysis are the GWP and the PE. The coherent results are displayed in Figure 4.4, with exact values in Table 4.7 and 4.8. The observations made for sustainability results are very similar to those of the cost results. It was expected, that Variant 1 has higher results for both considered indicators, because more layers are represented overall. Additionally, these layers represent insulation, and therefore are added on top of the load bearing material layer. Sustainability results are also deviating less between the variants, compared to cost results. A possible explanation is given in the next section.

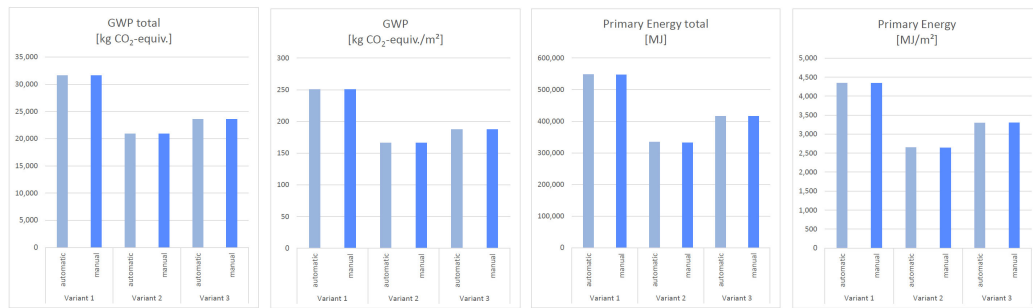


Figure 4.4: LCA calculation results concerning global warming potential and primary energy. (1) Total GWP and (2) GWP per m² net gross area. (3) Total PE and (4) PE per m² net gross area. Graphs are displayed in full size in Appendix 5-8

Table 4.7: Calculation results concerning the global warming potential.

GWP [kg CO ₂ - equi.]	Variant 1		Variant 2		Variant 3	
	Automatic	Manual	Automatic	Manual	Automatic	Manual
total	31581.42	31580.84	20919.85	20919.85	23607.47	23607.47
1/m²	250.65	250.64	166.03	166.03	187.36	187.36

Table 4.8: Calculation results concerning primary energy.

PE [MJ]	Variant 1		Variant 2		Variant 3	
	Automatic	Manual	Automatic	Manual	Automatic	Manual
total	548020.46	547277.38	334318.35	332740.91	415612.06	415610.27
1/m²	4349.37	4343.47	2653.32	2640.80	3298.51	3298.49

4.2.4 Sustainability and Cost Comparison

The calculated outcomes are very reasonable, considering the used templates. The more layers and materials added to the variants, the higher the outcome in all investigated sustainability sectors.

The differences between different variants are higher for cost results than for environmental indicators. This can be explained, because assembly effort increases with more layers, which was not considered for the environmental

simulations. It is to be noted, that for the investment costs, construction prices are considered as well as material prices, because the cost databases only incorporate one value for both. For the LCA, only the production, replacement, disposal and recycling phases were considered. The assembly and disassembly phases are neglected, because environmental impacts are often not monitored and are minor compared to the other phases. This is reasonable, since personnel costs are a big share of the overall construction costs, but for environmental impacts, personnel has only a minor effect.

Nevertheless, comparing the absolute calculation results does not yield any benefits for a design decision for the chosen variants. Too many important factors are not included in this calculation, which are needed to evaluate a variant over the whole life cycle of a building.

The first example is, that most cost factors of the use phase of the building are not considered. When comparing different variants, for example with different levels of insulation, the savings in heating expenses are huge over a life span of 50 years. The second example is, that not all factors are included in sustainability analyses. By considering the calculation results, bricks are having both a better price and environmental impact compared to reinforced concrete. On the other hand, the components need to be thicker in order to fulfill static needs. For higher buildings, which are mainly build in areas with high property prices, this means a loss of usable gross net area, since more of each floor is blocked by walls. A more expensive material and construction method could therefore be favored, if higher revenues are compensating the investment costs.

Further steps to solve these problems and get calculation results, which can be compared in a meaningful design process are discussed in the next chapter.

5 Project Review and Outlook

5.1 Usability

5.1.1 Mapping Method

The chosen mapping procedure at the interface between IFC file and sustainability database is enabled by an external template catalog, as it is not in the scope of this thesis. Since the benefits of the early planning phases, for example less resistance to changes, are very important to the sustainability impacts of a construction project, simulations have to be made with the available information included in the model. The possibility to test several building or component alternatives is still given with this method.

The different variants can either be included in the model or be established externally. Including variants to directly to the BIM model could be achieved through different templates or template families. However, material data is not always given in the corresponding building models during the early design phases. Therefore, a component catalog linked to the BIM output and sustainability database is a working method during the most LODs, even in later planning stages.

This possibility is very interesting, if basic materials or components are reconsidered in the later planning phases. The BIM model will then already be much more complicated than during the early planning phases. Therefore, many more circumstances would need to be considered and changing variants in the model might not be easily possible. This could lead to a much more complicated calculation process. An external template catalog could still be used with only geometric information, which will be roughly the same in the later design phases.

5.1.2 Manual Work Steps

The most manual work to perform the analyses is establishing a reliable component catalog as well as the manual mapping of single datasets to component layers. Especially if many templates are to be created and many different materials are to be considered. This work step will even get worse with more

databases used in the process. Often, materials from environmental and cost databases do not precisely fit each other, and adjustments must be made to one of the datasets. On the other hand, once established, a standard catalog of components can be used for calculations with several building models. Therefore, the overall effort gets smaller with every calculation.

Another manual process is preparing the IFC export or the corresponding code to work with different property sets. Although this is an unpleasant procedure, once tuned, further exports from the same modeling software do not need preparation again. Suppose the BIM model is changed to incorporate more information for further analysis. In that case, it might be better to change the property sets in Revit to ensure the output is always saved with the wanted keywords. Nevertheless, once one of both methods is performed, the code will work automatically with further model exports.

In summary, the prototypical implementation is usable for analyses, still with many manual interfaces to be mapped. These have been solved or worked around for the example project. Possible solutions have been given for permanent implementation.

5.2 Research Question Review

Since the project was designed to fulfill the hypotheses elaborated from the research questions, each will be reviewed in the following.

First:

- **Research Question:** How can data regarding multicriterial properties of materials be combined in a single database to provide a basis for comprehensive analysis methods?
- **Hypothesis:** With the appropriate database design, various criteria can be included in the automatic calculation of construction projects sustainability impacts.

The condition derived from the first hypothesis is: using various criteria during the procedure. This goal is accomplished by combining environmental indicators with investment costs. These represent two of the three sustainability sectors, even though only for the construction and demolition phase. Concerning construction projects, the social aspect is tough to quantify. Therefore, it

is not implemented in the process. Difficulties for combining different criteria mainly concern the deviating reference units and calculation methods. This challenge was solved by using a common point, the reference unit $1/m^2$, to combine the LCA and LCC processes. This is probably not possible for all methods of sustainability analyses, but all assessments considering buildings need a quantifiable reference unit, which can be used as an intersection point. The database was designed to include the data from several sources and transform all datasets to the shared reference unit. For each calculation method can contribute its data at the fitting intersection by storing the data on different levels, from material to component. Therefore, the first hypothesis can be fully verified.

Second:

- **Research Question:** How can different design and component alternatives be implemented in a database to enable an optimization through analyzing different variants?
- **Hypothesis:** The comparison of variants, materials and designs of a building project in automatic calculations is possible in the early design phases if appropriate interfaces and data structures are considered in the execution.

The second statement sets the conditions of comparing variants, materials, and designs during the early planning phases. The possibilities during LODs 200 and 300 were investigated to make sure the procedure represents the early design stages. This circumstance leads to restricted information incorporated in the BIM-based building model.

To fulfill the set condition of comparing different variants, several design decisions have been made. Due to the limitations through early design phases, a component catalog has to be established to compare different variants and materials. This is done by outsourcing the templates from the modeling software to a separate data base. With such a catalog established, comparing variants is easily possible by running the calculation several times with different components mapped before the procedure. To fulfill the second statement, the process has to be automated completely. Methods and challenges regarding this fact are given in the Section 5.4.

Third:

- **Research Question:** Which information for an automatic, multi-criteria building analysis is already contained in an early phase BIM-based model?
- **Hypothesis:** The required information for different levels of automated sustainability calculation is known and therefore are the possible detail grades of calculations with an early-phase BIM-based model.

Fourth:

- **Research Question:** Which information is typically missing an early stage BIM-based model and which can be complemented?
- **Hypothesis:** For multi-criteria sustainable building analyses, all necessary information can be obtained from an early-phase BIM-based model or added to the model early on, according to the requirements of the analysis.

As the last two hypotheses are very closely related to each other, they are reviewed combined. The third statement sets the condition that the information needed for certain levels of automated calculations is known. In contrary, the fourth hypothesis states, that the possible levels of automated calculation with the given information can be anticipated. To create automated LCAs and LCC, several data sources are needed. Firstly, material data for all criteria that are to be investigated. Secondly, mass and volume data of the concerning building model. Thirdly, information that functions as keywords between both data types. The higher the LOD, the higher the level of information already included in the building model. Therefore, with a higher level of information, more calculation and mapping processes can be automated.

This coherence is illustrated in Table 5.1. X's represent necessary information for the desired analysis and vice versa. (a)'s and (b)'s represent the need, to fulfill at least one of each. For example, the automated mapping of materials is possible if material information is either included in the model or stored in an external source.

To fulfill the third hypothesis, the table can be read from top to bottom, and by knowing the included information the possible stages of automation can be read. For example, a standard BIM-based model with the LOD 200 includes geometrical information as well as component types. Therefore, by establishing an external template catalog, the basic analysis and automated template mapping are possible. For the fourth hypothesis, the table is read from left to right.

Table 5.1: Matrix representing the connection between used model information and possible automated analyses.

	Model: Geometric Information (LOD 200)	Model: Cost or component type (LOD 200)	External: Template catalog	Model: Material Information (LOD >200)	External: Detailed Material Require- ments	Model: Detailed Layer Information (LOD >300)
Basic analysis	x					
+ template mapping	x	x	x			
+ material mapping	x	x	(a)	(a)		
+ template establishing	x	x	(a)	(a)	(b)	(b)

The target type of analysis is known and therefore is the required information to execute it. Using this matrix, crucial information can be identified, and the fitting analyses type can be chosen. For the example project, the basic analysis + template mapping was chosen because it can be established with a LOD 200 building model and an external template catalog.

5.3 Challenges

The method of combining the different data sources for automatic analysis of several sustainability criteria has shown many challenges to overcome. Suitable solutions were found for some, others were avoided through workarounds, and some could not be solved during this thesis. In the following, the remaining challenges are presented with possible solutions, where they are available.

5.3.1 Sustainability Databases

Consistency

Inconsistency is a problem of the featured LCA and LCC databases. Every analysis that is performed based on a sustainability database highlights this challenge. However, combining different data sources is making this problem even more striking.

The first challenge is that the proper reference units or additional material information are missing for datasets in several cases, even though they are generally represented in the database. These datasets have then to be avoided

or supplemented with crucial information. If additional material information is missing, which is crucial for the calculation process, it must be added separately. If environmental indicator values are missing, the result is compromised. Both cases are far from optimal for reliable calculations, especially when mapping materials and components is automated. Missing values need then also be detected automatically. A workaround for this problem is to combine several datasets. Duplicate values can be averaged, and missing values will be covered.

In comparison to the environmental databases, cost databases are more regional and far more specialized. The DBD Database is available for Germany, but still regional differences are divided as far as single counties (DBD, 2021), whereas environmental databases are divided to countries at a maximum, sometimes the values are even considered valid for a whole continent (BMI, 2021). Both of the used options have provided consistent information for all included datasets but were limiting these datasets to rather specialized components and modules. Especially the selection of possible component templates is restricted a lot since datasets often represent components as a whole without taking different thicknesses or other options into account.

Availability of data

Another problem that concerns the most databases is availability due to license restrictions. The gathering and managing of a database can need a lot of time and money. Therefore the prices are reasonable. However, every user will need several licenses for software that can enable automatic calculations for several criteria. As an example, the goal of Ecoinvent is to make sustainability data easily accessible. (ecoinvent ASSOCIATION, 2021). Nevertheless, no download of the whole database in a common format is possible even with a license purchased. Even though these license restrictions are considerable hurdles, without the possibility to make a profit by providing databases, the selection would be limited to open source projects.

As investigated in this thesis, it is possible to combine different databases into one calculation on a technical level. If the license hurdles can be overcome, sustainability assessments will provide more consistent results by using the advantages of several sources. An example for an open source database is the Ökobaudat, which is provided under an open-source license by a German ministry (BMI, 2021). On the other hand, it is typical that companies have to buy crucial information from institutions. An example are DIN standards, which are established by the "Deutsche Institut für Normung". The standards are sold

and every company operating in Germany has to comply to them. Databases might fall under the same requirements for investment costs for companies.

5.3.2 BIM-based exports

The possible interfaces to extract data from a BIM model have been discussed already in Section 2.3. From this basis, the IFC format was chosen as the best option since it is intended to be used with open BIM as a shared interface between different software. During the project, however, the exchange requirements did cause some problems, even though Revit is licensed software certified explicitly for the IFC 4 format. Still, the problem of differences in keywords has been experienced. If IFC is the format to be used with open and big BIM, those have to be consistent. Otherwise, the data exchange between different interfaces is not functioning automatically. One solution to this is to specify exchange requirements for each software, which can be imported by the users.

5.3.3 Calculation Process

Some challenges do as well remain considering the established calculation process. One hurdle to calculating bigger models is that the diversity of possible component types is limited. For example, only one window type is mapped in the different variants. However, typical larger building projects feature multiple types of windows. It is possible to introduce another keyword to distinguish further between the different components to solve this problem. This solution could be integrated without additional material information and would be compatible with the chosen mapping method. For example, the BIM-based process could include small, medium and large windows. Each type could then be mapped to a different template.

Another problem concerning the calculation outcomes is that only the construction and demolition phases are considered. The whole life-cycle has to be considered to use the results in meaningful comparisons because building operation processes can account for a large share of CO₂ emissions and energy consumption during the life cycle. By integrating the learning from this thesis into a complete process, the usage of more cost and environmentally expensive materials can be justified if the life cycle compensates these. Another possible solution is to create a separate life cycle energy calculation depending on the established variants.

5.4 Outlook

This project is one part of a fully automated process to calculate multi-criteria sustainability analysis from a BIM-based model. It provides an overview of the different parts necessary for assessing several sustainability indicators and investigates possibilities for well-known databases. By looking into different LODs, which are represented by a BIM model, the requirements for different levels of automation can be coupled to information sets. Considering the whole method, interfaces are established to map different kinds of data to the analysis process. New requirements are taken into account, as open interfaces are available for further data input. Besides this thesis's contribution to the whole process, some challenges are still to be solved in further investigations.

5.4.1 Improvements for the established Method

The first challenge concerns the data extraction from a BIM model. It would be beneficial to be flexible when it comes to selecting the modeling software. The problem, that character sets differ even for open BIM formats and certified software, has to be addressed. Additionally to the already mentioned solutions, a well-designed program might identify the source of the model and adapt accordingly, if the character sets for the most-used modeling environments are identified.

Despite the possibility of mapping materials to components and extracting the components directly from the IFC file, the component templates themselves have to be created somewhere. It is worth investigating if it is possible to create component families in Revit or any other modeling software, which incorporate several variables in one template. That would solve the problem of establishing several models, to investigate several alternatives and is a step towards a single source of information, namely the BIM building model.

5.4.2 Improvements beyond the scope

Concerning the whole frame of a fully automatic project, further challenges have to be solved. The general framework of this thesis already excluded some crucial steps for fully automatic analyses, and in FORTH et al., 2021, the aim for a holistic method is described. Missing functions include the mapping between the different project parts, which was done manually for this project. This method needs a high effort process of linking material datasets to modules

and components to BIM model objects. If more of the involved processes can be automated, the initial effort to use the calculation methods is smaller. The first step is to map datasets concerning costs and environmental indicators to the established templates. That would replace the time-intensive search process in different databases.

Additionally, some variant feedback is aspired, to create new insights on the generated results and automatically tune the investigated variants. If this full workflow can be completed, it is possible that the methodology improves the variants during several iterations and reaches a optimized result for the corresponding building.

However, as shown through the methodology of this thesis, variants can not be compared meaningful, if the sustainability simulations are not holistic. Therefore, either use phase calculations have to be included within the framework, or established outside the frame and used for the decision making process.

If these requirements are met, a holistic approach for multi-criteria variant comparison on basis of an early design stage BIM model is possible.

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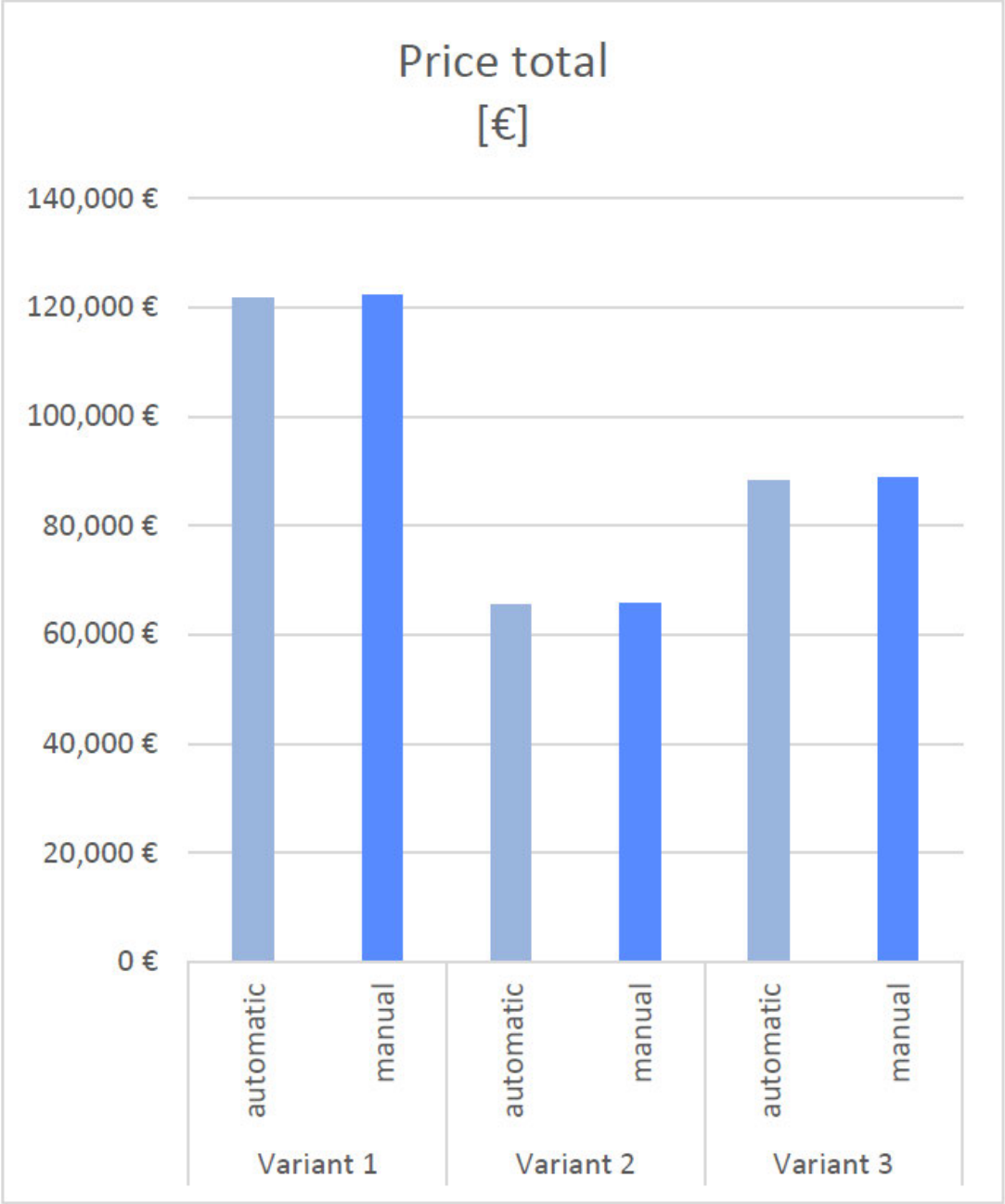
A Appendix

Material Number	Material Name	Source DB
1	Kalk-Gips-Innenputz	Oekobaudat
2	Mauerziegel	Oekobaudat
3	Gipsputz (Gips-Kalk-Putz)	Oekobaudat
4	Fassadenfarbe Dispersionsfarbe	Oekobaudat
5	Anstrich, wasserverdünnbar, 2 Anstriche	KBOB
6	WDVS mit EPS geklebt	Oekobaudat
7	PIR Hartschaum	Oekobaudat
8	Gipsputz (Gips-Kalk-Putz)	Oekobaudat
9	Estrichmörtel-Zementestrich	Oekobaudat
10	XPS-Dämmstoff	Oekobaudat
11	Kies 2/32	Oekobaudat
12	PU-Dämmplatten aus Blockschaumstoff	Oekobaudat
13	Aussentüre, Holz, Glaseinsatz	KBOB
14	Innentüre, Holz	KBOB
15	Bewehrungsstahl	Oekobaudat
16	Beton der Druckfestigkeitsklasse C30/37	Oekobaudat
17	Konstruktionsvollholz (Durchschnitt DE)	Oekobaudat
18	Lose Zellulosedämmung	Oekobaudat
19	Oriented Strand Board (Durchschnitt DE)	KBOB
20	Mitteldichte Faserplatte (Durchschnitt DE)	KBOB
21	WDVS mit EPS Dämmplatte geklebt	Oekobaudat
22	Estrichmörtel-Zementestrich	Oekobaudat
23	Fensterrahmen Holz	KBOB
24	Isolierverglasung 2-fach, Ug-Wert 1.1 W/m ² K, Dicke 18 mm	KBOB
25	[GLO] market for concrete, 20MPa	Ecoinvent
26	door, outer, wood-aluminium	Ecoinvent
27	door, inner, glass-wood	Ecoinvent
28	window frame, wood-metal	Ecoinvent
29	flat glass, coated	Ecoinvent

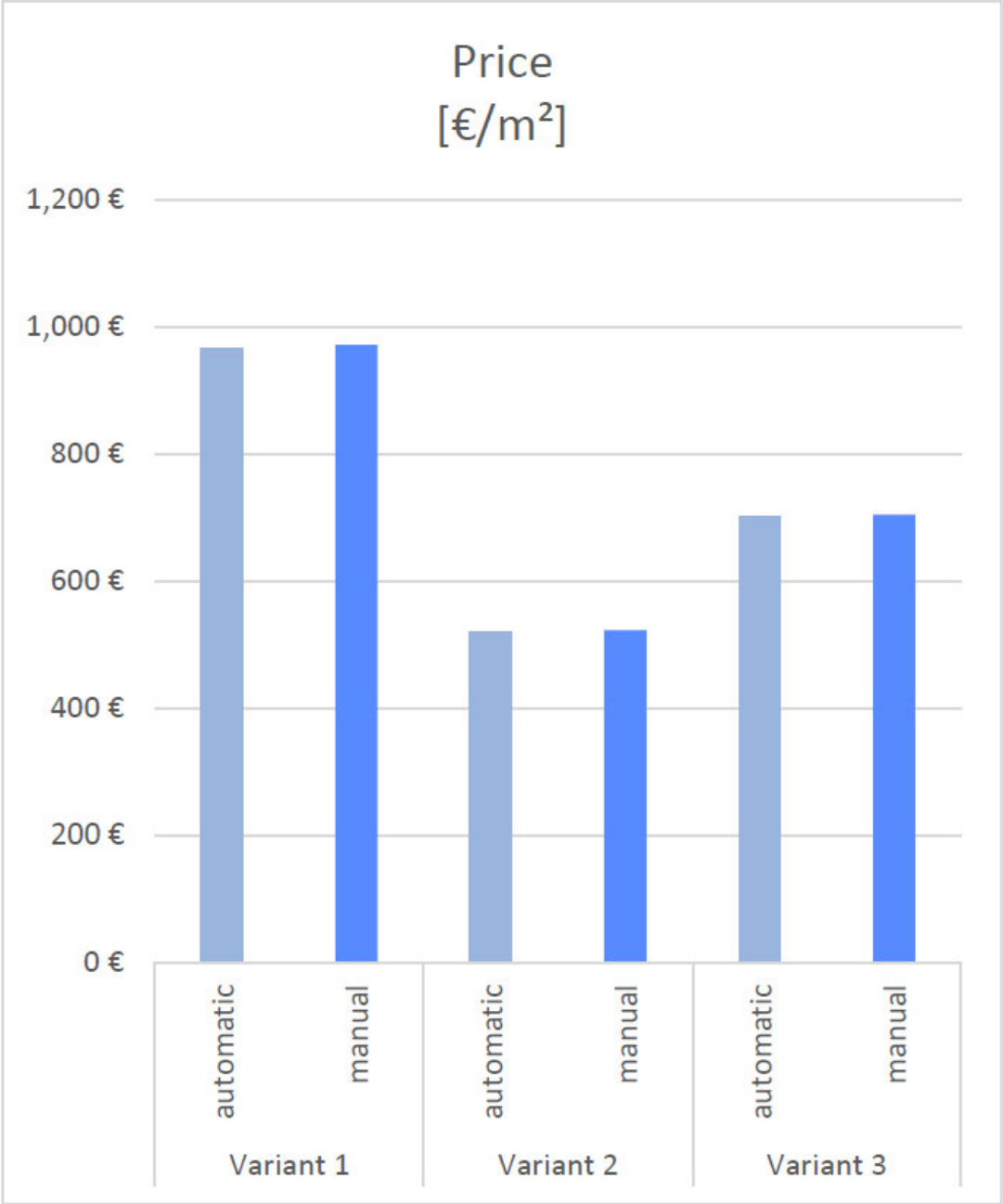
Appendix 1: All environmental datasets used in the case study. Names in original database language.

Nr.	Component Description	Pos.	Module Name	Thickness [mm]
01	Brick wall*	1	Bricks	240
02	Brick wall, insulated composite system *	1	Bricks	240
		2	EPS composite system	180
03	Brick wall, non-bearing*	1	Bricks	175
04	Reinforce concrete*	1	Reinforced concrete C20/25	200
05	Reinforce concrete, non-bearing*	1	Reinforced concrete C20/25	120
06	Reinforced concrete, outer dampening *	1	Reinforced concrete C20/25	200
		2	EPS outer dampening	60
07	Reinforced concrete, insulated composite system *	1	Reinforced concrete C20/25	200
		2	EPS composite system	180
08	Solid wood construction, insulated composite system *	1	Prefabricated wall construction	380
09	Reinforced concrete flooring, floor screed	1	Reinforced concrete C30/37	200
		2	Floor screed	50
10	Reinforced concrete flooring, perimeter insulation, floor screed	1	Reinforced concrete C30/37	200
		2	XPS perimeter dampening	200
		3	Floor screed	50
11	Reinforced concrete ceiling, filling*	1	Reinforced concrete C30/37	200
		2	Gravel fill	50
12	Reinforced concrete ceiling, solid foam dampening	1	Reinforced concrete C30/37	200
		2	EPS solid foam, plastered	190
13	Reinforced concrete flight	1	Reinforced concrete C30/37	200
14	Reinforced concrete flight	1	Reinforced concrete C30/37	300
15	Outer door, glas insert	1	Outer door	-
16	Inner door	1	Inner door, wood	-
17	Window, wood, 2-pane isolation	1	Wood window frame	-
		2	2-pane isolation	-
18	Outer door, wood and aluminium	1	door, outer, wood-aluminium	-
19	Inner door, wood with glas insert	1	door, inner, glass-wood	-
20	Window, Wood and metal, 3-pane isolation	1	Window frame, wood-metal	-
		2	Flat-glass, coated (x3)	-
*	Plastered and painted	1	Plaster	10
		2	Paint	1

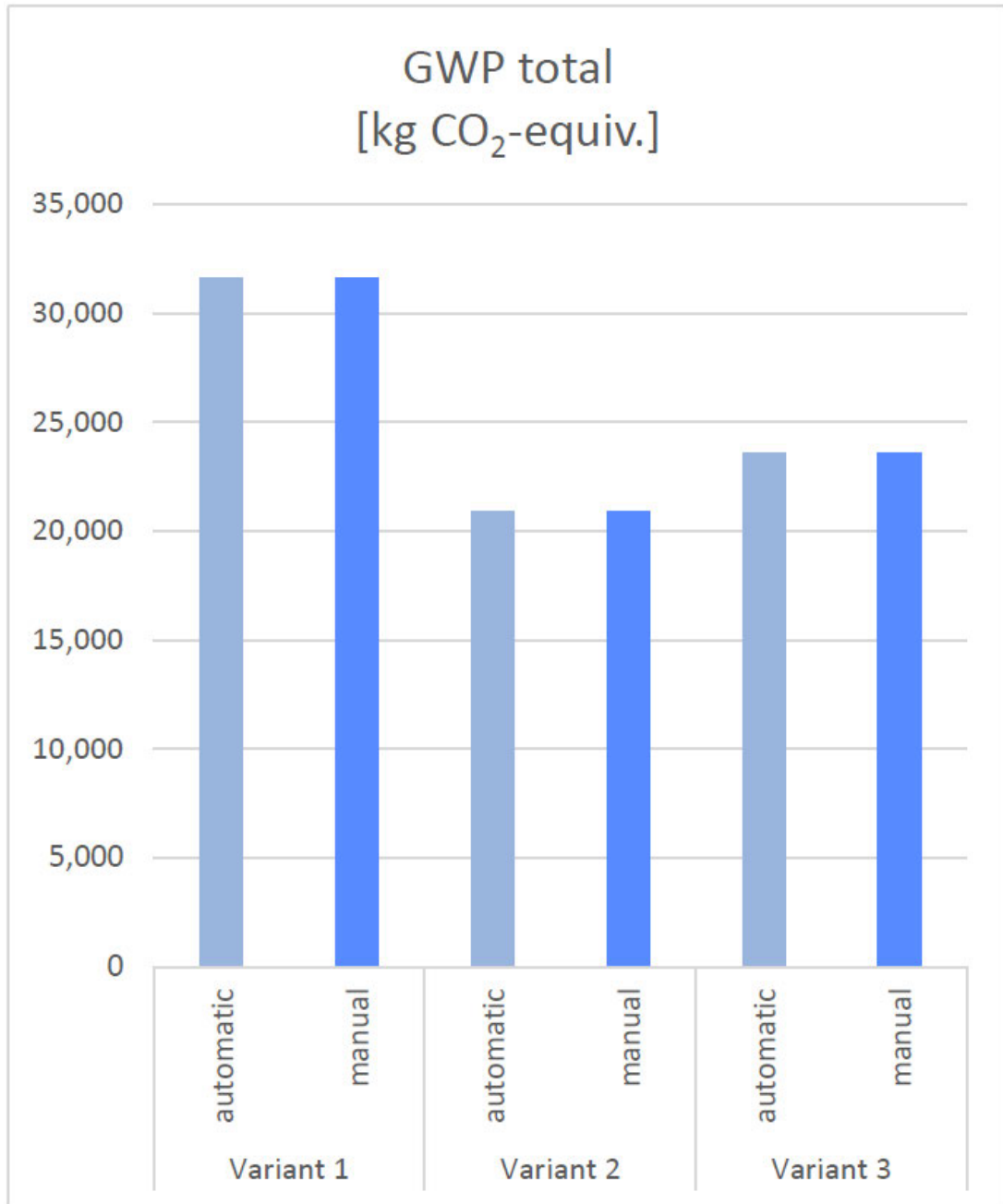
Appendix 2: Example components established for the case study.



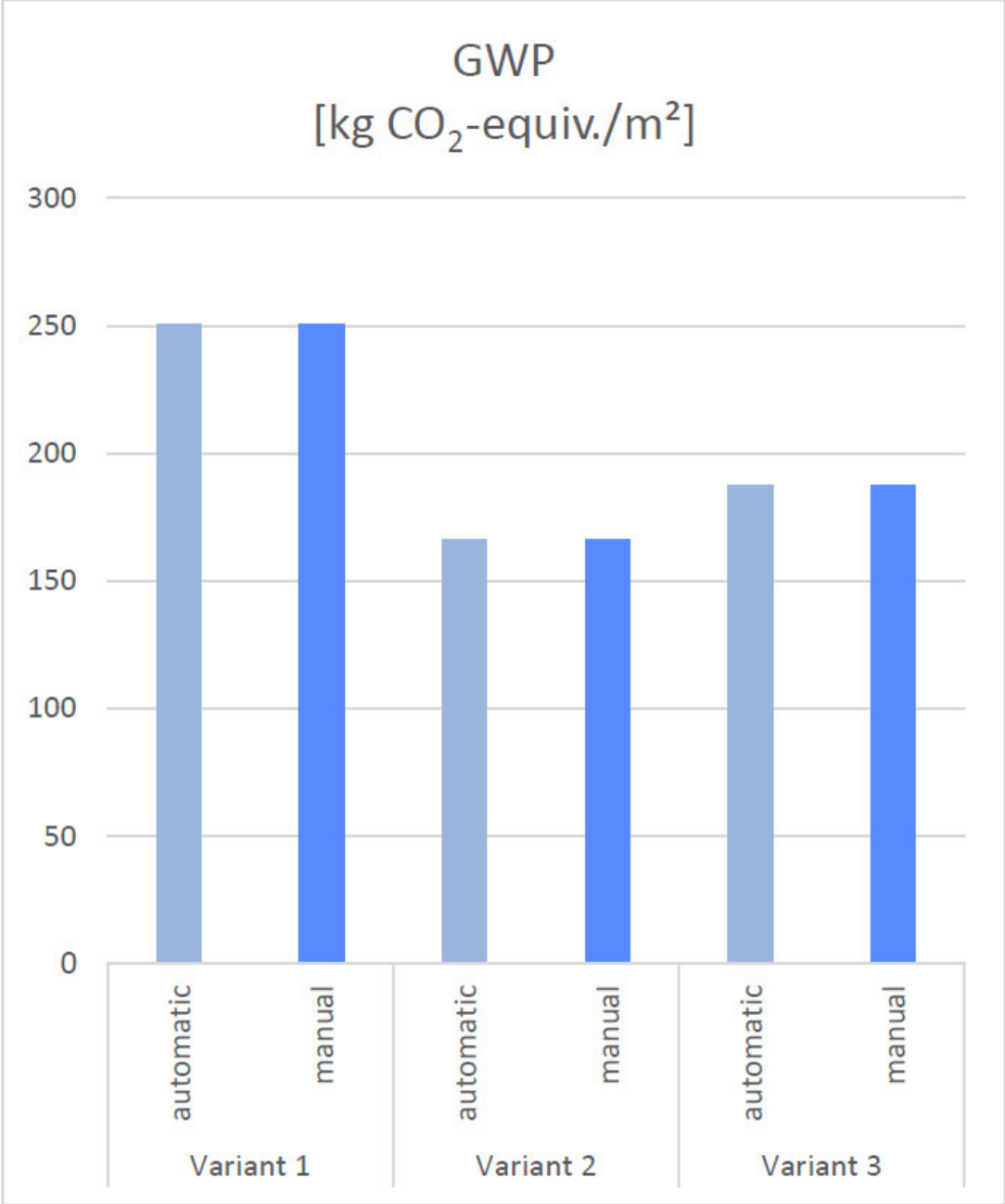
Appendix 3: LCC calculation total cost.



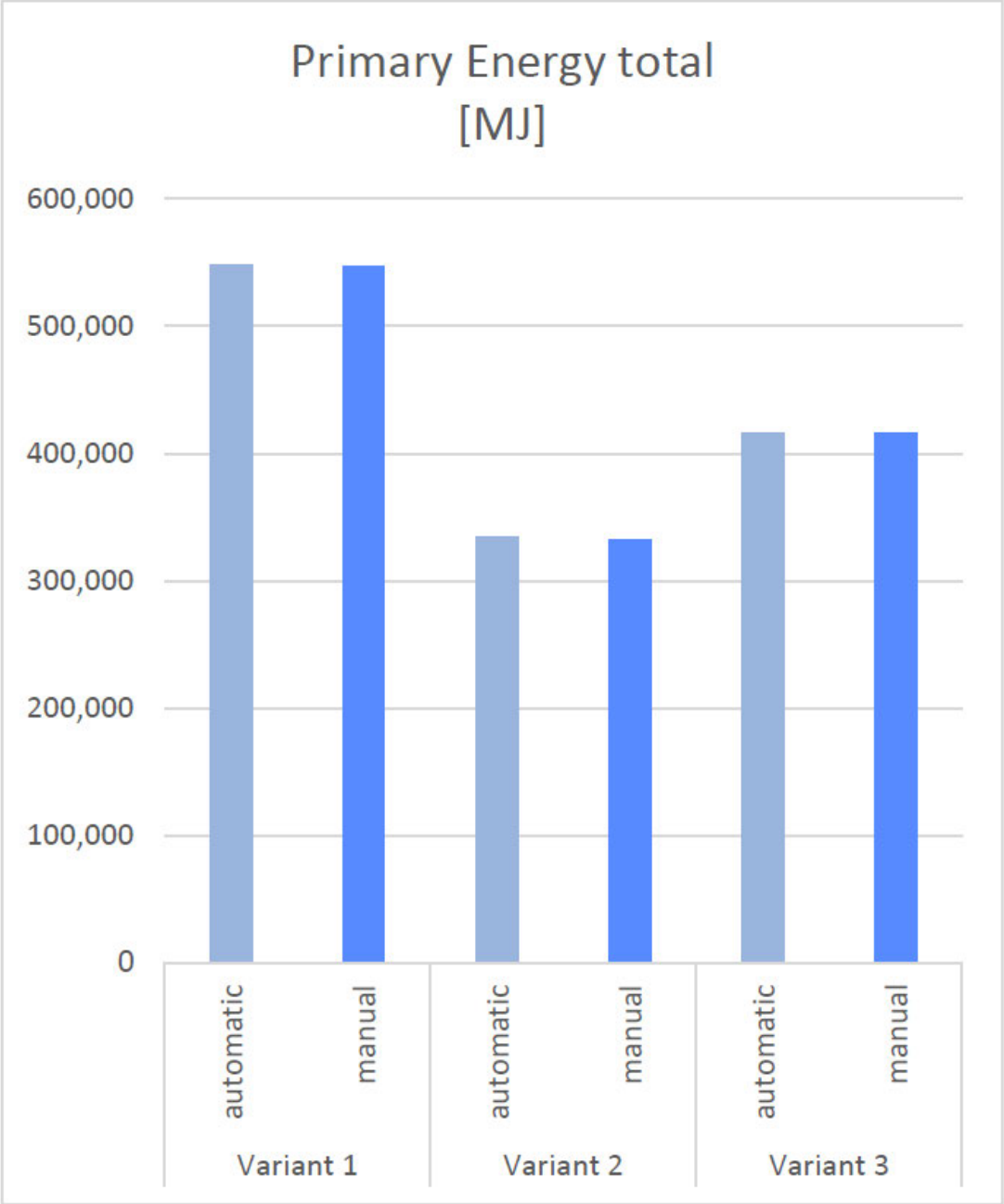
Appendix 4: LCC calculation cost per m².



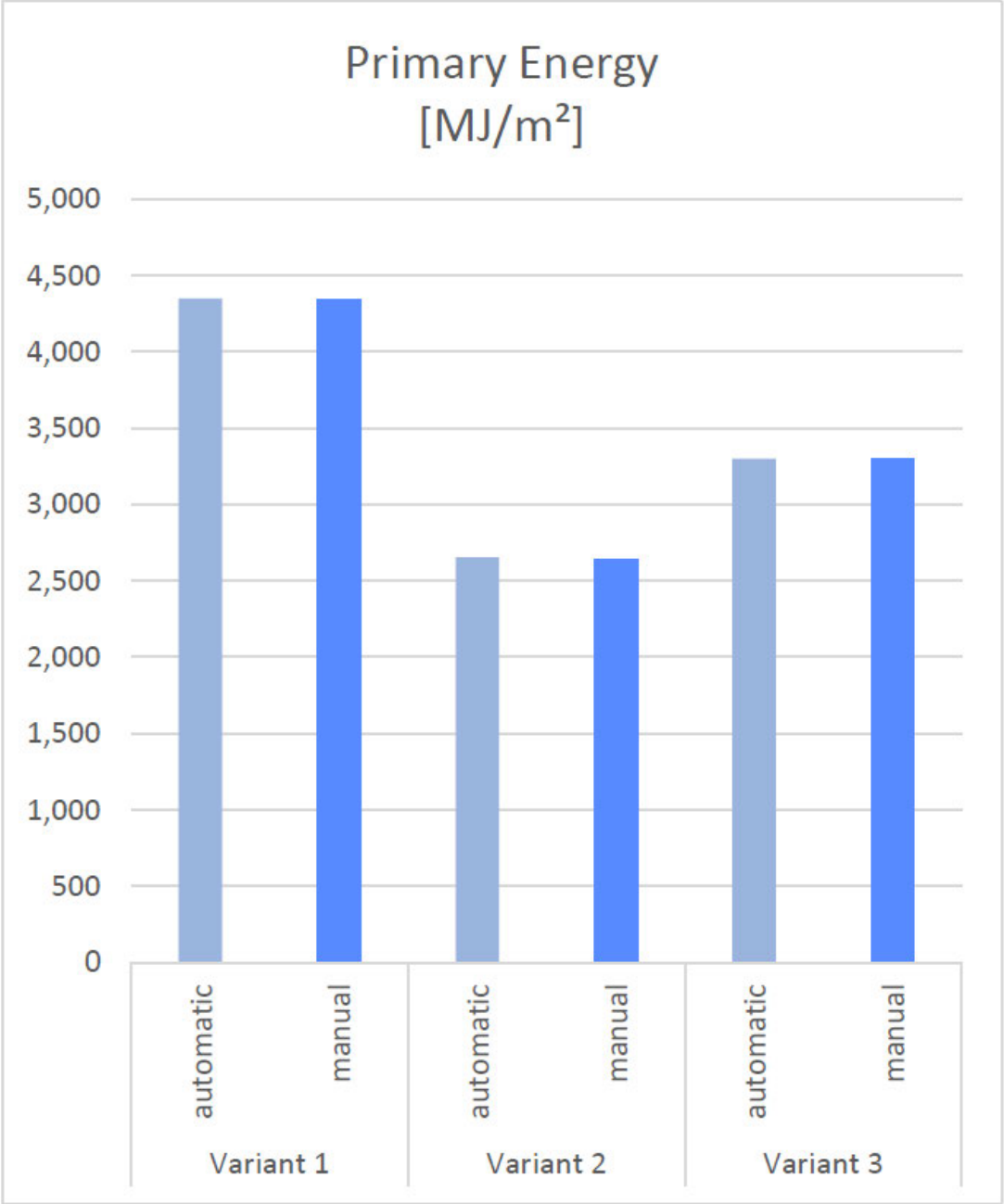
Appendix 5: LCA calculation total GWP.



Appendix 6: LCA calculation GWP per m².



Appendix 7: LCA calculation total PE.



Appendix 8: LCA calculation PE per m².