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Analysis of integrated LCA tools in BIM platforms for prefabricated timber construction

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Abstract

UN Sustainability Goals aim to reduce environmental impacts by resource efficiency and create more sustainable cities and communities until 2030. Since AEC industry makes a significant contribution to the global environmental pollution by using 37% of CO2 emissions, it is necessary to reach a holistic understanding of the circular economy of the construction sector and to reduce the environmental impacts of the building industry faster and more efficient (United Nations Environment Programme, 2021).

There are different measures to reduce environmental impacts. Life cycle assessment (LCA) is one of the systematic and acknowledged ways to analyze the environmental footprint of buildings. However, sufficient LCA analyses require a highly complex approach to achieve meaningful results. Lately, Building Information Modeling (BIM) offers a great potential to accelerate and simplify this process with the project data it holds.

Similarly, besides their cost and time efficiency, prefabricated construction technologies have shown their high potential to reduce waste in construction. Therefore, the present study aims to review BIM-based LCA tools for prefabricated constructions. Although these subjects and tools are not new to sustainability studies, there is still a gap in researching their combination.

BIM for prefabricated construction and BIM-integrated LCA tools will be tested by two case studies in prefabricated timber projects. Automatic and semi-automatic calculations of the tools and their workflows will be presented and discussed. This study gives insights into the characteristics of prefabricated timber construction for BIM and LCA tools.

Regarding the specific requirements of prefabricated timber projects, the present study shows interesting findings for the use of BIM-based LCA tools. For example, there can be significant discrepancies in the export files of the different

BIM tools if the relevant BIM family parameters are not defined directly from the beginning of the project. Furthermore, the varying standards and databases of the BIM tools can manipulate the key figures of a prefabricated building project in different ways. As these findings and further results of this study show, BIM-based LCA tools can only have a positive effect on the grade of sustainability in prefabricated timber construction projects, if the handling of these tools follows specific processes and accurate working methods.

Keywords: BIM, LCA, Prefabrication, Prefabricated Timber Construction, BIM-based LCA, Sustainable Construction, Circular economy

Kurzfassung

Die UN-Nachhaltigkeitsziele zielen darauf ab, Umweltauswirkungen durch Ressourceneffizienz zu reduzieren und bis 2030 nachhaltigere Städte und Gemeinden zu schaffen. Da die AEC-Industrie mit 37% der ausgestoßenen CO2-Emissionen einen erheblichen Beitrag zu den globalen Umweltbelastungen leistet, ist es erforderlich, ein ganzheitliches Verständnis der Kreislaufwirtschaft des Bausektors zu erhalten und die Umweltauswirkungen der Bauindustrie schneller und effizienter zu reduzieren (Umweltprogramm der Vereinten Nationen, 2021).

Um Umweltbeeinflussungen zu reduzieren, gibt es verschiedene Maßnahmen. Die Ökobilanz (LCA) ist eine der systematischen und anerkannten Methoden, um den ökologischen Fußabdruck von Gebäuden zu analysieren. Jedoch erfordern hinreichende Ökobilanzanalysen sehr komplexe Maßnahmen, um zu aussagekräftigen Ergebnissen zu gelangen. Hier bietet Building Information Modeling (BIM) in letzter Zeit ein großes Potenzial, diesen Prozess mit den darin enthaltenen Projektdaten zu beschleunigen und zu vereinfachen.

In ähnlicher Weise haben vorgefertigte Bautechnologien neben ihrer Kosten- und Zeiteffizienz ihr hohes Potenzial zur Reduzierung von Abfällen im Bauwesen gezeigt. Die vorliegende Studie zielt deshalb darauf ab, BIM-basierte Ökobilanz-Tools für vorgefertigte Konstruktionen zu überprüfen. Denn obwohl diese Themen und Tools für die Nachhaltigkeitsforschung nicht neu sind, gibt es noch Lücken in der Erforschung ihrer Kombination.

BIM für den vorgefertigten Bau und BIM-integrierte Ökobilanz-Tools werden anhand zweier Fallstudien in vorgefertigten Holzbauprojekten getestet. Es werden automatische und halbautomatische Berechnungen der Werkzeuge und deren Arbeitsabläufe vorgestellt und diskutiert. Die vorliegende Studie gibt Einblicke in die Eigenschaften des vorgefertigten Holzbaus für BIM- und LCA-Tools.

Gerade in Bezug auf die speziellen Anforderungen von Projekten mit vorgefertigter Holzbauweise gibt die vorliegende Studie interessante Erkenntnisse für die Nutzung von BIM-basierten LCA-Tools. So können beispielsweise signifikante Diskrepanzen in den Exportdateien der unterschiedlichen BIM-Tools entstehen, wenn die entsprechenden BIM-Familienparameter nicht direkt am Anfang des Projekts definiert werden. Außerdem können die abweichenden Standards und Datenbanken der BIM-Tools die Kennzahlen von Projekten mit vorgefertigter Bauweise auf unterschiedliche Weise beeinflussen. Wie diese Erkenntnisse und weitere Ergebnisse dieser Studie zeigen, kann die BIM-basierte Ökobilanzierung nur dann einen positiven Effekt auf den Nachhaltigkeitsgrad von Projekten der vorgefertigten Holzbauweise haben, wenn im Umgang mit den entsprechenden Tools spezifische Prozesse und präzise Arbeitsweisen befolgt werden.

Keywords: BIM, Ökobilanz, Fertigbauweise, vorgefertigter Holzbau, BIM-integrierte Ökobilanzierung, nachhaltiges Bauen, Kreislaufwirtschaft

Contents

List of Abbreviations

3D	three dimensional
A1	Raw Material Supply
A2	Transport
A3	Manufacturing
ADPE	Abiotic Depletion Potential elements
ADPF	Abiotic Depletion Potential fossil
AEC	Architecture Engineering Construction
AP	Acidification Potential
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Methodology
C1	Demolition
C3	Waste Processing
C4	Disposal
CAD	Computer-aided design
CC	Climate Change Impact
CLT	Cross Laminated Timber
CO2	Carbon Dioxide
d	Diameter
D	Reuse / Recovery / Recycling Potential
DFMA	Design for Manufacturing and Assembly
DFD	Design for Disassembly
DGNB	German Sustainable Building Council
EPD	Environmental Product Declaration
EP	Eutrophication Potential
EU	European Union
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
gbXML	Green Building Extensible Markup Language

GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
LPH 1-9	Work stages 1-9 according to HOAI (Official scale of fees for services by architects and engineers)
ODP	Ozone Depletion Potential
PENRT	Primary Energy Non-Renewable Total
PERT	Primary Energy Renewable Total
POCP	Photochemical Ozone Creation Potential
Revit	Autodesk Revit 2020
RVT	Data exchange format of Revit
SWOT	Acronym for Strengths, Weaknesses, Opportunities, Threats
VDC	Virtual Design and Construction
XML	Extensible Markup Language

1. Introduction

1.1. Digitalization and Sustainability in the AEC industry

> *For everyone working in the construction industry, meeting the needs of our society without breaching the earth's ecological boundaries will demand a paradigm shift in our behaviour. . . . The research and technology exist for us to begin that transformation now, but what has been lacking is collective will.*
>
> *(Architects Declare, 2020).*

As known as a conservative industry, digitalization in the construction sector had not the same speed as in other economic sectors (Abanda et al., 2017; European Construction Sector Observatory, 2021). Furthermore, the construction sector is always working under the pressure of time and budget; as long as everything works out fine, there is rarely time for a significant change.

When the coronavirus crisis started in 2020, probably not many people thought the adjustments to our digital work processes would be fast and easy, but it was. Alternatively, maybe no one imagined the transition from office to home would be relatively smooth, but it was, too. Except for working internet connection, there was no significant barrier in the process. Bringing more digital processes into the working approach, such as design collaboration tools like Building Information Modeling (BIM) platforms showed how quickly and efficiently digital technologies in the Architecture, Engineering, and Construction (AEC) industry can be used.

While BIM makes an immense contribution to the construction industry today, it also changes it. Today what we define as BIM is far greater than its first design. With all the known advantages of BIM, such as having a realistic virtual 3D model of the structure for design and construction phases, additionally, we now have the ability to connect all the relevant data of the project from production to deconstruction. It creates an opportunity to evaluate whole life cycle of the building processes and optimize them for resource efficiency, quality, and cost-saving (Borrmann et al., 2018; Cavalliere, 2018).

Currently, another significant subject for the building industry is actually not a new one but it is still transforming the sector. In the last three decades, prefabricated construction became popular, and it offers designers a more efficient working approach in many ways. Prefabricated constructions are predictable, thanks to their high level of standardization (Ferdous et al., 2019, p. 883 ff.). Furthermore, they reduce costs, mistakes and they also help to minimize environmental impacts (Jin et al., 2020, p. 2 ff.). Industrialized modular prefabrication systems keep resource efficiency and quality higher. (Santana-Sosa & Fadai, 2019, p. 148 ff.).

Nevertheless, most construction projects are still conventionally built, and the popular BIM tools are mostly not optimized for prefabricated constructions. Similarly, the Life Cycle Assessment (LCA) analysis for conventional construction methods has a long history. Although prefabricated construction demonstrates positive environmental impacts compared to conventional ones, there are not yet many studies that examine the specific needs of prefabricated constructions in this topic (Kamali & Hewage, 2016, p. 22; Pons, 2014).

According to Rønning and Brekke (2014, p. 63), *"Life cycle assessment (LCA) is one such method which aims to scrutinise the environmental friendliness of products and services."* Therefore, the LCA of buildings plays a major role in predicting and controlling the environmental impact of the structure. If LCA is implemented in design phases, it is also possible to recognize early the future footprint of the building and act on it to improve its environmental impact. (Rønning & Brekke, 2014, p. 64).

However, LCA needs high-level data of projects and materials, such as production methods, resources, and geographical information, to make the assessment well. Here prefabrication combined with BIM could come more into the play. Prefabrication provides an excellent basis to assess environmental impacts, thanks to its standardized processes in a controlled environment and its high-level of material data. Moreover, BIM provides a solution with BIM-integrated LCA tools to reduce the complexity and time consumption of the LCA process. Therefore, the motivation of this thesis is to demonstrate the potential of prefabrication for BIM-based LCA and to promote new opportunities for higher sustainability in the building sector.

According to the EU Commission report, buildings in the EU are responsible for around 40% of energy consumption and 50% of raw material sources (European Commission, 2018, p. 1). Some studies even expect the environmental impact of buildings to double in the next two decades if the regulations for new and existing buildings do not change (Unep-Sbci, 2009, p. 9). That is why potential improvements in the construction or design processes of future projects could significantly change the energy consumption of the industry.

As Architects Declare (2020) states, the current Corona crisis should be an opportunity to rethink about the priorities of the built industry and to face better with another global crisis that we are in, the ecological crisis. Finally, this thesis is an attempt to contribute to more sustainability in the AEC industry with the help of BIM-integrated LCA and prefabricated construction.

1.2. Scope of the work

This thesis focuses on BIM-integrated LCA Tools and their assessment for prefabricated constructions. There are many LCA studies in the literature. Databases, LCA ratings, and certifications are also important parts of this research area. However, they are not a part of the present study.

The working approach consists of four phases (Figure 1).

Figure 1 – Working phases of the thesis

Phase A: Introduction and basics

Chapter 1 gives a general introduction to the problem and objective of this thesis and the structure. Chapter 1.1 shortly explains the structure of the work, and then Chapter 2 concentrates on the background of research subjects and the status quo. This chapter also describes the terms of prefabricated construction, BIM, life cycle assessment of prefabrication and their influencing factors. According to the literature review conducted in Chapter 2.3, Chapter 2.4 explains the research questions and hypotheses.

Phase B: Evaluation of the BIM integrated LCA tools

Chapter 3 focuses on the methodology of this study. This part is followed by the analysis chapter, which evaluates the BIM-integrated tools. Here, it is focused on the BIM-integrated LCA tools that are currently available on the market. According to their limitations and use cases, two of these applications are selected for further analysis. The next part describes these two selected BIM-integrated LCA tools followed by a comparison which provides information about the potential and application limits for prefabricated constructions.

Phase C: Case study on real construction projects

This phase begins with a detailed description of the case study projects in Chapter 4.2. These projects are provided by a prefabricated timber construction company in Austria and are realized by the time of writing this thesis. Then the case study projects will be tested according to the two BIM-integrated LCA applications which are checked in Phase B. Different uses of the buildings and materials will be taken into account. After that, the results achieved via these BIM-integrated LCA tools will be presented, including different user experiences, workflows, and LCA results.

Phase D: Summary and Outlook

The final phase of this thesis starts with Chapter 5. The results and challenges that are faced during the use of the software solutions will be summarized and discussed. This thesis ends with a perspective of possible future developments.

2. Background and State of the Art

This chapter describes the historical background and current situation of the research areas of this thesis, which are prefabrication, LCA, and BIM. In addition, a literature review is conducted to show the relations between the subjects. All of the parts provide a basis for the findings and justify the research questions and methods.

2.1. Background

2.1.1. Background – Prefabrication

As a building method, prefabricated construction intends that most of the building components are premanufactured or preassembled, and transported to the project site for installation (N. Davies & Jokiniemi, 2008, p. 292). Today, various terms are used to refer to buildings that use this method of construction, such as prefabricated construction, preassembly, modularization, modular construction, off-site fabrication, off-site production, or industrialized building (Cao et al., 2015, p. 131). In this thesis, buildings using prefabrication technology will be referred as "Prefabricated Construction".

Even though today's prefabricated construction is thought as a "modern" method in the construction industry, it has been used for hundreds of years. There are currently different prefabrication methods, but one common point of all is that prefabricated construction offers high predictability due to its level of standardization. (Ferdous et al., 2019, p. 883 ff.).

One of the earliest prefabrication examples in architecture history is Crystal Palace in London. This well-known building was built in 1851 for Britain's Great Exhibition. In only a few months, J. Paxton's project was realized partially with prefabricated cast iron and glass elements (Figure 2). Later, it was disassembled and rebuilt in another location in south London (McKean et al., 1994).

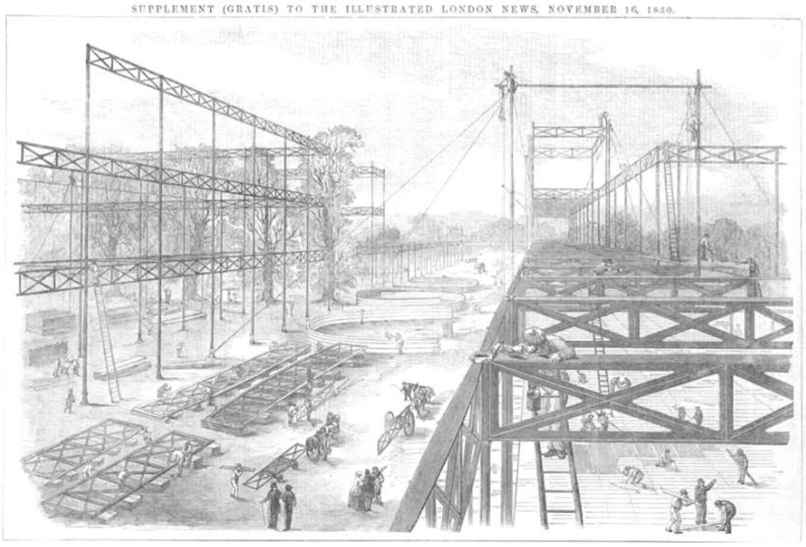


Figure 2 – Illustration of Crystal Palace Construction. Reprinted from" The Great Exhibition of 1851 - General View of the Works" in Illustrated London News, November 16, 1850, p. 16.

In the housing sector, prefabrication in architecture became more visible with Modernism. Davies (2005) explains this trend with the motivation of Modernism that wanted to bring the architecture to the masses and to create houses like factory-made cars. With the help of new developments of concrete use from the beginning of the 20th century, architects could now design prefabricated houses and try to make this dream real.

At that time, Le Corbusier was one of the first architects who had that vision of mass production in architecture. In 1923 he wrote a short chapter called 'Mass production houses' in his book *Vers une architecture*. Later he did his first project in this direction, the *Maison Citrohan* (Figure 3). The name was inspired by the French car brand *Citroën* to stress that this house can be seen as a product like a factory-made car. The materials and elements were designed for standardization. Finally, the *Maison Citrohan* was built in different cities and with different combinations 30 years after the first design. However, it never reached Le Corbusier's aim to be fully factory-made, and it was far from reaching the masses (C. Davies, 2005, p. 11 ff.).

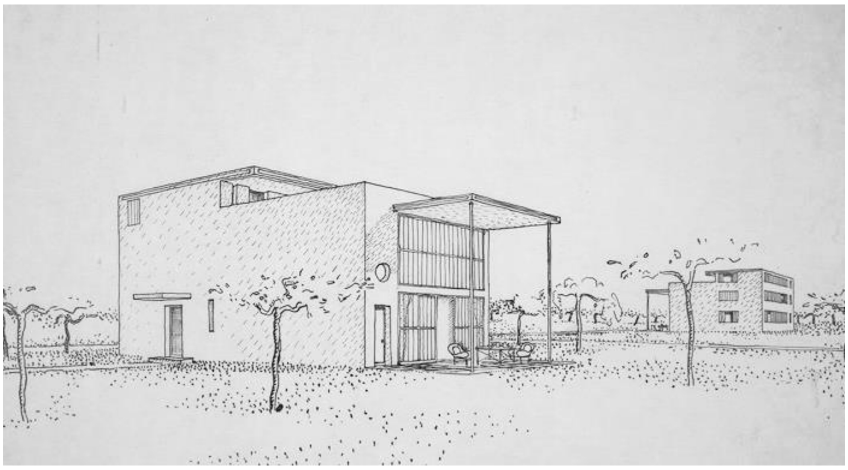


Figure 3 – Maison Citrohan. Reprinted from "Maison Citrohan, not located, 1922", n.d. Retrieved Juli 3, 2020 from Fondation Le Corbusier.

Davies (2005) notes that the non-architectural part of the history of prefabricated construction started even a bit earlier with the "balloon frame" invention in 1833. After a while, so-called "catalog houses" reached the masses in the USA. Between 1908 and 1940, the prefabricated housing sector had grown massively. Over 500.000 catalog houses were built with the method of prefabricated construction. Different companies offered mail-ordered houses. For example; one of the most famous of them, *Sears Roebuck & Co.,* claimed that the labor costs of these houses were 40% less than a conventional house (C. Davies, 2005). In 1937 the company wrote in one of their catalogs:

> *This is the age of modern efficiency. No longer can human hands compete with machine precision and production. Speed with accuracy is the watchword in any department of our great factory (Stevenson et al., 1986, p. 21).*

Prefabrication was even more popular after World War I and World War II because it offered minimum costs, quick construction, and, again, efficiency. So, many emergency buildings such as hospitals and schools were built by this method in the post-war years. Prefabricated housing became an effective solution to the housing shortage. However, these structures were also mostly poorly designed or had bad construction quality. Besides, these buildings often were criticized as inflexible and boring because of their orthogonal components and repetition of the elements. These had changed the image of prefabrication for designers. As a result, prefabricated constructions disappeared in nearly a few decades (C. Davies, 2005).

In the last decades of the 20th century, architects had started to be interested in prefabrication again when new technologies and building materials emerged (Pons, 2014, p. 436 ff.). Although prejudices of quality and inflexibility still exist for some design experts till today, the benefits of prefabrication are significant. Due to the standardization of the elements and production process, currently, prefabricated construction is fast, safe, and creates less waste than conventional construction methods. (Knaack et al., 2012, p. 8 f.). Therefore it is safe to say, today prefabrication finally made its second coming, and it does not seem to disappear again (Bernstein, 2015).

Today it is not possible to mention one kind of prefabrication. According to Pons (2014), prefabricated buildings can be categorized under different parameters, as follows:

- industrialization
- prefabrication amount
- standardization (repetition and modulation of prefabricated elements in a building)
- automation (amount of mechanical and automatic processes without direct human intervention)
- flexibility
- completeness (if the system employed is used to build the whole building or only parts of it)
- structural behavior (Pons, 2014, p. 437).

To the classification of Pons, it is possible to add:

- the disassembly and reuse amount of the material
- system of prefabrication

The criteria, such as standardization and completeness of the construction, are essential aspects of prefabrication. For example, modular construction, a type of prefabrication, is based on the standardization of construction elements and the repetition of the constructed modules. That is why, modular construction is mainly used in residential buildings, hospitals, and offices where these repetitive units are common (Ferdous et al., 2019, p. 883).

While early prefabricated buildings had a reputation of having low construction standards, the quality of the constructions changed to the opposite with the help of technological and material developments. In the end, whatever the type of prefabricated construction method is - because the manufacturing process is made in a controlled environment - controlling and evaluating the resource efficiency is easier, and the quality is higher than conventional on-site construction methods (Santana-Sosa & Fadai, 2019, p. 148 ff.).

2.1.2. Background – LCA

Life Cycle Assessment (LCA) is a well-known approach to assess the environmental impacts of the products, services, or activities. Although the first thoughts of LCA for products go back to the 1960s and 1970s, LCA started to become a part of the legislation and procedures with the involvement of the International Organization for Standardization (ISO) in 1994 (Guinée, 2012, p. 9 f.). Besides other sectors, since the 1990s, LCA studies are also used to evaluate buildings and building materials in the construction sector.

The process of LCA is currently defined in two international standards, ISO 14040 and 14044. According to the standards, LCA is described as *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (ISO 14040, 2006, p. 7). It is planned to assist in improving the environmental performance of the products, identifying the possibilities for improvement, selecting relevant indicators and measurement systems and informing the industry about these (ISO 14040, 2006).

LCA studies include four phases. These are:

- the goal and scope definition
- inventory analysis LCI
- impact assessment LCIA
- interpretation

The relationship between the phases is illustrated in Figure 4 (ISO 14040, 2006).

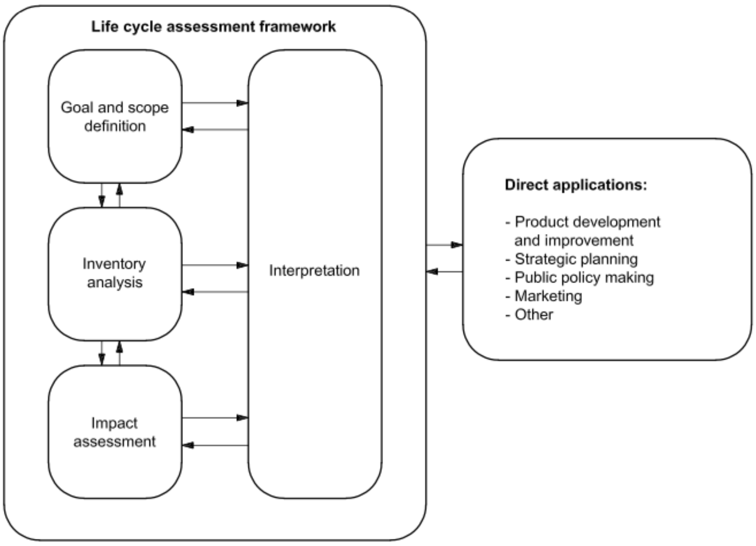


Figure 4 – Stages of LCA. Reprinted from "ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework" by International Standard Organization, 2006.

LCA of buildings is defined by standard EN 15643:2010. According to that, the life cycle of a building includes four stages (Figure 5): Product Stage (A1-A3), Construction Process Stage (A4-A5), Use Stage (B1-B5), and End-of-life Stage (C1-C5). Module D is defined as *"Supplementary Information Beyond the Building Life Cycle."* This module includes reusing, recycling, and recovering the potential of the building elements (EN 15643-2, 2011). Module D is currently used optionally in building assessment. However, it allows benefiting from recycling and reusing potentials of the construction.

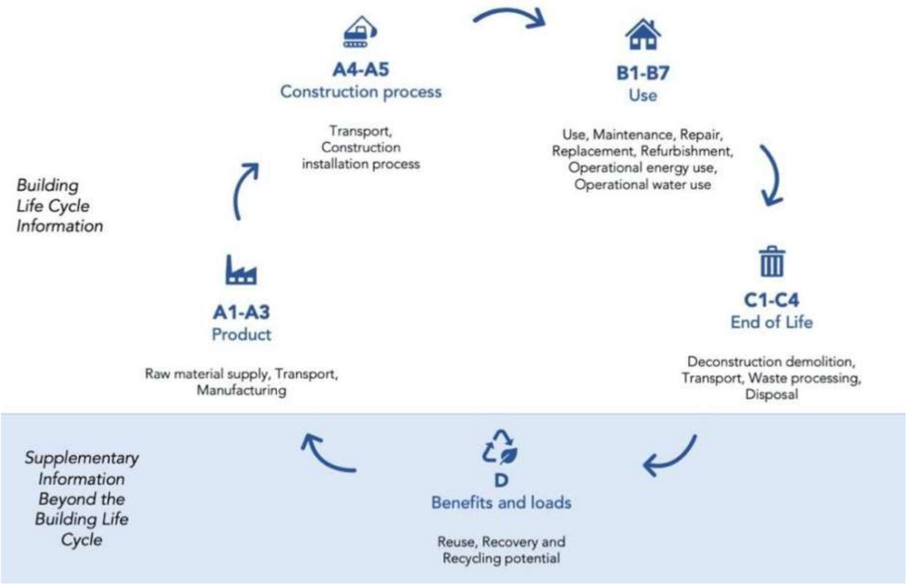


Figure 5 – Life cycle modules based on ISO 14040. Adapted from "ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework" by International Standard Organization, 2006.

Since the 1990s, LCA studies have been developed fast. Although today LCA is globally recognized as a complete tool for building environmental impact assessments, it is still not widely used in the construction industry. Lack of information, complex and time-intensive processes and the necessity of expertise are some reasons for that (Shahabian et al., 2020). Therefore, researchers suggested a few approaches to simplify the process, such as reducing the data acquisition phase by focusing on larger building elements, simplifying inventory analysis, simplifying the calculation, and reducing the time by using CAD applications (Cavalliere, 2018, p. 31 ff.).

The EeB Guide Project provided a guidance document to the LCA experts defining how and when to perform simplifying approaches according to the need and scope of LCA studies. Based on this document, there are three different types of LCA studies:

- Screening LCA
- Simplified LCA
- Complete LCA (*EeBGuide Project*, 2012).

As shown in Figure 6, the studies could be iteratively performed by need, level of detail, and different stakeholders.

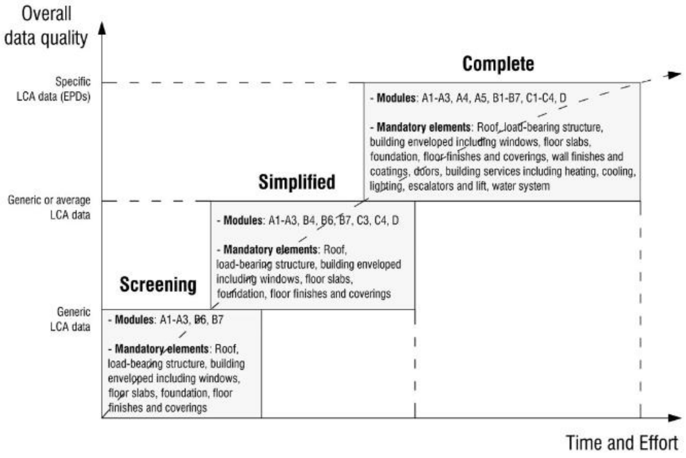


Figure 6 – LCA study types, based on EeB Guide Project, 2012. Reprinted from "BIM-led LCA" by C.Cavalliere, 2018.

2.1.3. Background – BIM

Building Information Modeling (BIM) is a well-known term in the AEC industry today. The technology of drawing systems like Computer-aided design (CAD) made it possible to model complex structures, and it also helped to open the door to create new building forms. In this regard, BIM opens new "doors" and promises a fundamental change in planning, construction, and operational processes (I. Kovacic, 2012).

As we know it today, the first concept of BIM dates back to the late 1970s. It was called "Building Description Systems" and designed as a building database for easier coordination in the project processes by Prof. Eastman (1975, p. 46 ff.). Today BIM is not only a database; it has several faces. It is used as a process, a management method, and a data representation. BIM is transforming AEC industry by defining new working processes, responsibilities, and planning roles. However, as Cavalliere (2018, p. 63 f.) states, this transformation is also a "necessary evolution" regarding the increased complexity of the projects.

The strength of BIM comes from allowing a more collaborative information flow. Different disciplines and stakeholders add the information embedded in a digital model such as design, MEP-engineering, costs, or construction. With these involvements, BIM becomes an object-oriented digital representation of a building that can include both geometric and non-geometric data through its life cycle (Figure 7) (Cavalliere, 2018, p. 74 f.; Gu & London, 2010, p. 988).

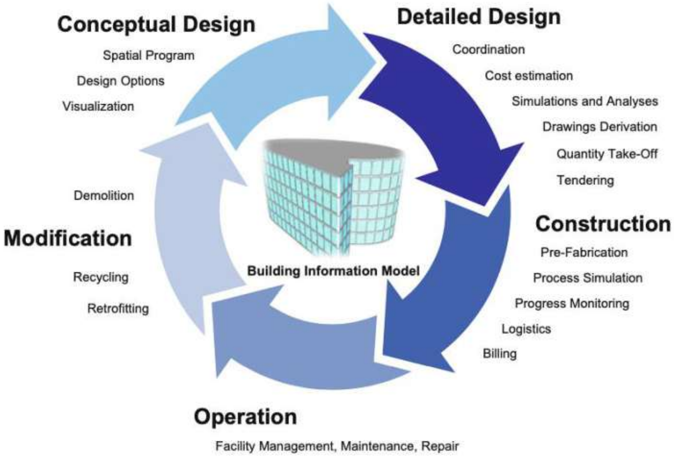


Figure 7 – The concept of BIM. Reprinted from "Building Information Modeling: Technology Foundations and Industry Practice" by A.Borrmann, M.König, C.Koch, and J.Beetz, 2018.

According to different stakeholders and project stages, information in a BIM model can also vary. BIM dimensions define which specific kind of data is embedded in a BIM model. These dimensions start from 3D and could be linked up to nD. In other words, the 3D means a building model itself, the 4D is a model that includes time-related data, and the 5D is a model that includes cost-related data. The 6D and 7D dimensions are also mentioned in recent research, although there is no general agreement for the definitions of these dimensions yet (Cavalliere, 2018, p. 74 f.). According to Charef et al. (2018), the industry uses mainly the name "sustainability" for 6D and "facility management" for 7D (Figure 8).

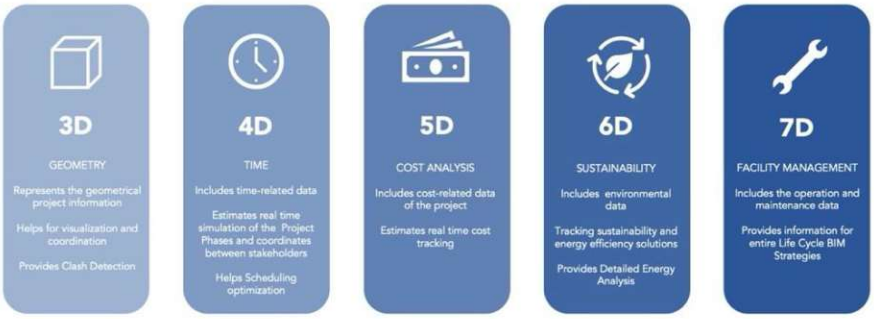


Figure 8 – BIM Dimensions. Adapted from "Beyond the Third Dimension of BIM" by R. Charef, H. Alaka, S. Emmitt., 2018.

The collaborative information flow of BIM depends on data exchange between the multidisciplinary stakeholders. It also indicates the problems of interoperability between the different formats and interfaces. Therefore, certain data exchange standards are created. For example, Industry Foundation Class (IFC) is a widely recognized standard for interoperability developed by *buildingSmart International*. IFC makes it possible to exchange data between different software applications and it includes both geometric and semantic information of the building elements (Cavalliere, 2018, p. 74 f.).

Another common standard is green building XML (gbXML). gbXML is an open schema operating between BIM and energy analysis tools. It transfers the related data such as the data of geometry or properties which is stored in the BIM model to the energy analysis tools (gbXML, n.d.).

Transitioning to BIM to fully collaborate in construction projects is a complex and tedious process for the AEC industry. The UK BIM Task Group (Bew & Richards, 2011) recognized this challenge in 2008 and developed a model called "BIM Maturity Levels" which explains the levels of a BIM implementation (Figure 9) (Borrmann et al., 2018, p. 13 ff.).

According to Bew and Richards (2011), there are four levels of a BIM implementation:

Level 0 explains the phase of working with paper-based 2D CAD drawings. In this phase, information is shared through these paper-based drawings.

Level 1 requires a partial 3D model, although the main design is still made in 2D. Data exchange is based on separate files shared between the stakeholders, but interoperation is still not available.

It is possible to mention a BIM model collaboration with Level 2. In this phase, a 3D BIM model of the project involves sub-models from other disciplines. This so-called federated BIM model coordinates the project, and 2D drawings of the project are extracted from this model.

Finally, Level 3 represents the concept of a complete BIM implementation which is a single project model used for collaboration. The whole data exchange is integrated into this model throughout the building's lifecycle (Borrmann et al., 2018, p. 13 ff.).

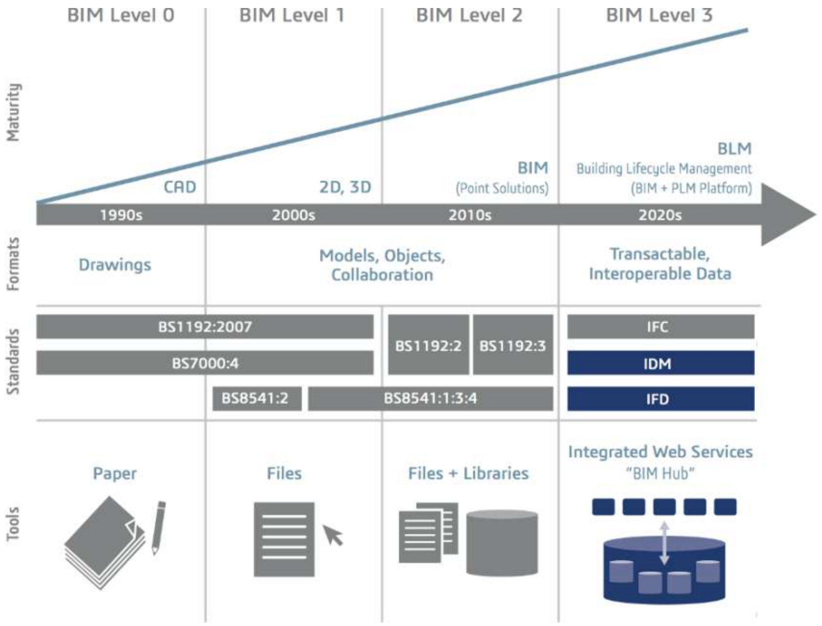


Figure 9 – BIM Maturity Levels based on Bew and Richards, 2008. Reprinted from "End-To-End Collaboration Enabled By BIM Level 3" by Dassault Systems, 2014.

There are different ways of working with BIM; open vs. closed BIM and little vs. big BIM. Little and big BIM differentiate in the *"extent of BIM use"* cases. While open or closed BIM distinguishes if BIM use is based on an *"insular solution"* or not (Borrmann et al., 2018). Borrmann et al. (2018) explain the concepts with the matrix below (Figure 10).

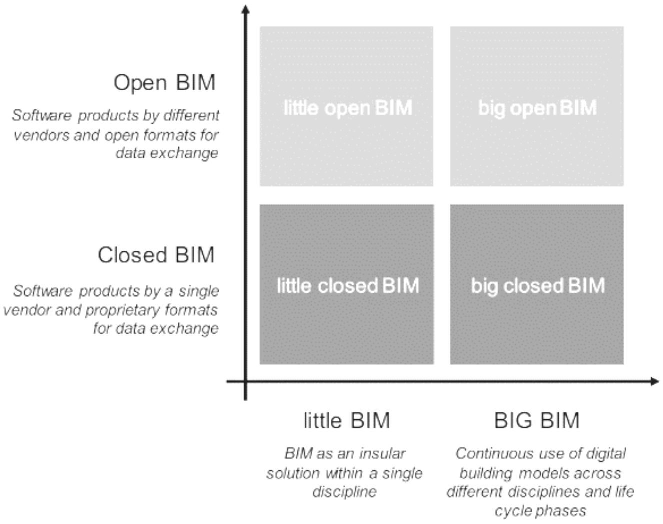


Figure 10 – BIM Usage Matrix. Reprinted from "Building Information Modeling: Technology Foundations and Industry Practice" by A.Borrmann, M.König, C.Koch, and J.Beetz, 2018.

Level of Development (LOD) is a BIM concept refers to the amount of information in the BIM model. It was developed by *Vico Software Company*. Later the *American Institute of Architects* (AIA) and the *BIMForum* worked on this concept and updated the specification. In 2008, AIA defined five stages of LOD: from LOD 100 to LOD 500. The higher the LOD number is, the more detailed BIM models become. Later in 2013, *BIMForum* published an updated LOD specification which included a new level, LOD 350, and deleted the LOD 500 (Cavalliere, 2018). As explained in Table 1, LOD is also an essential concept for LCA-BIM implementations.

Table 1 – Comparison of different LOD definitions of *AIA* and *BIMForum*. Reprinted from "BIM-led LCA" by C.Cavalliere, 2018.

<table>
<tr><th>LOD</th><th>AIA Document G202-2013</th><th>BIMForum (2018)</th></tr>
<tr><td>100</td><td colspan="2">Generic representation, including symbols, showing the existence of a component but not its shape, size, or precise location.</td></tr>
<tr><td>200</td><td colspan="2">Generic representation with approximate quantities, size, shape, location, and orientation.</td></tr>
<tr><td>300</td><td colspan="2">Specific representation in terms of quantity, size, shape, location, and orientation as designed can be measured directly from the model without referring to non-modelled information for the manufacture of the component.</td></tr>
<tr><td>350</td><td>Not defined</td><td>Specific representation in terms of quantity, size, shape, location, and orientation, including interfaces with other building systems and such items as support and connections.</td></tr>
<tr><td>400</td><td colspan="2">Specific representation in terms of quantity, size, shape, location, and orientation with detailing, fabrication, assembly, and installation information.</td></tr>
<tr><td>500</td><td>Corresponding to the as-built model, since it belongs to the field of the representation of the elements checked in the building site.</td><td>Not defined</td></tr>
</table>

2.2. State of the Art

2.2.1. State of the Art – Prefabrication

Off-site construction and manufacturing have been gaining attention in the last years resulting in a large number of studies in the field of research. The current technological research and development can be categorized as Design and Planning, Fabrication, Transportation, Construction, Operation, and Beyond (Hou et al., 2020).

The prefabricated construction world shapes itself new again and gets ready for future changes and challenges in the sector. BIM, the development of CNC technologies, and new materials such as CLT have already brought a new life to the industry (Pons, 2014). Also, automation, lean construction, affordable housing, resource efficiency, and reuse of the systems and materials have been key topics. The prefabrication's tomorrow will be strongly affected by the development of BIM, resource efficiency and circular construction, robotics and 3-D printing, and mass customization (Fadai & Stephan, 2019, p. 1 ff.; Honic et al., 2019, p. 795 f.; Yin et al., 2019, p. 85). Moreover, BIM for prefabrication benefits and their assessments, cloud BIM-based data exchange for OSC, and BIM-enabled big data analytics towards best OSC practice were suggested as further potential research subjects (Yin et al., 2019, p. 72 ff.).

The study from Aberger (2017) shows that integrated design practice will replace the linear planning process also in prefabricated timber construction. This practice reduces the loss of information between technical planners and designers. With the combination of BIM, the highest efficiency can be reached by minimizing the loss of information and planning errors through central data management. However, Aberger (2017) notes that timber construction differs from conventional methods. Therefore, it is still necessary to think about the processes and standards and create guidelines regarding timber construction to fully adopt and use the potential of BIM and integral planning.

The transition to the circular economy has become a central theme also for the construction industry. Similar to Aberger's (2017) notes, the circular economy approach in the AEC industry breaks the linear model and creates a building design optimized to reuse and recycle or minimize and eliminate waste.

Prefabricated constructions come forward with their advantages in DFMA, DFD, resource, and waste efficiency so that they become an integral part of the current circular economy research and discussions for buildings.

The project *The Cradle* in Düsseldorf is one of the latest examples of this approach. *HPP Architekten* designed the 5800 m² project according to "Cradle-to-cradle" principles. The office building is created as a material warehouse, and therefore its timber hybrid structure is planned with details that allow easy disassembly and reuse of its elements (HPP Architekten, 2021). That is why, unlike the conventional planning methods, the sustainable and detailed design of the end-of-life phase of the building was highly essential for the project(*The Cradle*, 2021).

The example of *The Cradle* shows that prefabricated timber construction needs a change of thinking and design processes focusing on sustainability. While the challenge is not to make better-detailed solutions or more efficient designs anymore, the future of prefabrication depends on the flexibility and reusability of systems, sustainability, and ability to recycle materials (Knaack et al., 2012, p. 115 ff.).

2.2.2. State of the Art – LCA

Supporting sustainability goals changed how the construction sector is acting. LCA studies for the new buildings have become more in demand and have been widely researched in the last three decades (Yılmaz & Seyis, 2021). However, prefabricated construction has just started to be interesting in the research area. Prefabricated construction has lower environmental impact on the construction stage and end-of-life stage. It also shows better performance in reusing and recycling materials than non-prefabricated ones (Pons, 2014; Wadel, 2009). Therefore assessing the life cycle of the prefabricated constructions is significantly important. As a result, it contributes to the sustainability of the AEC industry.

However, Kotula (2020) stressed that the LCA research still lacks clear frameworks. Various tools and methods differ in many levels, such as impact categories, system boundaries, and calculation scheme. Similarly, Forth (2018) also mentioned that BIM model and LCA integration for BIM-based LCA is still a big challenge.

Cavalliere et al. (2019) noted another critical point about LCA calculation based on a BIM model. If the project BIM model updates materials or quantity, most tools do not auto-update and generate the assessments in real-time.

Lu et al. (2021) stated that declaration of LOD in studies mainly was lacking according to their review. Furthermore, they found out that LOD 300 and up is suitable for integrating LCA and LCC into BIM (Lu et al., 2021).

LCA studies today extend their scope for a holistic approach not only to environmental impact but also to financial and social impacts. In this context, Life Cycle Sustainability Assessment (LCSA) is a model suggested by Kloepffer (2008) and Guinée (2012), which extends the LCA Studies with Life Cycle Cost (LCC) and Social Life Cycle Assessment (SCLA). LCC analysis is developed to research the economic impact during a building's life cycle, and SLCA investigates the social aspects. (Guinée, 2012, p. 90 ff.; Kloepffer, 2008, p. 89 ff.).

Parallel to the holistic approach in LCA, Circular Economy is an economic model that took attention in construction in the last decades. Circular Economy is a key concept where the building's resources are kept in a *"closed-loop at their highest value."* (Ellen MacArthur Foundation, 2017). This means that buildings are managed as "material banks"; components should be deconstructed at their end-of-life phase so that building materials can be reused (*BAMB2020*, n.d.).

Mhatre et al. (2021) mention that the adoption of the Circular Economy in the construction industry took longer than other products. Moreover, this could be supported now with complete LCA studies (Mhatre et al., 2021).

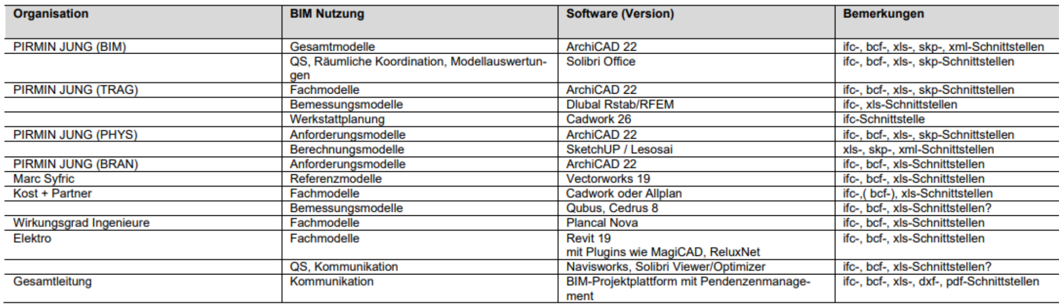
2.2.3. State of the Art – BIM

BIM offers a lot to the AEC industry. Instead of a linear work process, it suggests an integrated planning process. BIM helps to create sustainable construction projects and leads to performance improvement by accurate information and less errors. In the end, BIM leads to a higher quality of projects and cost savings (Cavalliere, 2018). However, in order to go further, a holistic and long-term approach is crucial in BIM (I. Kovacic, 2012).

Nyffeler (2017) says that the digital revolution in the construction industry is currently known with the names BIM and also Virtual Design and Construction

(VDC). *The Center for Integrated Facility Engineering Stanford* defines VDC as "*the use of multidisciplinary performance models of design-construction projects, including the product (i.e., facilities), work processes, and organization of the design-construction team to support business objectives*" (Fischer & Kunz, 2004, p. 5). VDC is also a superior term that combines BIM with process and organization. Kunz and Fischer (2020) explain the meaning of BIM for VDC as BIM describes the content and *"focusses on the building physical elements of the VDC Model."* Although the BIM content of building elements and systems is valuable, they also mention that it is limited to manage the entire project-related interactions with this content. Therefore, VDC uses - and needs - BIM as one of its core elements with Integrated Concurrent Engineering (ICE) and Product Production Management (PPM).

Additionally, Nyfeller (2021) explains how a timber building company can use the VDC with their own project example. She notes that even though there is currently no single tool satisfying the needs of various integrated planning departments, BIM still opens new potentials for timber construction. (Figure 11).



Organisation	BIM Nutzung	Software (Version)	Bemerkungen
PIRMIN JUNG (BIM)	Gesamtmodelle	ArchiCAD 22	ifc-, bcf-, xls-, skp-, xml-Schnittstellen
	QS, Räumliche Koordination, Modellauswertungen	Solibri Office	ifc-, bcf-, xls-, skp-Schnittstellen
PIRMIN JUNG (TRAG)	Fachmodelle	ArchiCAD 22	ifc-, bcf-, xls-, skp-Schnittstellen
	Bemessungsmodelle	Dlubal Rstab/RFEM	ifc-, xls-Schnittstellen
	Werkstattplanung	Cadwork 26	ifc-Schnittstelle
PIRMIN JUNG (PHYS)	Anforderungsmodelle	ArchiCAD 22	ifc-, bcf-, xls-, skp-Schnittstellen
	Berechnungsmodelle	SketchUP / Lesosai	xls-, skp-, xml-Schnittstellen
PIRMIN JUNG (BRAN)	Anforderungsmodelle	ArchiCAD 22	ifc-, bcf-, xls-Schnittstellen
Marc Syfric	Referenzmodelle	Vectorworks 19	ifc-, bcf-, xls-Schnittstellen
Kost + Partner	Fachmodelle	Cadwork oder Allplan	ifc-,(bcf-), xls-Schnittstellen
	Bemessungsmodelle	Qubus, Cedrus 8	ifc-, bcf-, xls-Schnittstellen?
Wirkungsgrad Ingenieure	Fachmodelle	Plancal Nova	ifc-, bcf-, xls-Schnittstellen
Elektro	Fachmodelle	Revit 19 mit Plugins wie MagiCAD, ReluxNet	ifc-, bcf-, xls-Schnittstellen
	QS, Kommunikation	Navisworks, Solibri Viewer/Optimizer	ifc-, bcf-, xls-Schnittstellen?
Gesamtleitung	Kommunikation	BIM-Projektplattform mit Pendenzenmanagement	ifc-, bcf-, xls-, dxf-, pdf-Schnittstellen

Figure 11 – Used software - Reprinted from "Digitale Transformation eines interdisziplinären Ingenieurbüros für Holzbau" by A.Nyffeler, 2021.

Therefore VDC suggests that it is essential not to focus on the software but the method and potentials. According to this approach, a hierarchic central database with part-BIM models and other integrated data should be created to manage an interdisciplinary working environment (Nyffeler, 2021) (Figure 12&13).

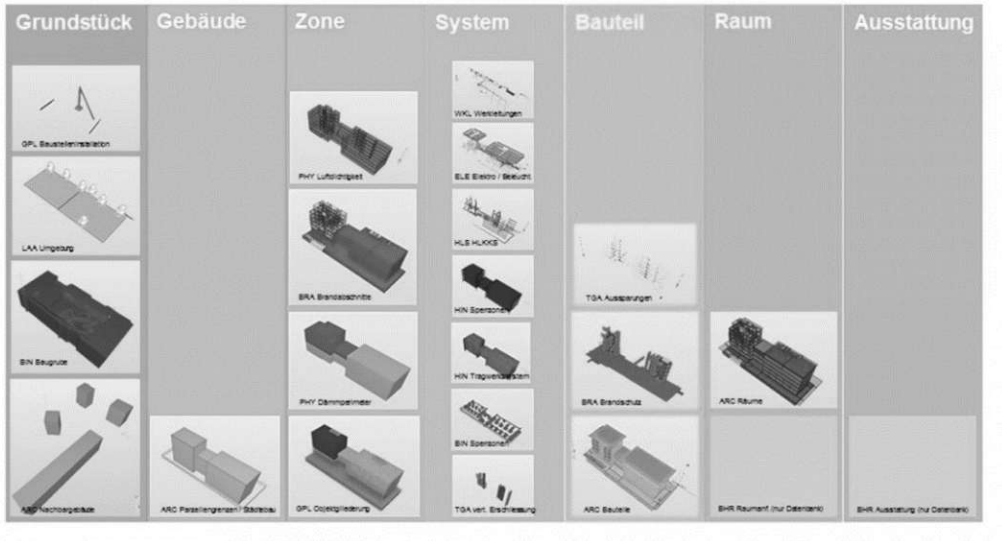


Figure 12 – Part Bim Models. Reprinted from "Digitale Transformation eines interdisziplinären Ingenieurbüros für Holzbau" by A.Nyffeler, 2021.

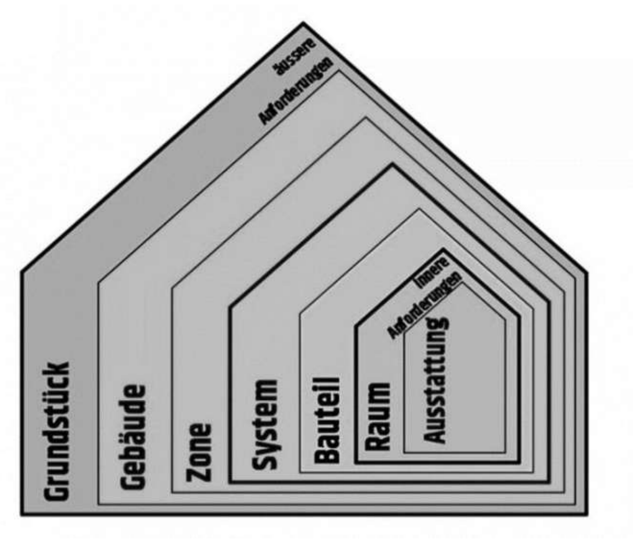


Figure 13 – Hierarchic data container system. Reprinted from "Digitale Transformation eines interdisziplinären Ingenieurbüros für Holzbau" by A. Nyffeler, 2021.

In his book "The BIM Manager", Baldwin (2019) explains a similar problem as an "one model myth". He notes that the idea of one single BIM model is not realistic and it gives the false promise that every project data is available for every project participant. According to Baldwin (2019), firstly, it is impractical to work with one model, and secondly, there are no software products available covering every project phase and works. Therefore, working on exchange formats

– e.g., open BIM solutions – to create a practical project workflow for different disciplines is crucial.

As already mentioned, the importance of the BIM platform comes with the collected data through a project's and buildings' life cycle by project participants. This collected project data creates an excellent basis for integrating LCA and LCC to BIM for further analysis (Santos et al., 2019). Recent studies have contributed significantly to the integration of BIM-based LCA.

The application and integration of BIM-based LCA have been analyzed in various studies (Abanda et al., 2017; Ansah et al., 2021; Bueno & Fabricio, 2018; Cavalliere, 2018; Eleftheriadis et al., 2017; Forth et al., 2019, 2019; Hammad et al., 2019; Kim, 2019; Liu et al., 2021; Najjar et al., 2019; Röck et al., 2018; Santos et al., 2019; Soust-Verdaguer et al., 2020). Lu et al. (2021) reviewed the studies focusing on BIM integration of LCA and LCC in a novel paper. According to this paper, the studies had various focuses such as the life cycle stages of a building, LODs, use cases, BIM software, and LCA Database. Lu et al. (2021) show that current research focuses more on early design stages rather than other stages. They also noted that 72% of their reviewed case studies used BIM only for exporting data to external software such as Excel sheets for the bill of quantities. (Lu et al., 2021).

The digital twin is also a frequent concept in BIM studies. *Autodesk (2021)* defines it as follows: *"A digital twin for AEC is a dynamic, up-to-date replica of a physical asset or set of assets—whether it's a building, a campus, a city, or a railway—that brings together design, construction, and operational data."* The determining point of a digital twin is that it is dynamic and never done. Although creating a digital twin without BIM is possible, BIM gives an excellent fundamental beginning for these dynamic systems and data integrations to run efficiently (Autodesk, 2021) (Figure 14).

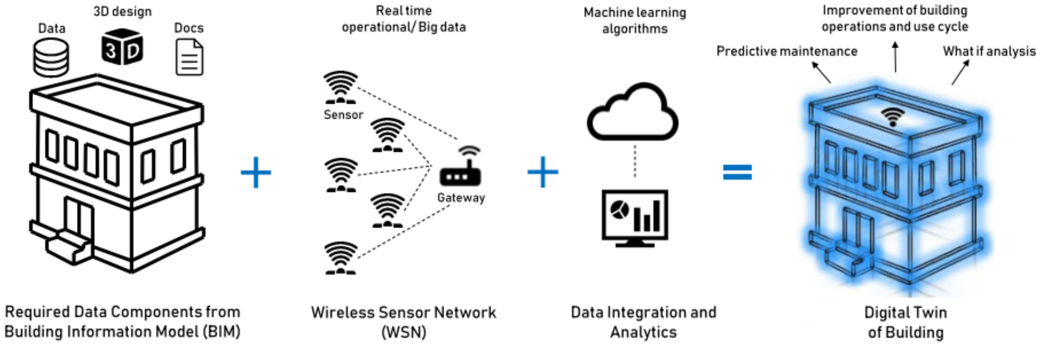
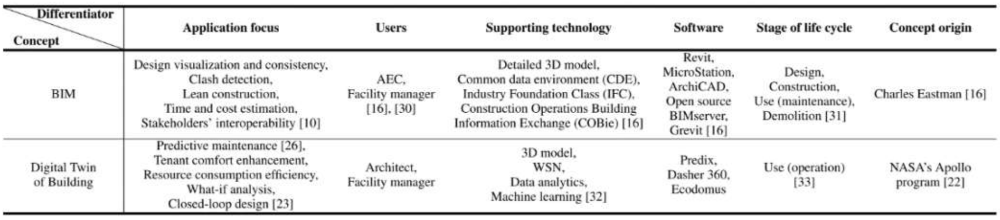


Figure 14 – Essential components to create a digital twin of building and difference with BIM. Reprinted from “Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings” by S. Khajavi, N. Motlagh, A. Jaribion, L.Werner, and J. Holmström, 2019.

Khajavi et al. (2019) compare digital twins for buildings and BIM in their paper and explain how they are connected (Table 2). Digital twins for buildings are important, especially if operation and use phases of the projects are going to be researched and monitored. Additionally, they store the data for the Circular Economy research of the projects during the building’s whole life cycle.

Table 2 – A detailed comparison of BIM and digital twin of building. Reprinted from “Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings” by S. Khajavi, N. Motlagh, A. Jaribion, L.Werner, and J. Holmström, 2019.



Differentiator / Concept	Application focus	Users	Supporting technology	Software	Stage of life cycle	Concept origin
BIM	Design visualization and consistency, Clash detection, Lean construction, Time and cost estimation, Stakeholders’ interoperability [10]	AEC, Facility manager [16], [30]	Detailed 3D model, Common data environment (CDE), Industry Foundation Class (IFC), Construction Operations Building Information Exchange (COBie) [16]	Revit, MicroStation, ArchiCAD, Open source BIMserver, Grevit [16]	Design, Construction, Use (maintenance), Demolition [31]	Charles Eastman [16]
Digital Twin of Building	Predictive maintenance [26], Tenant comfort enhancement, Resource consumption efficiency, What-if analysis, Closed-loop design [23]	Architect, Facility manager	3D model, WSN, Data analytics, Machine learning [32]	Predix, Dasher 360, Ecodomus	Use (operation) [33]	NASA’s Apollo program [22]

Other research areas are also developed with the data-driven construction and potentials that BIM creates. One of them is investigating the material potential of buildings. As they are called, *Material Passports* show information of buildings’ existing materials and their recycling potentials (Honic et al., 2019). *Material Passports* are necessary to apply Circular Economy successfully in the built environment. They help to acquire and manage the information through the building's life cycle, such as material properties, quantity, environmental impacts.

BIM-based digital workflows for Material Passports uses BIM as a data container for already available and collectible information from models.

Parallel to the UN sustainability goals 2030, Buildings as Materials Banks (BAMB) work to create a circular solution for the AEC industry. As a part of this solution, BAMB work on analyzing the material value of buildings via BIM-based *Material Passports* in order to create less waste and increase resource efficiency (*BAMB2020*, n.d.). Also, some private institutions are working and providing platforms specializing in this topic, such as *Madaster* and *Concular* (van den Bosch & Campanella, 2021).

2.3. Literature Review

The literature review of this study is based on current literature. Only literature in the English language is selected for further analysis, and the type of literature is limited to book chapters, journal articles, and conference proceedings. The review is conducted to discuss research about "Life Cycle Assessment," "Building Information Modelling," and "Prefabrication." To understand the status quo of the subjects, first, the keywords are defined, and then keywords and their combinations are searched in multiple online databases such as Scopus, Web of Science, and Google Scholar.

Existing literature related to the subjects is retrieved by using various keywords for each subject. The keywords used for the search are shown in Figure 15. The key aspects of this review are well-connected with technological developments. Therefore, the articles between 2010 And 2021 are taken into account in the search. It is observed that there is a higher tendency on the number of articles researched on these subjects in the last five years.

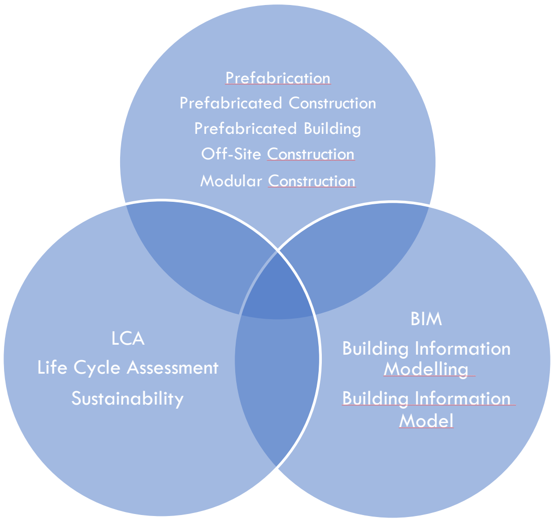


Figure 15 – Keywords used for search.

Initially, the articles that are not falling into the AEC category and do not focus on the subjects of the thesis are removed, and 27 articles are reviewed. Finally, the key findings of the literature review are divided into three groups according to their focus and relevance to the thesis.

2.3.1. Prefabrication and LCA

The life cycle performance and environmental impacts of prefabricated constructions are well-researched subjects. In the case of environmental impacts, many studies show that prefabricated construction demonstrates more advantages compared to conventional methods (e.g., Cao et al., 2015; Kamali & Hewage, 2016; Pons, 2014).

Pons (2014) suggested that according to his case study, in which prefabricated and on-site school projects in Catalonia were compared, prefabricated construction is more sustainable than on-site construction. Nevertheless, the sustainability grade of a building project depends on the decision of prefabricated technology and the transportation distance between the production plant and construction site. (Pons, 2014, p. 451 f.).

In their comparative study, Cao et al. (2015) also illustrated that a prefabricated sample building was more efficient than a traditional residential building. The prefabricated sample had 20% less total energy consumption, 36% less resource depletion, and 3% less ecosystem damage.

Similarly, Kamali and Hewage (2016) confirmed that modular construction methods had lower environmental impacts and provided better life cycle performance than conventional methods, especially regarding the end-of-life and the construction phases. However, it was also observed that LCA of the operation and end-of-life stages in off-site constructions was mostly overlooked (Jin et al., 2020, p. 2 ff.).

Honic et al. (2019) created a material passport and compared a residential building model with two construction alternatives. The alternative with the timber construction showed positive results for cumulative recycling potential and environmental impacts.

Hong et al. (2016) compared the life cycle energy performance of prefabricated components. According to their study, transportation and on-site construction phases used slightly less embodied energy compared to the other phases. They also noted that the energy-saving range in the recycling stage of a prefabricated construction could be between 16% to 24%.

In a novel study, Tavares et al. (2021) analyzed the potential contribution of prefabrication to the EU building stock and improvements of environmental and economic impacts. Their work was based on a comparison of energy equilavalent buildings such as new prefabricated with new conventional buildings. Finally, they found out that prefabrication can reduce the embodied and end-of-life impacts immensely (embodied 40% and end-of-life 90%). They also pointed out that the carbon emission of the EU building stock could be reduced by 6% with prefabrication (Tavares et al., 2021).

Ferdous et al. (2019) also identified modular systems as sustainable construction methods. Besides, they emphasized that economic, social, and environmental impacts should be evaluated together for sustainability. However, their review of different studies showed that the assessments were limited, and mainly social and economic life cycle analyses were missing. That is why they pointed out that it is necessary to have a combined LCSA with a clear LCC and SLCA to help to reveal a realistic "sustainability score" of building projects. This score would also support the decisions in the construction industry regarding to reach sustainability goals. (Kamali & Hewage, 2016, p. 1081 f.). The paper from Jin et al. (2018, p. 1217) also underlined the need for a holistic performance indicator system including cost, social and environmental indicators for prefabricated construction projects. They pointed out that the challenges to create such a system are the decision of the system boundary and accessing the data accuracy.

Jin et al. (2020) questioned the lack of systematic review of prefabricated built facilities in their paper. They identified that most of the existing studies focused mainly on carbon emissions and energy consumption; however, only these two indicators might not be sufficient for realistic assessments. Indicators like global warming, ozone exhausting, and water consumption should be also taken into consideration.

2.3.2. Prefabrication and BIM

Like any other part of the AEC, BIM is also used more and more in prefabricated construction. Much attention has been drawn to the studies about BIM and prefabrication, especially after 2005.

However, Yin et al. (2019) underlined that less attention was directed to the combination of these subjects than conventional construction and BIM. They proposed that future research of prefabrication and BIM could improve the efficiency and quality of prefabrication with BIM-based generative design. Also, the information sharing process in prefabricated construction projects would be different with BIM. This could lead to changes in the organizational structure, such as a flatter structure instead of a vertical structure of information flow. The new organizational structure could improve the coordination between project stakeholders, materials, and the labor force leading to an increased efficiency, reduction of construction waste and environmental impacts. As mentioned before, some potential research areas were suggested as "*BIM-based generative design for prefabrication, Cloud BIM-based data exchange for OSC, robotics and 3D printing for OSC, BIM-enabled big data analytics toward best OSC practice*" (Yin et al., 2019, p. 72 ff.).

In their paper, Hao et al. (2020) pointed out that *"the framework carbon emission reduction through prefabrication based on BIM was often neglected."* This paper presented a BIM-based framework that provided a better understanding of the potential for emission reduction by using prefabrication. This framework focused on the manufacturing phase but also suggested that future studies should focus on the stages of the operation and the end-of-life (Hao et al., 2020, p. 7 f.).

Another study from Akanbi et al. (2019) developed a BIM tool named *Whole life performance estimator*. This Revit plug-in helped designers to analyze the impacts of building materials and showed the level of recoverable materials at the end-of-life phase. It supported decisions for better demolition scenarios and for the implementation of Circular Economy principles and objectives. (Akanbi et al., 2019, p. 386 ff.).

BIM-DAS Study by Akinade et al. (2015) aimed to create a *BIM-based Deconstructability Assessment Score*. According to Akinade et al. (2015), using prefabricated elements was essential to ensure the building's deconstructability because, with this method, material waste was significantly lower, and joints could easily be disconnected without damage. In the end, prefabrication could reduce up to 84.7% of construction waste. (Akinade et al., 2015, p. 174 ff.).

Hammad et al. (2019) presented a BIM integrated framework to compare modular and conventional construction methods based on economic, social, and environmental factors. Although the decision of construction method should not be generalized and should be evaluated by the project itself, they noted that modular construction was found to be cheaper compared to the costs involved in the conventional construction method (Hammad et al., 2019, p. 1266 ff.)

Ajayi et al. (2015) mentioned in their paper that prefabricated construction was highly influential in waste reduction. There were different preventive measures, and they should be implemented directly at the design stage. The widened usage of BIM would improve the situation, and together with the other measures, it could lead to a cheaper approach to waste management (Ajayi et al., 2015, p. 104 ff.).

Abanda et al. (2017) conducted a literature review for BIM-applied off-site constructions. The findings from Abanda et al. (2017) confirmed some positive arguments of the prior studies about BIM adoption. They noted that the benefits of BIM for prefabricated constructions could be even more significant than conventional construction methods. Although they pointed out that there have been challenges. They stated that most of the studies they had reviewed did not have a holistic view or use whole life cycle assessments. Due to the lack of some quantitative aspects, such as the number of components, level of prefabrication, or type of construction, it was complex to conduct a comparison between the studies.

Another study by Gbadamosi et al. (2019) focused on the design for manufacture and assembly (DFMA) and lean construction principles for prefabricated construction and assessing them through BIM. Their assessment system proposed a better understanding of *"the implications that designs have on the manufacturing and assembly process*" and therefore claimed to minimize waste and efficiency. (Gbadamosi et al., 2019, p. 22)

According to Patlakas et al. (2015), the discussions regarding the subjects BIM and prefabrication gained importance in recent years. However, little research was conducted to show the relationship between BIM and prefabricated timber construction. Therefore, their paper focused on identifying the potential, benefits, and challenges of this area.

Patlakas et al. (2015) grouped the benefits and limitations of BIM for prefabricated timber constructions under five categories: 'increasing design flexibility', 'integration in the off-site manufacturing process', 'on-site delivery, assembly, and erection process', 'structural performance', and 'environmental performance and sustainability'. They noted that the timber-based prefabricated systems have well-known and well-documented sustainability advantages. BIM-integrated information can encourage designers to use them in practice. Another opportunity of the prefabricated timber system is having the advantage of being simpler and smaller than other prefabricated systems like concrete and steel, and therefore the prefabricated timber industry could think ahead with BIM and map out the research area.

2.3.3. BIM and LCA

The combination of BIM and LCA is a widely researched topic in the literature. About 60% of the reviewed literature focuses on this area.

Kovacic et al. (2018) mentioned that it is necessary to have an integrated LCA tool as decision support for the stakeholders to be able to optimize the material inputs and energy performance. However, the lack of methodology and standards for LCA and especially for the economic aspects of LCC makes it more complicated.

Similarly, Hammad et al. (2019) noted that it is necessary to involve all three pillars of sustainability (social, environmental, and economic) to reach higher sustainability performance in the AEC industry. However, as in the review of Lu et al. (2021) noted that combining SLCA with BIM drew less attention in the research.

Furthermore, the study of Ajayi et al. (2015) also identified the increase of efficiency and time-saving opportunities with the BIM-LCA integration.

The paper by Won et al. (2016) focused on BIM-based design validation and evaluated this issue by using two case studies in South Korea. At the end of the evaluation, they showed that BIM-based design validation could reduce construction waste between 4.3 - 15.2%.

Some studies showed that the LCA tool used in the early design stage also has some limitations. Santos et al. (2019, p. 130) investigated LCA implementation to BIM in their paper. According to Santos et al. (2019, p. 130), only generic LCA data could be included in early design stages (lower than LOD 300). Additionally, in the review of Lu et al. (2021), it is also seen that BIM integration of LCA and LCC is recommended from LOD 300 and higher because this allows inserting the specific product information (e.g., EPDs).

Hollberg et al. (2020) investigated a BIM model with an LCA tool for the embodied GWP throughout the whole design stages. They found out that the embodied GWP during the design phase was evaluated twice as high as the final building.

Similarly, Soust-Verdaguer et al. (2017, p. 118) also mentioned that it is necessary to have a LOD 300 or above to achieve a complete LCA from BIM model. They also found out that it is hard to assess all of the phases – especially operation and End of Life – and most studies were required to adjust manually if the quantity and materials change (Soust-Verdaguer et al., 2017, p. 118).

Ansah et al. (2021) discussed the development of a BIM-based LCA approach for high-rise modular buildings in a novel paper. They noted that most of the studies in that area focused on the early stage, and the studies did not systematically include the different prefabrication levels. This research gap should be acknowledged.

The SWOT analysis from Anton and Diaz (2014) summarized the features of BIM-LCA integrations for early design stages. Their results are shown in Table 3.

Table 3 – SWOT analysis on BIM-based LCA for early phases, Reprinted from “Sustainable Construction Approach through Integration of LCA and BIM Tools” by L. Antón and J. Díaz (2014).

Strengths	**Weakness**
Higher capacity for accommodating the three pillars of sustainability	Different stakeholders involved must be trained to consider environmental criteria
Extended use of environmental criteria by various stakeholders	LCA process and way of presenting data are not standardized
Increased efficiency, easy to use, and less time consuming of activities	Lack of environmental data for carrying out an LCA
Avoidance of manual data re-entry and easy access to the information	Assumptions lead to increase uncertainties
More project information available during early phases	Interoperability between BIM and LCA software must be improved
Higher effectiveness of environmental assessment when performed in early design phases	
Possibility to make comparisons and chance to learn from experience	
Opportunities	**Threats**
Efforts have been undertaken by Governments to make the environmental analysis compulsory	Stakeholders are not aware of the importance of considering environmental aspects at an early stage
Increased demand for sustainable constructions in the markets	Some stakeholders refuse to implement BIM-based LCA due to the efforts required
BIM-based LCA tools exists and they only need to improve synergies	There is a lack of research and development in the construction industry
There is a real need of tools with such features in the market	The variety of stakeholders in the construction industry hinders standardisation
Tools for early design phases could contribute to change the way of working in the construction industry	Lack of interoperability between the different software systems
BIM-LCA integration make environmental assessments more acceptable for the stakeholders	

Safari and AzariJafari(2021) reviewed the articles related to BIM and LCA. They created a timeline that shows the development of BIM and LCA studies (Figure 16). They illustrated that studies focused on BIM and LCA studies developed more in the last decade. Also, they found out that studies primarily were based on generic data due to a *"lack of regionalized database or incomplete databases"* (Safari & AzariJafari, 2021, p. 13). It showed that the identification of the LOD directly impacts the quality of the results. Furthermore, Cavalliere et al.(2019) noted that different LCA databases should communicate with each other to achieve realistic LCAs for different LOD of BIM.

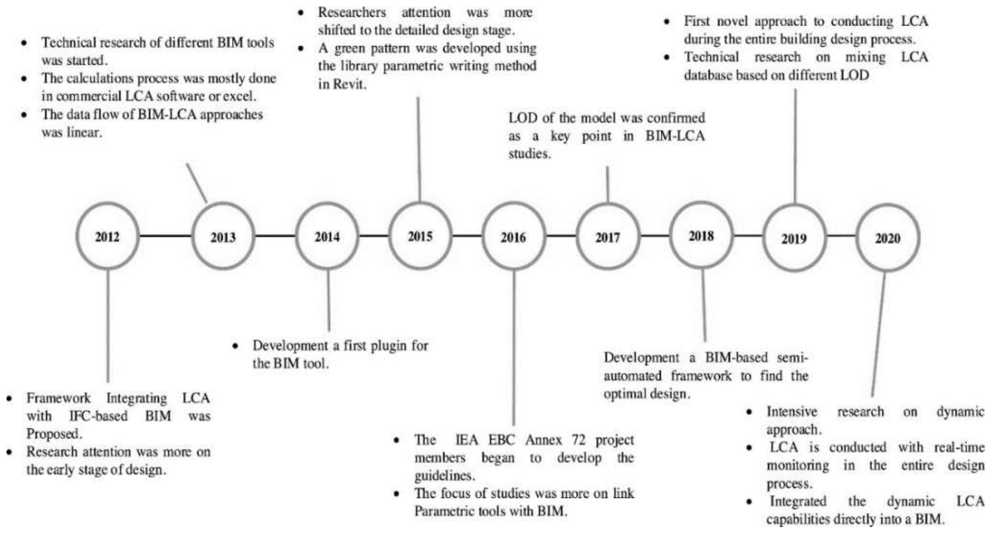


Figure 16 – Advances and development in the field of integrating BIM and LCA since 2012 (Safari & AzariJafari, 2021).

Lu et al. (2021) reviewed BIM-based LCA approaches and summarized them in a workflow with three approach categories (Figure 17). They also suggested that future BIM and LCA studies should focus on the following: BIM integration of LCA and LCC, incorporation of building certification to BIM-based LCA and LCC, monitoring the applications of design, operation, and demolition stages via IoT and BIM-based cloud technologies, solutions for automatic data exchange between BIM and LCA/LCC, and combination of SCLA and BIM (Lu et al., 2021).

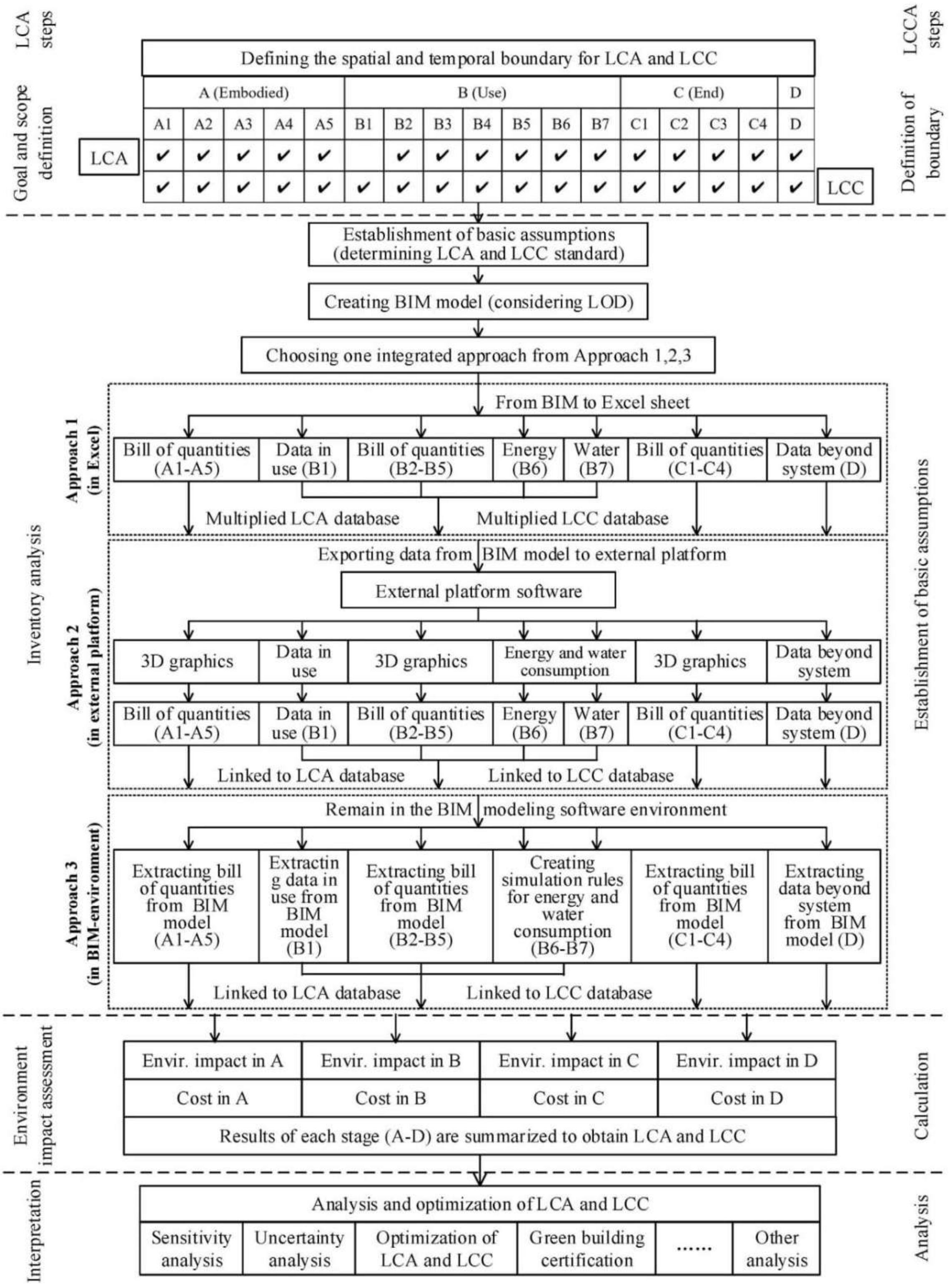


Figure 17 – Methodology framework of integrating LCA and LCC using BIM. Reprinted from “Integration of life cycle assessment and life cycle cost using building information modeling: A critical review” by . Lu, K. Jiang, X. Yu, J. Tam, V. Skitmore, M.

2.4. Research Questions

Today BIM and BIM-integrated LCA tools help to make a complex and time-intensive process easier for designers, and they offer guidance to achieve sustainability in the construction industry.

As seen in the literature review chapter earlier, there has been much research done regarding LCA and also regarding BIM. The subject of prefabrication (off-site and modular construction) has been present in researches in the last decade as well. However, the papers, which investigated the combination of these subjects, are limited.

Therefore, this thesis tries to help for filling this gap and aims to understand better the environmental impacts of prefabricated construction with the help of BIM and BIM-integrated LCA tools. The following questions have been raised according to the literature review and research:

- What are the differences between conventional and prefabricated construction methods in BIM implementations?
- What are the differences between conventional and prefabricated construction methods in LCA assessments or implementations?
- What are the challenges in BIM-LCA integrations concerning prefabricated buildings?
- To what extent the usual BIM-integrated LCA tools can be used for prefabrication?
- How can the BIM-integrated LCA processes be evaluated and, if necessary, be optimized?

Furthermore, this study includes two real prefabricated construction projects as case studies. Both projects are analyzed with two different BIM-integrated LCA tools according to their environmental impacts. The collected data, user experience, and the tool performance for prefabricated projects are evaluated. The results and challenges of this analysis are used to identify the relevant LCA indicators for prefabricated construction and to optimize the BIM-implementation of these.

At the end of the study, it is expected to see:

- How the BIM-LCA integration works with different software and if there are interoperability problems during the process.
- How the LCA phases differ to the conventional construction studies; e.g., if end-of-life and module D phases positively affect LCA studies for prefabricated construction.
- How to improve the tool workflows for higher quality of the assessments.

In the end, this study aims to give an up-to-date review to assess more efficient LCAs for the prefabricated construction sector and to help to reduce the environmental impacts of the AEC industry for the future.

3. Methodology

In the previous chapters, the foundation and the state of the art of the subjects, prefabrication, LCA, and BIM, have been identified. Here the methodology of the thesis will be described.

To give a comprehensive view, it is necessary to review the relationships between BIM and prefabrication, BIM and LCA integration, and the combination of these topics. Therefore, the first part of the methodology focuses on using BIM for prefabricated construction. The second part will explain the BIM-based LCA tools and their integration process. For the case study analysis, these two topics will be merged. Finaly, the last part of the methodology explains the process of conducting the case study.

3.1. Methodology of BIM for Prefabricated Timber Construction

Based on the findings of Chapter 2.2 (Abanda et al., 2017; Aberger, 2017; Gbadamosi et al., 2019; Kaufmann et al., 2017; Patlakas et al., 2015) and on the SWOT analysis of Anton and Diaz (2014), a SWOT Analysis of BIM for Prefabricated Timber Construction is generated in the present study (Table 3).

Via the two case study projects, the analysis part of this study monitors the mentioned aspects in the following table.

Table 4 – SWOT analysis on BIM for prefabricated timber construction

Strengths	Weakness
Standardization and industrial production Lower preliminary costs, Increase certainty-less risk, Increased in added value, Lower overheads, Less on-site damage and Less waste (Blismas et al. 2006; Elnaas et al. 2014; Serial productions leads to significant reduction in formwork and hence cost (Alvarez-Anton et al., 2016). Lower accidents (Delcambre, 2014).	**More detailed and longer planning phase** As in conventionally built projects, prefabricated construction also needs more detailed planning with BIM compared to the 2D methods. In the case of prefabricated timber construction, this detailed planning phase involves growing number of specialists and this causes a more extended planning phase (Kaufmann et al., 2017).
Reducing errors and increasing efficiency Clashes detected virtually leads to significant cost savings (Azhar, 2011; Bryde et al., 2013). Collaborative viewing of models leading to improved communications and trust between stakeholders and enabled rapid decision making early in the process leads to cost savings (Azhar, 2011). Efficient nD scheduling leads to projects to be delivered in time and budget (Azhar, 2011). Pre-design investigation that prevents costly and time-consuming redesign at later stages (Azhar, 2011). Prefabricated timber construction is a well-documented system therefore it provides a data rich project platform. Geometry and Information combination in BIM helps increasing efficiency and sustainability in project (Aberger, 2017; Patlakas et al., 2015).	**Interoperability and Interface Problems** Interoperability problems resulted with data loss reduce the collaboration between project participants. When the interface problems between those involved in planning, production and execution have not been resolved due to the different software and the problems with data exchange and it leads to an additional economic effort. For totally functioning BIM-System still the software solution remains open (Kaufmann et al., 2017).
Data driven quality Quality of data in BIM is improved and highly accurate leading to improved quality of building components (Wong and Fan, 2013; Suermann and Issa, 2009; Stanley and Thurnell, 2014). Building or components can be virtually built and tested in the factory before erecting on site (Shade et al., 2011). This minimises errors that could possibly jeopardise quality (Abanda et al., 2017).	**Performance of entire digital process chain** The end-to-end digital process chain from planning to prefabrication has not yet been achieved in practice. Moreover software and training costs for BIM method are not profitable for smaller firms / projects at the moment (Kaufmann et al., 2017).
Collaboration Collaboration between the planners should be more intensive in prefabrication, because need of detailed planning phase. Conventional LPH 5 details in prefabricated timber construction should be shifted to LPH 3. BIM makes it easier and quicker (Kaufmann et al., 2017).	

Opportunities	Threats
Innovation Potential Standardization is claimed to be the reason for lack of flexibility in prefabricated construction. However, BIM could define and examine this limitation and "give the designer more freedom without having to rely on external specialists" (Patlakas et al., 2015).	**Lack of research** BIM has been primarily applied in conventional construction and has not been fully utilized to assist prefabricated construction. (Jin et al., 2020)
Pre-designed details and design optimization Besides clash detection and economical feasibility in early phases BIM Method provides a possibility to early design optimization with information collected from different project participants. This could be used to act early on waste management, provide a higher resource efficiency of the project (Abanda et al., 2017; Honic et al., 2019; Santana-Sosa & Fadai, 2019).	**BIM Adoption** While the benefits of BIM are widely recognized, BIM adoption is still limited in the industry. Lack of know-how and required investment in software and training also a concern for especially smaller firms (Kaufmann et al., 2017).
Design for Manufacture and Assembly (DFMA) and Design for Disassembly (DFD) A better understanding of "the implications that designs have on the manufacturing and assembly process" could be assessed through BIM and waste could be minimized, resource efficiency could be optimized (Gbadamosi et al., 2019).	**Lack of standardized tools and protocols** There is no standard BIM-based workflow for prefabricated construction. Multidisciplinary nature of BIM brings also needs defined liability process for every project participant.(Aberger, 2017; Kaufmann et al., 2017)
Change of work processes The growing number of specialist planners and different planning depths make the coordination increasingly complex for big prefabricated timber construction projects. Working with the BIM method will certainly change work processes and activity profiles, but timber construction should understand this opportunity in order to be able to perform larger and more complex tasks economically. (Aberger, 2017; Kaufmann et al., 2017; Patlakas et al., 2015).	**All-in providers** There is a tendency to "Closed Silo" mentality in prefabrication industry – Some companies includes engineers, designers, and manufacturing facilities. This kind of approach leads to few big players and restricts the creativity and innovation for smaller companies (Patlakas et al., 2015).
Integration of supply chain BIM can be used to integrate supply chain which improves performance (Papadonikolaki et al., 2016).	**Resistance to Change in business practice** AEC is a conservative industry, very resistant to change (Abanda et al., 2017). It needs support from directives and legislation.

3.2. Methodology of BIM-based LCA Analysis

This methodology chapter will examine the connection between BIM and LCA under two focuses. The first part discusses the methods of BIM-LCA integration and which one will be used in this thesis. In the second part, BIM-based LCA, the methodology of the case study will be explained.

3.2.1. BIM Platform

Revit 2020 is the chosen BIM software to perform modeling and analysis, as it is noted that it has most interfaces to the LCA databases (Forth et al., 2019). In addition, the BIM model of the case study projects was provided as Revit files (.rvt).

LOD's of the models are defined according to LOD definitions of the *BIMForum* (BIMForum, 2020).

3.2.2. BIM - LCA integration

As previously mentioned, BIM-LCA integration is a known topic in the recent literature (Antón & Díaz, 2014; Gourlis & Kovacic, 2017; Hammad et al., 2019; I. Kovacic, Reisinger, et al., 2018; Kreiner et al., 2015; Santos et al., 2019; Zhang et al., 2018).

Santos et al. (2019) group the integration of LCA/LCC with BIM by three approaches. In summary, these three approaches are, use several programs to conduct the analysis, use the quantity take-off method derived from the BIM model, and use information based on the BIM model, which could be edited and used later by every stakeholder (Santos et al., 2019, p. 128 ff.). The analysis part of the thesis focuses on the second approach of Santos et al. (2019) for BIM-Integrated LCA and LCC tools.

Two of the BIM-Integrated LCA tools are selected to be applied to the case study. In Chapter 4.1, their workflow and properties will be evaluated under the aspects mentioned in the literature review.

3.2.3. BIM-based LCA analysis through Case Studies

For further investigations, this thesis uses a case study methodology. Two prefabricated timber building projects are reviewed as case studies. The detailed information of these projects is given in Chapter 4.2.

According to Santos et al. (2020), there is a six-step methodology to conduct a BIM-based LCA/LCC analysis on a project. The analysis of the case study projects uses this method for the LCA analysis through two software applications. The steps are as follows:

- A single model should be analyzed for a holistic comparison. That is why in the case of different architectural and structural models, they should be merged.
- BIM model information should be analyzed by exporting the quantity take-off list.
- The exported list should be checked for duplicates.
- To prevent possible errors and so that the LCA tools can read the project information correctly, the project's data should be analyzed. If needed, the material names should be ordered so that the same material with different dimensions is defined as two different materials.
- If necessary, the environmental, economic, and mechanical information should be added, and a .xls spreadsheet should be created, including all elements and materials of the project.
- After the previous steps are completed, a streamlined and Complete LCA can be performed (Santos et al., 2020, p. 2 ff.).

4. Analysis

The following chapter begins with explaining and evaluating existing building-related LCA tools. The selected BIM-integrated LCA tools will be analyzed by using the two case studies in the second part of the chapter. Information about these case studies is will be described in Chapter 4.2, and after that, the projects will be evaluated through selected BIM-based LCA tools. The workflows and implementation processes of the tools, as well as the LCA indicators, will be assessed regarding prefabricated construction. Finally, the analysis results will be presented at the end of this chapter.

4.1. Comparison of LCA tools for buildings

The LCA tools have been a known topic in the AEC sector in the last years (see Table 5) (Cavalliere, 2018; Hollberg & Ruth, 2016). As in the methodology mentioned, there are tools with several approaches on the market. The first approach uses different software and building performance tools for the assessment process. These are software tools particularly specialized for one single area; that is why, they are harder to be adopted for every stakeholder of the building process. Additionally, using several tools and several files allows the error transfer between the steps. In this approach, editing information between the LCA steps is also harder and the used processes are more linear than collaborative process (Santos et al., 2019, p. 128 ff.; Thiebat, 2019, p. 18).

The second approach reduces the error transfer and simplifies the assessment by using BIM-integrated software tools. Recent research studies use mostly this approach in their BIM-LCA integration. Under this category, it is to mention that the tools are integrated into a BIM software, such as Tally (2016), or One Click LCA (2015). These tools are designed as additional plug-ins to BIM softwares. Therefore, the necessary building data such as materials, mass or size are taken from BIM model without an extra step. There are tools in which this process happens full-automatically. However, some of the tools need the material data to be integrated as a separate excel file. If information is not included in the model from the beginning, it could be edited later via excel file (Forth, 2018, p. 41 f.; Santos et al., 2019, p. 128 ff.).

Table 5 – Most used LCA tools based on lists of Hollberg et al. and Cavalliere. Adapted from "BIM-led LCA" by C.Cavalliere, 2018.

Type	Name	Country	Link
Generic LCA tools	Gabi	Germany	gabi-software.com
	SimaPro	Netherlands	simapro.com
	OpenLCA	Germany	openlca.org
	Umberto	Germany	ifu.com/umberto/oekobilanz-software
	EIO-LCA*	US	eiolca.net
Spreadsheet-based tools	Envest	UK	clarityenv.com.au/envest
	Ökobilanz Bau	Germany	oekobilanz-bau.de
	SBS Building Sustainability	Germany	gabi3.com
	eTOOL	Australia	etoolglobal.com
	Athena Impact Estimator	Canada	athenasmi.org
	Legep	Germany	legep.de
	Elodie	France	logiciels.cstb.fr
	LCAbyg*	Denmark	lcabyg.dk
Component catalogues	Eco2soft	Austria	baubook.info/eco2soft
	Bauteilkatalog	Switzerland	bauteilkatalog.ch
	eLCA	Germany	bauteileditor.de
	BEES	US	ws680.nist.gov/Bees2
CAD integrated	Impact	UK	bregroup.com/impact
	Cocon-BIM	France	cocon-bim.com
	Lesosai	Switzerland	lesosai.com
	Tally	US	choosetally.com
	CAALA*	Germany	caala.de
	One Click LCA* Formerly 360optimi	Finland	oneclicklca.com
	EVE-BIM Elodie**	France	logiciels.cstb.fr
	Pleiades**	France	izuba.fr/logiciels
	GENERIS**	Germany	generis.live

* not included in the list of Hollberg et al. (2016)

** not included in the list of Cavalliere (2018)

Santos et al. (2019) explain the third approach as the approach suggested by Anton and Diaz (2014). This approach requires a BIM platform, which works as a data repository. This means that all the project data is included within the BIM model and LCA/LCC studies could be done directly in the BIM platform. In this way, the AEC industry can get one step closer to the idea of generating a sustainability score with one single tool. Although this is the most promising approach, the research area is still relatively unexplored, and there is no working all-in-one platform available on the market yet (Santos et al., 2019, p. 128 ff.).

This thesis focuses on the second approach, BIM-Integrated LCA and LCC tools. Therefore, two tools of this approach are chosen to be tested on both case study projects. These are Tally (2016) and CAALA (2017). Further chapters will investigate these tools based on their similarities, differences, working processes, and databases.

4.1.1. LCA-Tool Tally

Tally (2016) is a Revit plug-in for BIM-integrated LCA assessments. It was developed by *KT Innovations* in the USA and supported by *Autodesk* and *Thinkstep*. This plug-in uses a custom-designed database which is based on *GaBi* Database for the assessments. According to their webpage (*Tally*, 2020), it is possible to assess "Cradle-to-grave" impacts with the plug-in. It gives the option to include other modules when needed, such as construction and operational energy for a full building assessment, although no LCC option is included. "Cradle-to-grave" Whole building assessments generated by Tally could be used for a *LEED* credit (*Tally*, 2020).

Tally (2016) is only compatible with the Revit platform; therefore, it is a closed BIM[1] application (Borrmann et al., 2018, p. 12). The plug-in needs an architectural and structural model to work with. The quantity take-off is taken from the Revit BIM model automatically. However, the material information should be manually assigned to the plug-in (Forth, 2018; *Tally*, 2020).

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[1] Closed BIM: Software products by a single vendor and proprietary formats for data exchange (Borrmann et al., 2018).

4.1.2. LCA-Tool CAALA

CAALA (2017) is a product of *CAALA GmbH* in Germany. The company emphasizes that CAALA is the first plug-in for a holistic building design. It offers energy, ecological, and economical building optimization for the early design phase. CAALA includes Modules A1-3, B3, B6, C3, and C4 for assessments. Module D could also be included separately. The tool uses the simplified procedure of *DGNB* as the basis for the calculations. Besides *DGNB*, these calculations could be used for certification systems *BNB* and *BNK* (*CAALA*, 2020).

Currently, CAALA (2017) can be integrated into Sketchup and Rhino as a plug-in. For Revit and Archicad use, it is necessary to use company's web tool. Therefore, the BIM model should be exported as gbXML and imported to the cloud-based CAALA web tool. The tool uses the *ÖKOBAUDAT* database, and when needed, the company offers to import the EPDs, which are not included in this database (*CAALA*, 2020).

An overview of the tested tools can be seen below in Table 6.

Table 6 – Summary of the LCA tools used in this thesis.

Name	**Tally**	**CAALA**
Developer	KT Innovations, Thinkstep, and Autodesk	Caala GmbH
Country	US	Germany
Website	choosetally.com	caala.de
Type	Plug-in	Plug-in & Web-based
Assessment	Complete building Analysis	Complete building Analysis
Compatible with	Revit 2015 - Revit 2020	Revit, Archicad (with gbXML import - Cloud-based) Sketchup, Rhino (Plugin)
Database	GaBi 8.5 using GaBi 2018	ÖKOBAUDAT
Certifications	LEED	DGNB, BNB, BNK

4.2. Case Studies

The analysis part of this thesis was supported by two case study projects– a residential and a school building. The projects' system is based on standardized, eco-certified, and industrial production in a modular system. Both projects are built with an industrialized modular timber system that lets the construction extend and disassemble if needed.

The collaboration for the study was based on the exchange of the documents regarding the project. These documents consisted of files with BIM models, reports, material information, and component details. The BIM models are provided as Revit files and consist of architectural and structural models. The standardized system of the projects provides a good level of primary data for a realistic assessment for this thesis. It gives an excellent opportunity to review the goal of the study.

Both of the projects are realized at the time of this writing. The related information of the projects is summarized in Table 7 and Table 8.

LOD levels of the projects are defined according to *BIMForum* definitions (BIMForum, 2020).

Table 7 – Project data – Case Study A - Residential Building

Project A	**Project Data**
Building type	Residential building
Building dimensions	11,02 x 24,64 m
Total floor area	548,01 m²
Net floor area	444,56 m²
Floors	2
Construction system	Prefabricated timber frame construction
Floor construction	Prefabricated CLT
BIM model	Revit 2020, LOD 400, LOI 300

Table 8 – Project data – Case Study B - School Building

Project B	Project Data
Building type	School building
Building dimensions	54,42 x 34,92 m
Total floor area	4000 m²
Net floor area	3492,21 m²
Floors	3
Construction system	Hybrid - Prefabricated timber frame and steel construction
Floor construction	Prefabricated CLT
BIM model	Revit 2020, LOD 300, LOI 200

In Chapter 4.2.3, LCA Analyses of both projects will be conducted. The goal and scope definition of the LCA studies will be explained in detail in the Chapter "BIM-based LCA Analyses".

4.2.1. BIM Model for Prefabricated Timber Construction

Figure 18 – Project BIM Model

The case study projects were collected as a BIM model (Revit 2019) (Figure 18). As the planning system and building components are mainly similar, this analysis chapter will examine one of the projects. In the next section, the model information will be summarized, and the BIM model of Project A will be analyzed according to the SWOT analysis in Table 3.

This BIM model includes different 2D and 3D drawings from structure, surveying, HVAC & electric disciplines. Collected drawings are integrated as separate files into the collaboration BIM model. Collaboration between different planning teams is managed by a central model. Quantity and dimensions could be derived from this central model. However, collaboration with other parties outside of the planning department was not included in the working process. The project's BIM model is used for coordination and 2D drawings creation.

4.2.2. The SWOT Analysis of the Case Study

- **Strengths**
  - *Standardization*

The project includes system components in its own BIM library. The project has been designed with a high proportion of standardized prefabricated components. Therefore, these standard components, such as beams, columns, or facade elements, are designed as parametrized families in the BIM library. These parametrized families contain different types of the components, which are generated by various sizes of components and other construction details. As a result, a facade element could easily be optimized by selecting the suitable type of the parametric families in the design stage, according to different room heights and various window or material compositions (Figure 19 & 20).

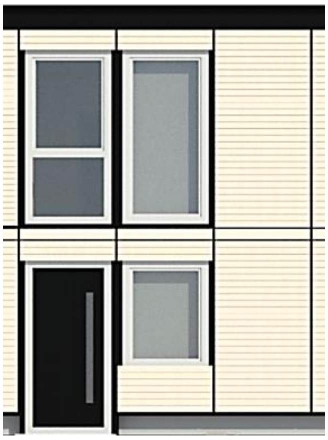
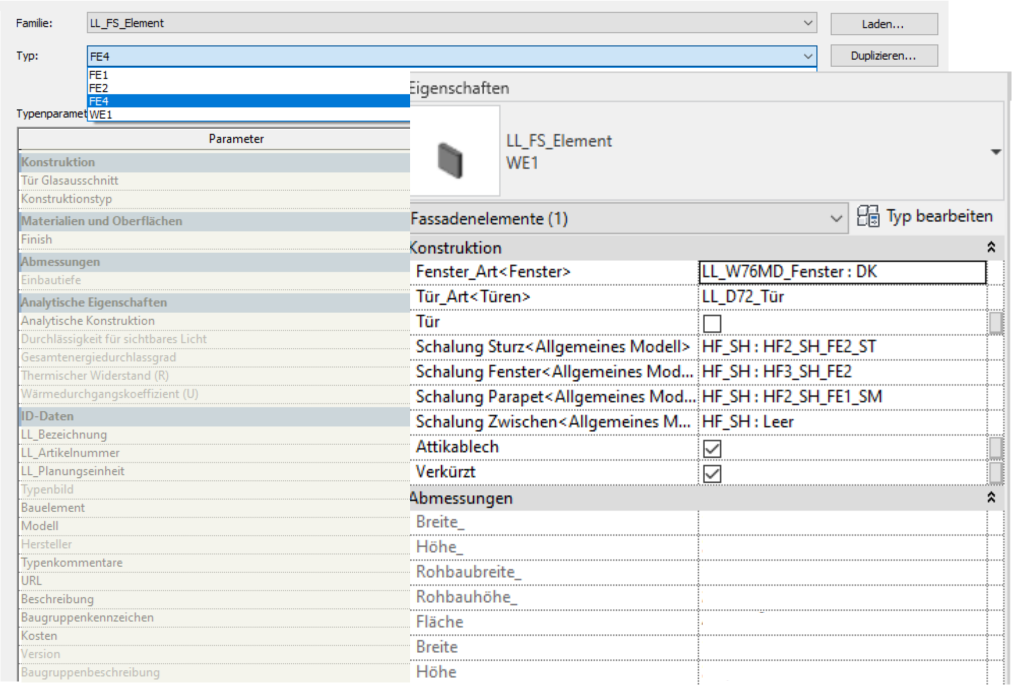


Figure 19 – Different facade element types



Familie: LL_FS_Element

Typ: FE4

FE1
FE2
FE4
WE1

Typenparamet

Parameter

Konstruktion
Tür Glasausschnitt
Konstruktionstyp
Materialien und Oberflächen
Finish
Abmessungen
Einbautiefe
Analytische Eigenschaften
Analytische Konstruktion
Durchlässigkeit für sichtbares Licht
Gesamtenergiedurchlassgrad
Thermischer Widerstand (R)
Wärmedurchgangskoeffizient (U)
ID-Daten
LL_Bezeichnung
LL_Artikelnummer
LL_Planungseinheit
Typenbild
Bauelement
Modell
Hersteller
Typenkommentare
URL
Beschreibung
Baugruppenkennzeichen
Kosten
Version
Baugruppenbeschreibung

Eigenschaften

LL_FS_Element
WE1

Fassadenelemente (1)

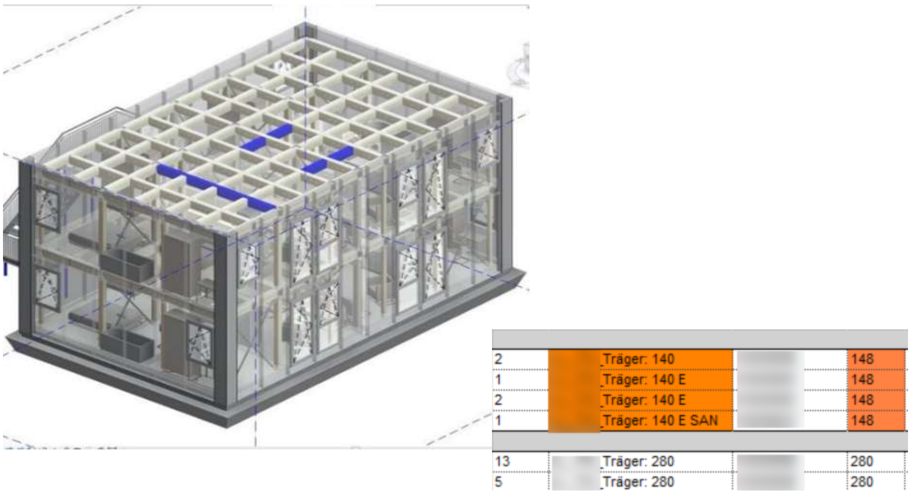
Konstruktion	
Fenster_Art<Fenster>	LL_W76MD_Fenster : DK
Tür_Art<Türen>	LL_D72_Tür
Tür	☐
Schalung Sturz<Allgemeines Modell>	HF_SH : HF2_SH_FE2_ST
Schalung Fenster<Allgemeines Mod...	HF_SH : HF3_SH_FE2
Schalung Parapet<Allgemeines Mod...	HF_SH : HF2_SH_FE1_SM
Schalung Zwischen<Allgemeines M...	HF_SH : Leer
Attikablech	☑
Verkürzt	☑
Abmessungen	
Breite_	
Höhe_	
Rohbaubreite_	
Rohbauhöhe_	
Fläche	
Breite	
Höhe	

Figure 20 – Facade combinations in BIM Library

Different elements include different information attributes in their families. For structural elements, specific span values and loading values are included in BIM components that provides an interface to a structural calculation. Multi-layered components, such as walls or roofs, are defined with different material dimensions in construction types. Therefore, they could be used to create quantity take-offs. The standard components are connected to project component lists, which automatically update the quantity take-off. The information, such as cost and environmental performance, is being planned, but has not been included in component attributes yet.

- *Reducing errors and increasing efficiency*

BIM helps for clash detection due to the 3D planning model and, therefore, reduces project errors. Additionally, the BIM model of this case study includes control views for the structural system (Figure 21). When an incorrect placed or sized element is planned, the related control view highlights the element in these control component lists as well as in the control 3D Model view. These preset views bring an additional dimension to the clash detection and duplicate control in BIM for the planners.



2	[redacted]	_Träger: 140	[redacted]	148
1	[redacted]	_Träger: 140 E	[redacted]	148
2	[redacted]	_Träger: 140 E	[redacted]	148
1	[redacted]	_Träger: 140 E SAN	[redacted]	148
13	[redacted]	_Träger: 280	[redacted]	280
5	[redacted]	_Träger: 280	[redacted]	280

Figure 21 – Control View in 3D Model and Bill of Quantities

- *<u>Data-driven quality</u>*

Time management of the projects includes also BIM use. Therefore, the tracked time during the projects is periodically analyzed and taken into account in planning and optimizing the following projects. The collected data is also used for generating reliable resource planning and forecasting.

Real-time data-driven analyses or improvements (e.g., operation and use phases) are not a part of this project.

- *<u>Collaboration</u>*

The project consists of a collaboration model and a building model. The collaboration model works as a host model of the project. This model provides topography, auxiliary and adjacent buildings and the building model. The nested building model is linked as an attachment and includes the building itself with all system components. Both models are regulated through building phase filters that control the display of scale, detailing and existing conditions.

The project browser (Figure 22) in BIM software is essential to have an accessible overview of the whole project. Therefore, it is structured according to usability in that order; project site, building, working phases, type of plans and building components (e.g., facade, structural elements, interior components, etc.).

- Ansichten (Gliederung)
  - 00_Allgemein
    - 030_Ebenen
  - 01_Modell
    - 100_Grundrisse
    - 130_3D
  - 02_Plan
    - 02_Entwurf
      - Ansicht
    - 03_Genehmigung
      - Grundriss
      - Schnitt
    - 04_Polierplanung
      - Detail
      - Grundriss
        - Grundriss: Aussenanlagen und Kanal
        - Grundriss: Aussenanlagen und Kanal, HKLS, ELT
        - Grundriss: PP_00_EG_FBOK
        - Grundriss: PP_01_OG_FBOK
        - Grundriss: PP_02_DA_ATOK
      - Schnitt
    - 06_Schalplan
      - Ansicht
      - Detail
      - Grundriss
      - Schnitt
    - 07_Bewehrung
    - 09_Verwertungsplan
      - Grundriss
- Legenden
- Bauteillisten/Mengen (Gliederung)
  - 00_Allgemein
  - 04_Mengen
  - 09_Verkaufsplanung
  - 90_Kontrolle
- Pläne (Gliederung)
  - LPH 0
  - LPH 3
    - Entwurf
  - LPH 4
    - Genehmigung
  - LPH 5
    - Bewehrung
    - Polierplanung
    - Schalung
    - Verwertungs
- Familien
- Gruppen
  - Detail
  - Modell
- Revit-Verknüpfungen

Figure 22 – Structure of Project browser

- **Weakness**
  - *More detailed and longer planning phase*

The nature of prefabricated construction is different from conventional construction. Additionally, a detailed planning phase is crucial in timber construction, and it takes longer than the conventional method (Kaufmann et al., 2017). Planning with BIM, especially at the beginning of the implementation phase, takes even longer. However, this project has no reliable data to compare the planning in BIM with the previous planning practices.

- *Interoperability and interface problems*

This BIM model is used only for planning purposes (LPH 1-5). The interoperability of the model between the other departments was therefore not adopted. However, the interoperability issues of BIM-integrated LCA tools will be examined and explained in the next chapter.

- *Full digital process chain*

This case study project uses BIM primarily for planning, and it does not include manufacturing and construction phases in the BIM model. These phases are managed with different software by other parties.

- **Opportunities**

- *Pre-designed details and design optimization*

In this project, design optimization is managed through various measures. Firstly, designing the building as a separate model allows the repetition of the model for the same project or other future projects. These building models use their own BIM library with parametrized standard components. These components help to create different options and see the immediate effect of change of the component types in the plans in early design phases. Besides, if a change request is needed in later phases, both the substructure and quantity take-offs will be automatically updated.

Design optimization is supported with detail catalogs for various constructions and pre-designed room layouts like the bathroom and kitchen. These partial room layouts are designed as separate model groups and include elements and information from HVAC to electrical plans. Therefore, they are easily usable for different stages, from conceptual design to execution planning. These types of repetitions create an opportunity to increase the efficiency and quality of planning.

- *Design for Manufacture and Assembly (DFMA) and Design for Disassembly (DFD)*

The project's system consists of a high degree of prefabricated building components, and they are already designed with the principles of DFMA, DFD and reuse. However, a direct BIM integration to manufacture is currently not available.

- *Change of work processes*

With the introduction of BIM, quality management measures for planning also changed and shifted to the cloud solutions, such as *Autodesk BIM 360*. These cloud solutions created the opportunity to have better communication with the construction site and collaboration purposes within different planning teams. Also, further controls are made through pre-designed 3D views on BIM models.

A total collaboration on the BIM platform was not possible. The other department involvements are currently in development.

- *Integration of supply chain*

This project model was developed for planning purposes. Integration of the supply chain is currently not available.

- **Threats**

  - *Lack of standardized tools and protocols*

The BIM implementation is a current ongoing process. Therefore, the information level of the models is defined through empirical approaches of the specialists in the planning team and BIM manager. General protocols and standards are not defined yet. According to these pilot project experience values, the company's own protocols for BIM working standards will be determined.

  - *BIM Adoption*

According to Aberger (2017), BIM adoption in the timber construction sector is higher than conventional construction. This positive tendency is also supported here. BIM is integrated into the company's daily workflows and in this project, it is used for the phases between LPH 1-5.

- *Resistance to change in business practice*

During the research, any resistance or hesitation to change in the process is not observed.

- *All-in providers*

Technical design and construction management were provided by the prefabricated timber construction company, and they also worked as the main contractor. Design and manufacturing phases were developed by other companies.

4.2.3. BIM-based LCA Analyses

This chapter describes the BIM-LCA integration and BIM-based LCA of the case study project. The selected tools are tested separately through the project to assess the usability of the BIM-integrated LCA for prefabricated construction. The following paragraphs will shortly explain the workflow and necessary information for the mentioned tools. Later, BIM-based LCA will be reviewed by two prefabricated timber projects.

In this phase, the six-step methodology of Santos et al. is used. (Santos et al., 2020). Firstly to achieve one single model for the assessments, the models of the projects are examined and merged. Building elements and material layers of the Revit model are controlled. After that, LCA unrelated components are defined and removed from the model (e.g., irrelevant DWGs, or surrounding elements). Quantity take-off lists are managed automatically by Revit and exported as Excel files. These files are checked for duplicate material or component naming. The found duplicates are removed. As the next step, eight incorrect material definitions are replaced with the correct naming.

The LCA aims to evaluate both projects through their whole lifecycle. The life span of the structures is selected as 50 years. As already mentioned in previous chapters, these projects are built with a very high degree of prefabricated components (A summary of project data is given in Table 9). The underground building components (e.g., foundation) are not taken into account. This review concentrates on the following building components:

- Exterior Walls
- Ceilings
- Structural elements
- Roof
- Windows

The LCA will focus on the following life stages:

- Module A1-A3 – Production
- Module C – End-of-life
- Module D – Reuse, recycle and recovery

The environmental indicators, which are taken into consideration in LCA assessment, are:

- Global warming potential (GWP) expressed in CO_2
- Primary energy demand (PED), expressed in MJ
- Acidification potential (AP), expressed in SO_2
- Eutrophication potential (EP), expressed in Neq

Table 9 – Project summary

	Case Study Project A	Case Study Project B
Building type	Residential building	School building
Building dimensions	11,02 x 24,64 m	54,42 x 34,92 m
Total floor area	550 m²	4000 m²
Net floor area	444,56 m²	3492,21 m²
Floors	2	3
Construction system	Prefabricated timber frame construction	Prefabricated timber frame and steel construction
Floor construction	Prefabricated CLT	Prefabricated CLT
BIM model, LOD	Revit 2020, LOD 400	Revit 2020, LOD 300
Building components	Exterior Walls Structural elements Roof Ceilings Windows	Exterior Walls Structural elements Roof Ceilings Windows
Building life	50 years	50 years
included LCA stages	Production - Raw Materials Supply - Transport - Manufacturing Construction - Transport End-of-life - Deconstruction - Transport - Recycling/re-use - Disposal Benefits and loads beyond the system boundary - Reuse - Recycling - Energy recovery	Production - Raw Materials Supply - Transport - Manufacturing Construction - Transport End-of-life - Deconstruction - Transport - Recycling/re-use - Disposal Benefits and loads beyond the system boundary - Reuse - Recycling - Energy recovery

4.2.3.1. Case Study Project A – Residential Building

Figure 23 – Model of the use case - Project A

Firstly, the model checked for the material and component duplicates for the preparation for the BIM-based-LCA assessment. Additionally, irrelevant data such as foundation, topography, and outside facilities are removed from the project model.

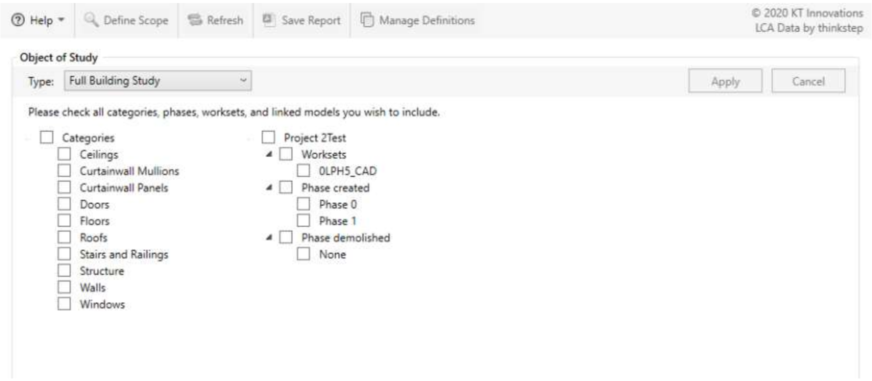
The 3D-Model of Project A (Figure 23) has LOD 400 (Quantity and detail of the elements and opening are correctly planned, structural elements have the related information and intersection with other disciplines are detailed planned and information is included to the model) and LOI 300 (Calculations are assigned to the related construction elements, specifications and certifications are included to the elements, room schedule is retrievable from 3D-Model).

Tally is tested with a student license. CAALA provided instead of a separate student license a CAALA Pro account for a certain period.

- **LCA with Tally**

To assess via Tally, working on an Autodesk Revit program is necessary. As the case study was already received as an RVT file, no IFC/gbXML export process was required.

As Forth (2018) stated, Tally's workflow is quite intuitive. Tally provides the study options of Full building study, Design option comparison, and Template File. Here the option "Full building study" is used. After selecting the study type, selecting which components and phases to include in the assessment is possible on the same interface (Figure 24). Here Curtainwall, Doors, Floors, Roofs, Structure, Walls, and Windows were selected.



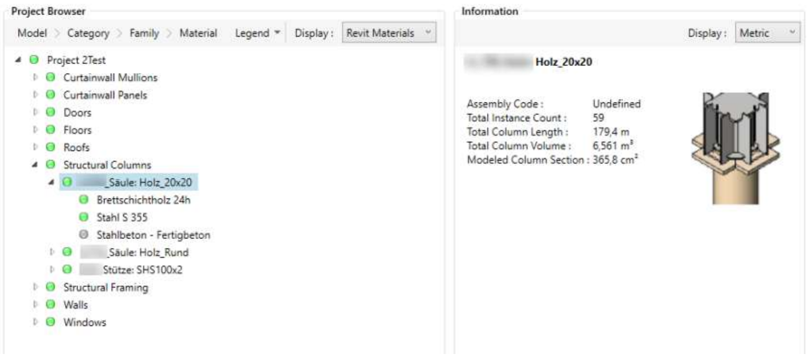
Object of Study
Type: Full Building Study

Please check all categories, phases, worksets, and linked models you wish to include.

- ☐ Categories
  - ☐ Ceilings
  - ☐ Curtainwall Mullions
  - ☐ Curtainwall Panels
  - ☐ Doors
  - ☐ Floors
  - ☐ Roofs
  - ☐ Stairs and Railings
  - ☐ Structure
  - ☐ Walls
  - ☐ Windows
- ☐ Project 2Test
  - ☐ Worksets
    - ☐ 0LPH5_CAD
  - ☐ Phase created
    - ☐ Phase 0
    - ☐ Phase 1
  - ☐ Phase demolished
    - ☐ None

Figure 24 – Tally input screen

As the next step, the tool opens the project browser. The project browser uses a hierarchy, consists of Model, Category, Family, and Material (Figure 25). According to this order, materials gathered from Revit could be seen and should be manually matched with the Tally materials database.



Display: Revit Materials

- Project 2Test
  - Curtainwall Mullions
  - Curtainwall Panels
  - Doors
  - Floors
  - Roofs
  - Structural Columns
    - [redacted]_Säule: Holz_20x20
      - Brettschichtholz 24h
      - Stahl S 355
      - Stahlbeton - Fertigbeton
    - [redacted]_Säule: Holz_Rund
    - [redacted]Stütze: SHS100x2
  - Structural Framing
  - Walls
  - Windows

Display: Metric

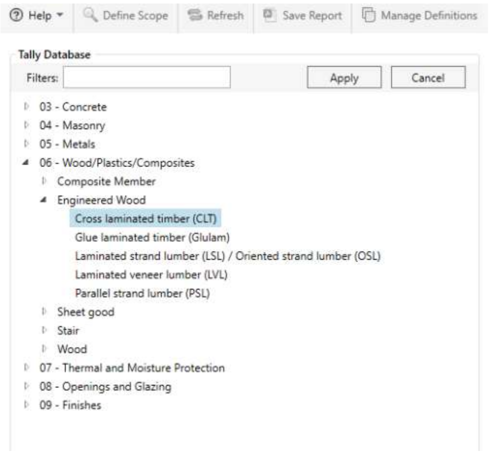
[redacted] **Holz_20x20**

Assembly Code : Undefined
Total Instance Count : 59
Total Column Length : 179,4 m
Total Column Volume : 6,561 m^3
Modeled Column Section : 365,8 cm^2

Figure 25 – Tally project browser

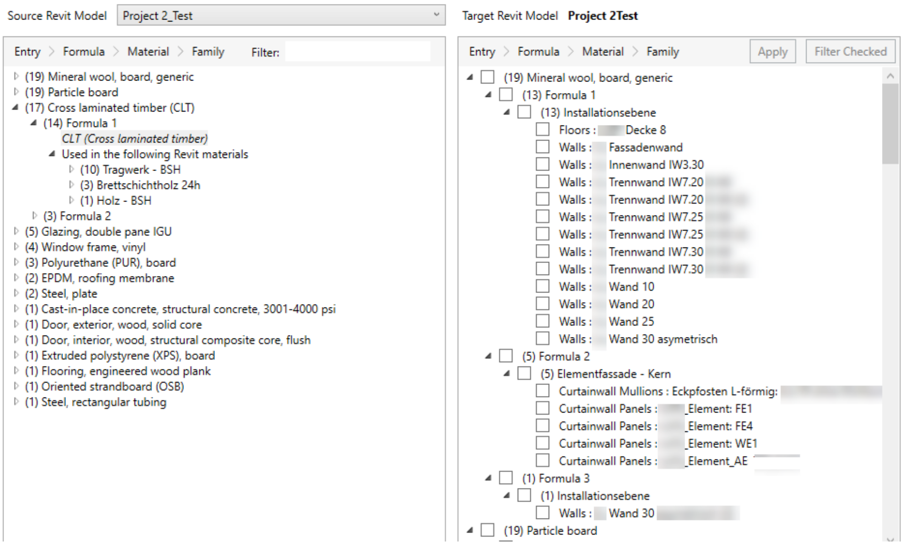
It is noticed that different definitions of the same materials existed after recognizing the building elements and materials. All used materials in the model were listed in Revit for controlling and, if necessary, combined.

Tally Database defines some materials groups according to use or material type (Figure 26). If the same Revit material is used more than once in the project components, the tool automatically asks if the others should be copied from that after the first one is defined. Under the menu "Manage definitions," this could also be controlled in later steps. "Manage definitions" also summarizes defined Tally materials in the project and an overview of families (Figure 27).



- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
  - Composite Member
  - Engineered Wood
    - Cross laminated timber (CLT)
    - Glue laminated timber (Glulam)
    - Laminated strand lumber (LSL) / Oriented strand lumber (OSL)
    - Laminated veneer lumber (LVL)
    - Parallel strand lumber (PSL)
  - Sheet good
  - Stair
  - Wood
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Figure 26 – Tally Materials

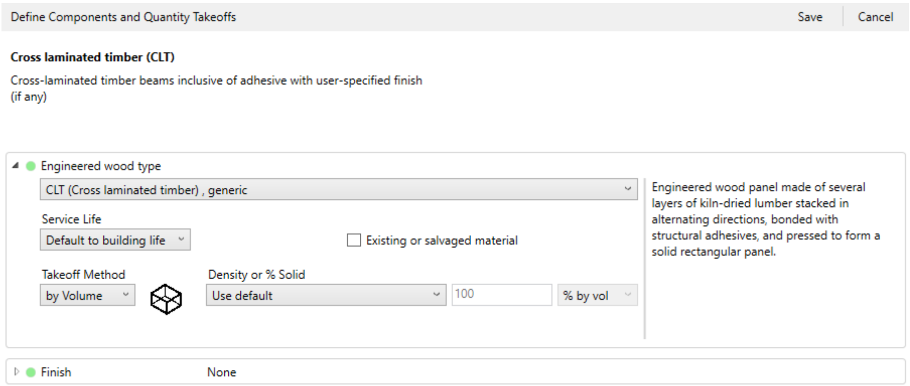


- (19) Mineral wool, board, generic
- (19) Particle board
- (17) Cross laminated timber (CLT)
  - (14) Formula 1
    - *CLT (Cross laminated timber)*
    - Used in the following Revit materials
      - (10) Tragwerk - BSH
      - (3) Brettschichtholz 24h
      - (1) Holz - BSH
  - (3) Formula 2
- (5) Glazing, double pane IGU
- (4) Window frame, vinyl
- (3) Polyurethane (PUR), board
- (2) EPDM, roofing membrane
- (2) Steel, plate
- (1) Cast-in-place concrete, structural concrete, 3001-4000 psi
- (1) Door, exterior, wood, solid core
- (1) Door, interior, wood, structural composite core, flush
- (1) Extruded polystyrene (XPS), board
- (1) Flooring, engineered wood plank
- (1) Oriented strandboard (OSB)
- (1) Steel, rectangular tubing

- ☐ (19) Mineral wool, board, generic
  - ☐ (13) Formula 1
    - ☐ (13) Installationsebene
      - ☐ Floors : [redacted] Decke 8
      - ☐ Walls : [redacted] Fassadenwand
      - ☐ Walls : [redacted] Innenwand IW3.30
      - ☐ Walls : [redacted] Trennwand IW7.20 [redacted]
      - ☐ Walls : [redacted] Trennwand IW7.20 [redacted]
      - ☐ Walls : [redacted] Trennwand IW7.25 [redacted]
      - ☐ Walls : [redacted] Trennwand IW7.25 [redacted]
      - ☐ Walls : [redacted] Trennwand IW7.30 [redacted]
      - ☐ Walls : [redacted] Trennwand IW7.30 [redacted]
      - ☐ Walls : [redacted] Wand 10
      - ☐ Walls : [redacted] Wand 20
      - ☐ Walls : [redacted] Wand 25
      - ☐ Walls : [redacted] Wand 30 asymetrisch
  - ☐ (5) Formula 2
    - ☐ (5) Elementfassade - Kern
      - ☐ Curtainwall Mullions : Eckpfosten L-förmig: [redacted]
      - ☐ Curtainwall Panels : [redacted]_Element: FE1
      - ☐ Curtainwall Panels : [redacted]_Element: FE4
      - ☐ Curtainwall Panels : [redacted]_Element: WE1
      - ☐ Curtainwall Panels : [redacted]_Element_AE [redacted]
  - ☐ (1) Formula 3
    - ☐ (1) Installationsebene
      - ☐ Walls : [redacted] Wand 30 [redacted]
- ☐ (19) Particle board

Figure 27 – Tally - Manage definitions

Materials are only selected from the Tally database. For the materials not available in the database, there is no possibility to add the related EPD manually. The material selection menu provides the possibility to define if the material is 'existing or salvaged.' This option is, in particular, for the reuse cases important. Also, the quantity take-off method of material and service life can be under this menu adjusted (Figure 28).



Cross laminated timber (CLT)

Cross-laminated timber beams inclusive of adhesive with user-specified finish (if any)

Engineered wood type: CLT (Cross laminated timber) , generic

Service Life: Default to building life

☐ Existing or salvaged material

Takeoff Method: by Volume

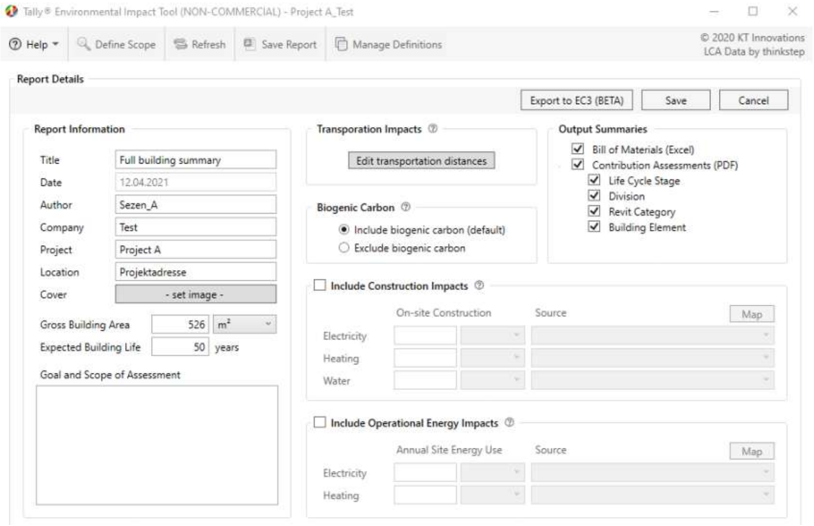
Density or % Solid: Use default | 100 | % by vol

Engineered wood panel made of several layers of kiln-dried lumber stacked in alternating directions, bonded with structural adhesives, and pressed to form a solid rectangular panel.

Finish: None

Figure 28 – Tally material selection

After the materials are defined, the report could be saved on the last screen (Figure 29). Here is also a summary of the project, which also requires fields about some project information to fill out. (e.g., the project's service life, location, etc.) At this step, some optional LCA impacts, such as transportation, construction, and operational impacts, could be selected to include in the report.



Report Information

Title: Full building summary
Date: 12.04.2021
Author: Sezen_A
Company: Test
Project: Project A
Location: Projektadresse
Cover: - set image -
Gross Building Area: 526 m²
Expected Building Life: 50 years
Goal and Scope of Assessment

Transporation Impacts

Biogenic Carbon
● Include biogenic carbon (default)
○ Exclude biogenic carbon

Output Summaries
☑ Bill of Materials (Excel)
☑ Contribution Assessments (PDF)
  ☑ Life Cycle Stage
  ☑ Division
  ☑ Revit Category
  ☑ Building Element

☐ Include Construction Impacts

	On-site Construction	Source
Electricity		
Heating		
Water		

☐ Include Operational Energy Impacts

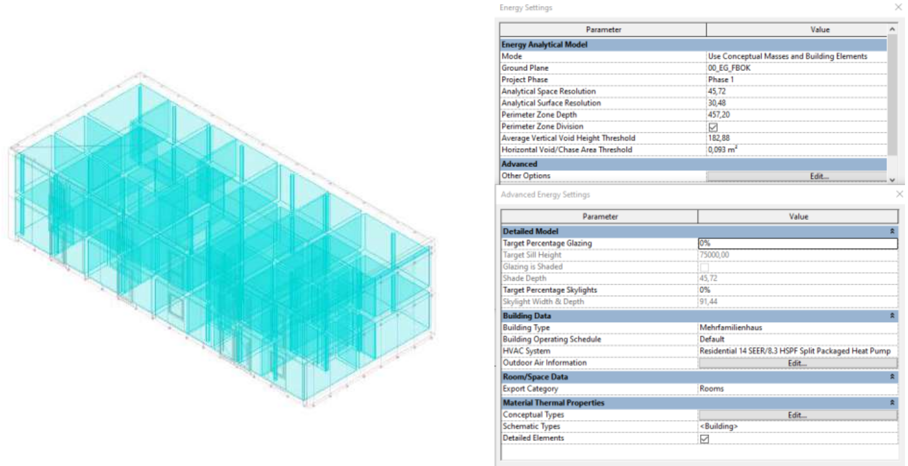
	Annual Site Energy Use	Source
Electricity		
Heating		

Figure 29 – Tally report screen

There was no option to include building type or construction method during these steps. The results of this assessment will be explained in detail in Chapter 5.1.3.

- **LCA with CAALA**

CAALA Version v1.21.12.15 is used in this review, and assessments are made with the CAALA Pro Account provided for students. CAALA has plug-in versions for Rhino and Sketchup; however, it does not work as a plug-in Revit. For Revit project models, a gbXML export from the model is necessary. Therefore firstly, an energy model that includes the project's energy settings should be created in Revit (Figure 30). The project could be exported as a green building XML (gbXML) file based on this model.



Energy Settings

Parameter	Value
Energy Analytical Model	
Mode	Use Conceptual Masses and Building Elements
Ground Plane	00_EG_FBOK
Project Phase	Phase 1
Analytical Space Resolution	45,72
Analytical Surface Resolution	30,48
Perimeter Zone Depth	457,20
Perimeter Zone Division	☑
Average Vertical Void Height Threshold	182,88
Horizontal Void/Chase Area Threshold	0,093 m²
Advanced	
Other Options	Edit...

Advanced Energy Settings

Parameter	Value
Detailed Model	
Target Percentage Glazing	0%
Target Sill Height	75000,00
Glazing is Shaded	☐
Shade Depth	45,72
Target Percentage Skylights	0%
Skylight Width & Depth	91,44
Building Data	
Building Type	Mehrfamilienhaus
Building Operating Schedule	Default
HVAC System	Residential 14 SEER/8.3 HSPF Split Packaged Heat Pump
Outdoor Air Information	Edit...
Room/Space Data	
Export Category	Rooms
Material Thermal Properties	
Conceptual Types	Edit...
Schematic Types	<Building>
Detailed Elements	☑

Figure 30 – Analytical model for gbXML export of the Project A and Revit energy model settings

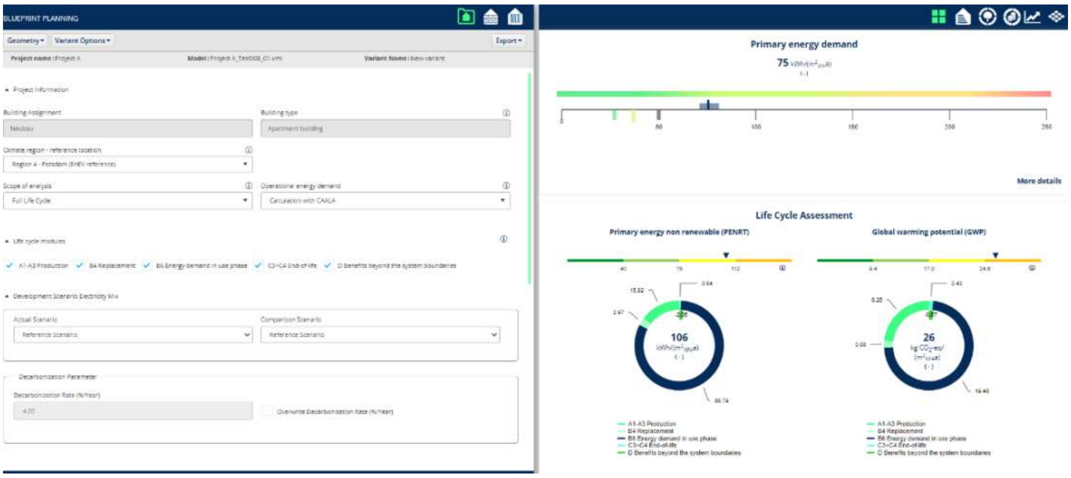
CAALA executes the next steps of the LCA assessment in the cloud and requires a CAALA Pro account. Here the gbXML file also will be imported for the calculations. After logging in, the first step is creating the project and adding information such as the location and climate. In this step, CAALA also demands the type of building as residential or non-residential.

Climate Region reference location is shown based on Germany. For this project, the enEv reference project data is selected. The given initial information for creating the project cannot be edited later.

After successfully creating the project, the next step is phase selection. One of the two options - Preliminary planning or blueprint planning – should be selected to start building assessment (Figure 31).

Figure 31 – CAALA Homepage. Reprinted from REVIT to CAALA by CAALA, n.d.

Project A Assessment in CAALA is made based on the blueprint planning option. After this step, models were uploaded to the cloud and continued with the two-divided screen. On the left side, project information is summarized and edited. Graphics are shown based on the project on the right side of the page, life cycle assessment, primary energy demand, and life cycle costing. According to the user's changes, these are updated in real time and give a quick summary of the assessment (Figure 32).


BLUEPRINT PLANNING

Project name : Project A **Model :** Project A_Test008_Cl.xml **Variant Name :** New variant

Project Information

Building Assignment: Neubau
Building type: Apartment building
Climate region - reference location: Region 4 - Potsdam (EnEV reference)
Scope of analysis: Full Life Cycle
Operational energy demand: Calculation with CAALA

Life cycle modules

✓ A1-A3 Production ✓ B4 Replacement ✓ B6 Energy demand in use phase ✓ C3+C4 End-of-life ✓ D Benefits beyond the system boundaries

Development Scenario Electricity Mix

Actual Scenario: Reference Scenario
Comparison Scenario: Reference Scenario

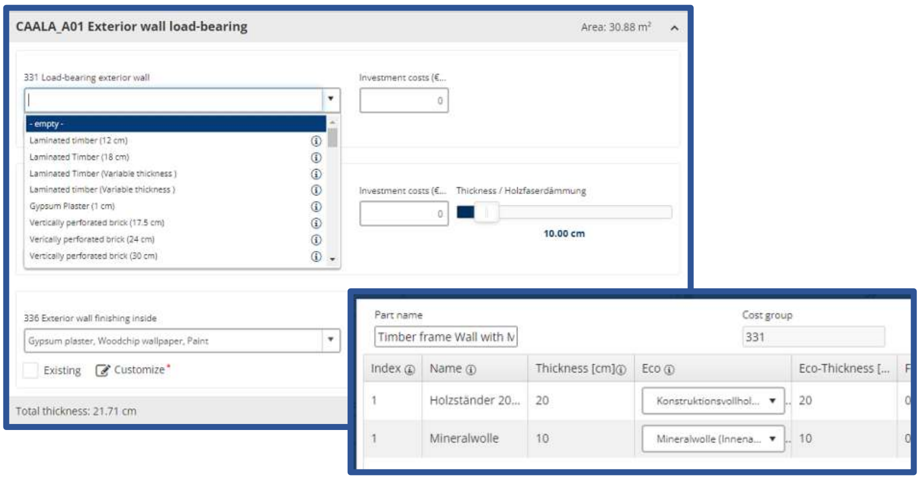
Decarbonization Parameter

Decarbonization Rate (%/Year): 4.00
☐ Overwrite Decarbonization Rate (%/Year)

Figure 32 – CAALA Assessment Home screen

The first board of the project shows what is recognized from the model, such as floor height, number of floor or net floor area, is presented. If necessary, it is possible to correct this information. In this step, also the building type (new or refurbishment), LCA period, and modules will be selected. For both projects for the assessments, the floor area was corrected and Module A1-A3 Production, B4 Replacement, C3-C4 End-of-life, and D Benefits beyond the system boundaries were included in the assessment.

The second board shows the material information. Here the building elements are recognized as Exterior Wall, Floor to unheated space, Ceiling, Interior Wall, Interior Door, and Sun protection. Materials could be selected from already defined compositions. Nevertheless, correcting or adjusting of compositions is possible on this board (Figure 33).



CAALA_A01 Exterior wall load-bearing

Area: 30.88 m²

331 Load-bearing exterior wall

- empty -
Laminated timber (12 cm)
Laminated Timber (18 cm)
Laminated Timber (Variable thickness)
Laminated timber (Variable thickness)
Gypsum Plaster (1 cm)
Vertically perforated brick (17.5 cm)
Verically perforated brick (24 cm)
Vertically perforated brick (30 cm)

Investment costs (€... 0

Investment costs (€... 0

Thickness / Holzfaserdämmung: **10.00 cm**

336 Exterior wall finishing inside: Gypsum plaster, Woodchip wallpaper, Paint

☐ Existing

Total thickness: 21.71 cm

Part name: Timber frame Wall with M

Cost group: 331

Index	Name	Thickness [cm]	Eco	Eco-Thickness [...	F
1	Holzständer 20...	20	Konstruktionsvollhol...	20	0
1	Mineralwolle	10	Mineralwolle (Innena...	10	0

Figure 33 – CAALA Material Selection and Editing Screen

After the corrected import of the geometry Exterior Wall, Roof, Floor to unheated space, Ceiling to unheated space, Window, Ceiling, Interior Wall, Interior Door were as building elements recognized. Timber cladding for the ceiling and interior walls was not available in the list. Therefore for both options, gypsum board cladding is selected.

For detailed constructions, there is an option to adjust the layers. This setting is recommended for the experts to use and requires detailed information of the material such as fraction, lambda and replacement period of the element. Moreover, this screen offers to create different variants of the elements and compare their impacts with each other. (see Figure 33)

The third board shows the Technical Building Equipment. Here the information about heating, electricity but also the direction of the building could be defined for solar energy. This assessment did not include the operation phase, so this board was not filled.

CAALA provides LCC assessments for the imported model. However, further aspects to track or measure could not be found.

4.2.3.2. Case Study Project B – School Building

Figure 34 – Project B - 3D Model

Similar to the first model, the model of Project B (Figure 34) also checked for the material and component duplicates for the preparation for the BIM-based-LCA assessment. Additionally, irrelevant data such as foundation, topography, and outside facilities are removed from the project model.

Unlike the first model, the 3D-Model of Project B has LOD 300. This BIM model is planned for the early design phase. Although the quantity and materials and their layers are correctly designed, intersections with the other disciplines are not included. The existing BIM model contains all the information related to the approval phase, but it does not include all the details, such as surface qualities or details of the static elements. As information level of the model is defined as LOI 200. Construction elements could be quickly listed, and the model can automatically generate quantities and area calculations. However, there is no information included, such as certifications or specifications of the elements.

- **LCA with Tally**

For this assessment, the same steps for Project A are repeated. Tally plug-in is directly Revit interface available; therefore, no data exchange process was necessary again here. As study type as full building study is selected and in the following step components are phases for the assessment repeated.

The issue of diverse naming for parameters of Project A is here also repeated.. There were various names defined for the same materials. The Listing in Revit was generated, and if necessary, materials were combined.

The element and material selections could be copied from Project A as long as the project in the tool is already defined and the material match completed. This function is not working with a trial license. Concluding the assessment, the rest of the materials and constructions were matched.

- **LCA with CAALA**

Assessment with CAALA is performed as explained in Chapter 4.2.2.1.1 The difference between Project A and Project B was that the building type was defined as “not residential”.

Similar to Project A, here was necessary to work on gbXML export (Figure 35). After importing the XML. file to CAALA, it was noticed that the recognition of the element had some errors. CAALA recognized Exterior Wall, Floor to unheated space, Ceiling, Interior Wall, Interior Door, and Sun Protection. As the roof and windows were not recognized, gbXML export was repeated with Revit 2022, and room heights were corrected. Additionally, the floor elements are divided into two different types for adding exterior and interior parameters separately.

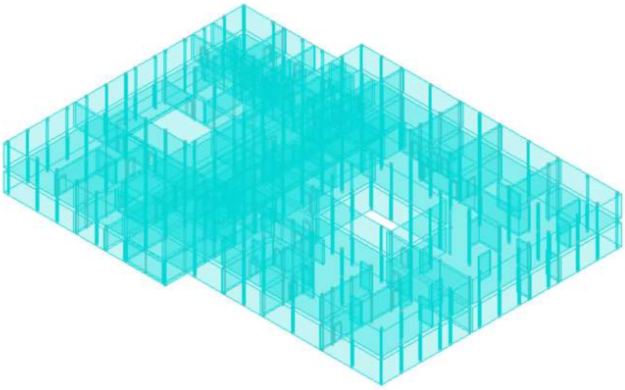


Figure 35 – Analytical model for gbXML export of the Project B

After the correction, the import process was repeated. The elements were recognized as Exterior Wall, Floor to unheated space, Ceiling, Interior Wall, Interior Door, and Roof this time.

In the following steps, the same process was repeated as Project A. The results of the assessment will be presented in detail in the following chapter.

5. Results and Discussion

5.1. Results

The following sections will explain the results of the chapter Analysis. In the beginning, the SWOT analysis results for the case study will be presented. LCA results of the projects will be shown in the second part of the chapter.

5.1.1. Use cases of BIM Model for Prefabricated Timber Construction

According to KIT (Karlsruhe Institute of Technology) (2018), BIM Use Cases are grouped under 59 categories concerning project roles and phases. This document lists the potential BIM use cases not only for planning also for further uses such as construction, manufacturing, operation, sustainability, etc.

Based on the classification of KIT (2018), BIM was used for the following use cases in both projects;

- Model-based, dynamic derivation of data (plans, lists, forms, etc.)

  Dynamic derivation of data for purposes of the current use phase, e.g., deriving 2D plans from 3D models

- Model-based visualization

  Visualization through representations/renderings, film sequences in the form of animations, or navigating through the entire model with or without virtual reality glasses

- Model-based inventory

  Modeling the terrain

- Model-based, geometric, and parametric modeling

  Creation of the geometric structures of the model

  Reading and creating data in the model

  Update the model and add changes

Dynamic derivation of the model type (draft model, competition model, presentation model, etc.)

Linking the technical model with calculation and evaluation or federated models

- Model-based variant analysis

  Evaluation of planning variants with regard to costs, deadlines, quality

  Carrying out a model-based object comparison in an architectural competition

- Model-based project development

  Preparation of forecasts for yield optimization, e.g., forecasted rentability

- Model-based model evaluation and rule checking

  Structural engineer: Linking the geometric model with an analysis model for static calculations or numerical simulations

The use cases explain that the BIM focus of the projects mainly was for planning-related purposes; further use for building construction, operation, or end of life phases was not included in BIM.

In the sections that follow, the results of the case study SWOT analysis will be shown, and the limitations will be described.

5.1.2. Results of the SWOT Analysis

5.1.2.1. Strengths

- **Standardization**

Standardization is a strength of prefabrication, and BIM can also bring that one step further. Most of the prefabricated system consists of standard and repetitive components. However, creating a workflow for building new components or new constructions of the standard components in the BIM platform is crucial. As Kovacic et al. (2018) mentioned, defining and working with clear standards -from component name to the included material information- is necessary to avoid later problems.

The component naming standards of the projects help define the standard and repetitive elements according to their thickness, location, e.g., interior or exterior, and materials. Different material definitions such as Interior Wall 20 with timber cladding or gypsum cladding are not included in the same component. This approach has an advantage for repetitive elements in LCA assessment in BIM.

- **Reducing errors and increasing efficiency**

Prefabricated construction immensely benefits from BIM. Workflow with BIM is easier and quicker to check for errors when the components are already defined. Besides the known measures like control views for clash detection and duplicate control, construction element families are designed for different LOD levels to reduce future errors and increase efficiency. Therefore, not necessary to make a new detailed model from scratch, only to change the detail level is required. Moreover, this also means for LCA from the beginning; it is possible with a higher level of information to assess.

- **Data-driven quality**

Quality controls regarding clash detection are managed by the BIM Platform itself. However, definition of quality control process based on open BIM standards is required for further cooperation in complex projects. For smaller projects, the cost and time efficiency should be considered.

- **Collaboration**

In this project, collaboration within the planning department itself worked appropriately. Defined working structure and using a cloud platform such as Autodesk BIM 360 creates the option for simultaneous document management and co-working within the team. In this case, collaboration occurred exclusively within the planning department; therefore, the number of involved parties was limited.

5.1.2.2. Weakness

- **More detailed and longer planning phase**

Prefabrication needs detailed planning. That is one of the essential points which separates prefabrication from conventional construction. Also, detailed planning needs of BIM projects result in a more extended planning phase. However, it is important to mention a change in the working process through integral planning. Furthermore, working with BIM results in less revision and design errors, which means finishing with the planned budget and time. All the aspects should be taken into account when length of the processes is evaluated.

- **Interoperability and interface problems**

Currently, the project BIM model is used just for planning purposes. Therefore, interoperability and interface problems could not be observed.

- **Full digital process chain**

To reach a fully digital manufacturing and process chain, to have a structured database that works seamlessly for different departments is necessary. This means related data from production, tendering, planning to construction, controlling, or accounting must be included and available. Besides, full digital process chain needs also right software solutions. For many companies, the solutions that they have, grown historically in time. Therefore, in an industry that deals with the daily high cost and deadline pressure, changing or transforming these processes is quite complex, and it needs a lot of investment and a long time to plan and implement.

5.1.2.3. Opportunities

- **Innovation Potential**

Pre-designed details and design optimization in the planning phase are already supported via some actions. The parametrized standard components, detail catalogs, and some pre-designed layouts are examples of these actions — further steps, finding repetitive units such as standard flat layouts. Currently, the

HVAC and electrical systems are included. More LCA and LCC relevant information could be involved for sustainability and economic feasibility.

All-in providers in the industry tend to lead into something that Patlakas et al. (2015) mention as a "closed silo" mentality. On the other hand, these companies could provide massive information from different phases from manufacturing to construction for future sustainability research.

- **Design for Manufacture and Assembly (DFMA) and Design for Disassembly (DFD)**

The project's system consists high degree of prefabricated building components, and they are already designed with principles of design for assembly, disassembly, and reuse. Where possible, the connections are designed with screw-type threaded fasteners rather than adhesives or flexible parts. Components are designed and installed according to "Cradle-to-cradle" principles. However, this system features currently not in BIM evaluable for future uses, and direct integration to manufacture is missing.

- **Change of work processes**

The conceptual design and detailed design phases are working more parallel with the BIM implementation process. Here these phases means more of an integrated planning workflow instead of a linear one. As Kaufmann et al. (2017) also show in their study, this is particularly in the case of prefabricated timber construction quite essential because the detailed design of some disciplines is needed much earlier than conventional construction. This approach results in involving structural planning to the conceptual phase earlier. This coordinated approach brings the clash detection earlier and saves time and costs.

- **Integration of supply chain**

To reach a complete digital manufacturing and process chain, it is necessary to have a structured database that works seamlessly for different departments. It means related data from production, tendering, planning to construction, controlling, or accounting must be included and available. It requires the right software solution. The solutions they use have grown historically in time for many companies. Therefore, in an industry that deals with the high cost and deadline pressure daily, changing or transforming these processes is quite complex, and it needs much investment, also a long time to plan and implement.

5.1.2.4. Threats

- **Lack of standardized tools and protocols**

BIM Planning is still a living and evolving process for prefabricated timber constructions. As the analysis chapter explained, the case study project used BIM primarily for planning purposes and does not include manufacturing, construction, or operation phases in the BIM model. However, even though this is the case, a planner uses 5-6 different software solutions daily for planning purposes. Collaboration and interoperability should be standardized to reduce those and make BIM a central data source. Additionally, as Aberger(2017) and Kaufmann et al.(2017) already mentioned, prefabricated timber construction compared to the conventional needs detailed information in earlier planning phases and requires that is why earlier interdisciplinary planning. That is why a change in the construction and planning process with BIM is also necessary.

- **Lack of research**

BIM is a widely researched area in the AEC world. However, as Aberger (2017) also mentions, the combination of BIM and Timber construction comprises a small part of it. This project helps to positively impact the industry and research cooperation in the research area.

- **BIM Adoption**

According to Aberger (2017), BIM Adoption in the timber construction sector is higher than conventional construction. This positive tendency is also supported here. BIM is incorporated into the company's daily workflows, and it is used for the phases between LPH 1-5 in this project. In this case, BIM Adoption is not a threat, and it has become more of an opportunity.

- **Resistance to change in business practice**

During the research, any resistance or hesitation to change of processes is not observed.

- **All-in providers**

According to Patlakas et al. (2015), prefabricated construction companies could be all-in providers, resulting in a closed-loop solution. Here it is not the case.

5.1.3. Results of BIM-based LCA

5.1.3.1. A brief summary of the test results

LCA assessments of both prefabricated buildings show that their BIM models have high–level information, even though they have different LODs and are not designed for LCA assessments. Still, it is important to mention that the comparability of the tools was not easy, as they use different methods, and databases and modules which are taken into account were also not the same. Table 10 compares both tested tools.

Table 10 – Summary of the tested tools in the case study projects

Name	Tally	CAALA
Revit	Revit 2020	Revit 2020 – Revit 2022
Database	GaBi 8.5 using GaBi 2018	ÖKOBAUDAT
Use	Bim-integrated Plug-in	gbXML export and online
LCA Module	A1-A3, A4, B2-B5, C2-C4 and D Optional: A5, B6	A1-A3, B4, C3-C4, and D
Environmental Impact Categories	GWP, ODP, AP, EP, SWP, PED, NRED, RED	GWP, ODP, AP, EP, POCP, PERT, PENRT.

Tables 11 and 12 summarize the BIM-based LCA assessments for both case studies. Followingly, Table 13 presents the issues encountered during the test and, if available, the solutions.

Table 11 – Summary of the environmental impacts – Tally

	Project A	**Project B**
Global Warming Potential (kgCO2eq/m^2)	172,413	119,171
Eutrophication Potential (kgNeq/m^2)	0,315138	0,120359
Ozone Depletion Potential (CFC-11eq/m^2)	1,86886E-05	5,12907E-06
Acidification Potential (kgSO2eq/m^2)	2,56038	1,31611
Primary Energy Demand (MJ/m^2)	245,61	283,19

Table 12 – Summary of the environmental impacts – CAALA

	Project A	**Project B**
Global Warming Potential Total (kg CO_2-eq/(m^2NFAa)	3,897	2,040
Eutrophication Potential Total (kg PO4eq/m^2a)	36,1221	13,2220
Ozone Depletion Potential Total (R-11eq/m^2a)	-2,42066E-07	-2,48824E-07
Acidification Potential Total (kgSO2eq/m^2a)	0,01421	0,01154
Primary Energy Demand Total (kWh/m^2a)	24,41	29,19

Table 13 - Issues encountered during the assessments

Model and Export Issues	**Tally**		**CAALA**	
	Project A Residential	**Project B School**	**Project A Residential**	**Project B School**
Deviation -Model/Element Dimensions, Total Area	Project total net area is given by user to the Tally	Same as Project A	- Tool recognizes the project net floor area of the gbXML. Deviation project net area between Revit Model and CAALA - 13,4 % *Solution: There is also an option to overwrite it. However how it is weighted should be studied.*	- Deviation project net area between Revit Model and CAALA - 72 % > 21 % *Solution: Corrections with gbXML viewer Deviation could be reduced to %21,3. In the next step, Net floor area via CAALA homescreen corrected.*
Building and Element Recognizition	- Elements and their layers were recognized directly from Revit. Exterior elements were not defined in families therefore as undefined identified. - No possibility to include building type	- Elements and their layers were recognized directly from Revit. - No possibility to include building type	- gbXML export and import to the tool is necessary - Roof, Exterior walls, Structural Columns, Gallery and False ceiling are not recognized *Solution: Room levels were adjusted in Revit and re-exported. That solved the problem with horizontal elements like ceiling and roofs but not the facade elements of exterior walls*	- gbXML export and import to the tool is necessary - Roof, False ceiling, Exterior walls are not recognized. *Solution: Room levels were adjusted in Revit and re-exported. That solved the problem with horizontal elements like ceiling and roofs but not the facade elements of exterior walls* - Floor to unheated space was not correct. *Solution: Room levels were adjusted and floor element was divided in two .* - gbXML editor is used to correct the element parameters
Material	- Material Recognition between the tool and Revit was not available. Material match had to be accomplished through Tally interface. -Same materials with different names existed in the model *Solution: Step back to the model and editing the material list to keep the model compact and leaner* - Wall material of the model could not be found in database. Instead of that Material Domestic Hardwood is selected. *Additional Solution: Contacting the company for adding EPDs.* - Material List mainly based on US	- Material Recognition between the tool and Revit was not available. Material match had to be accomplished through Tally interface. - Same materials with different names existed in the model *Solution: Step back to the model and editing the material list to keep the model compact and leaner* - Wall material of the model could not be found in database. Instead of that Material Domestic Hardwood is selected based on similarity. *Additional Solution: Contacting the company for adding EPDs.* - Exterior Wall - Reinforced Concrete was not designed with details in the model. *Solution: adding a material layer and adjusting the thickness in Tally* - Material List mainly based on US	- Here also material recognition between the tool and Revit was not available and made via CAALA homepage. - Timber Wall Construction was lacking *Solution: Defining new layers via Material Selection.* - Timber cladding for the interior walls was not included. *Solution: Interior wall cladding also selected from list available components as Gypsum board*	- Here also auto material recognition between the tool and Revit was not available and made via CAALA homepage. - Timber Wall Construction was lacking *Solution: Defining new layers via Material Selection.* - Timber cladding for the interior walls was not included. *Solution: Interior wall cladding also selected from list available components as Gypsum board*
Other	- The life cycle stages could not be defined(A1-A3, A4, B2-B5, C2-C4, and D) are assessed. - There is no possibility to add LCC or SLCA aspects to the assessments	- The life cycle stages could not be defined(A1-A3, A4, B2-B5, C2-C4, and D) are assessed. - There is no possibility to add LCC or SLCA aspects to the assessments	- The life cycle stages selection is possible between A1-A3, B4, C3-C4, and D. - LCC analysis is available, however SLCA impacts cannot be tracked	- LCC analysis and Energy demand calculations are available. However for non-residential buildings, it does not contain average data. The user should provide and give them to the tool. - Additionally SLCA impacts cannot be tracked.

In addition, the workflows of the tools are compared with each other (Figure 36). The findings will be explained more in the following two chapters.

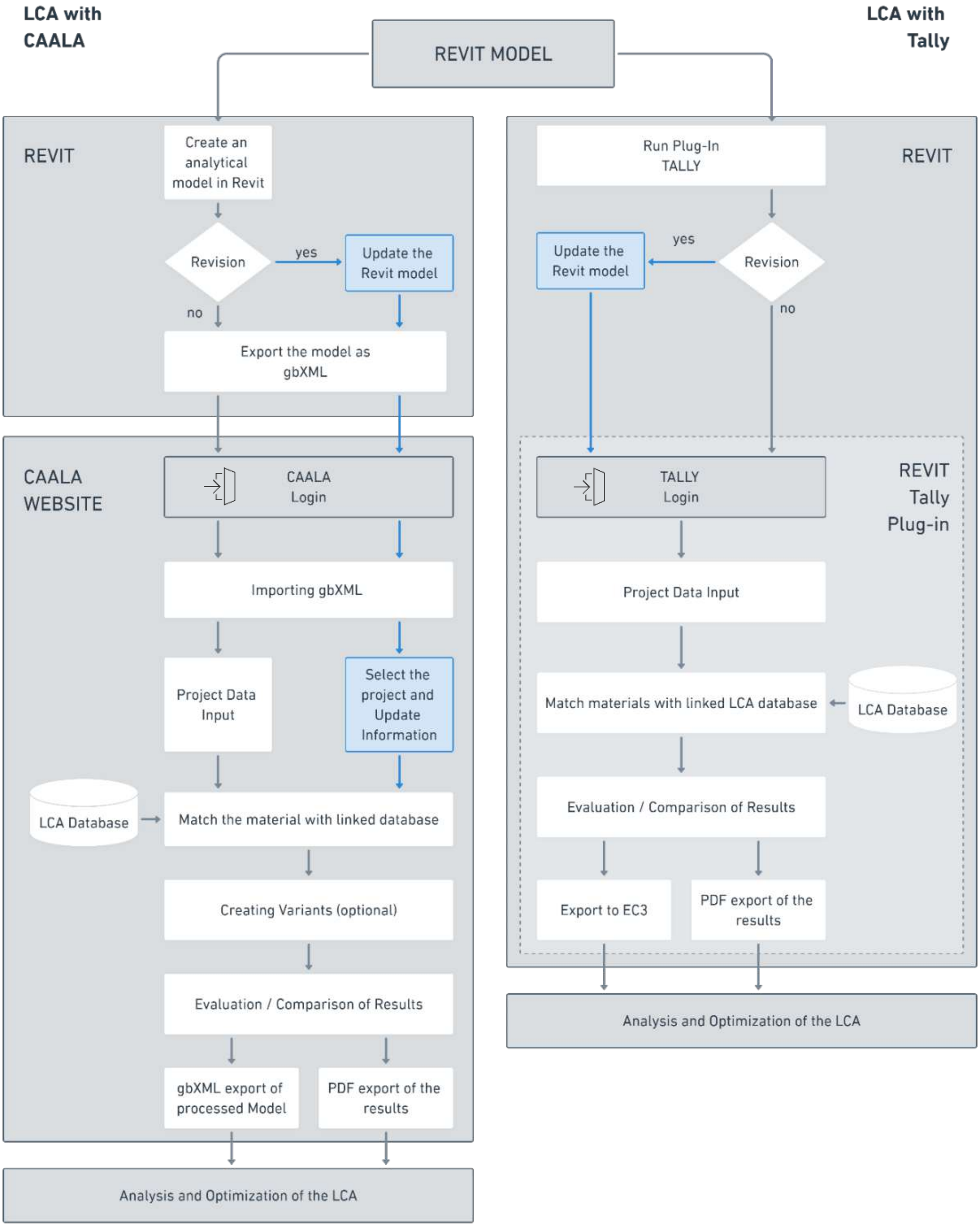


Figure 36 – Comparison of the tested tools' workflows

5.1.3.2. Detailed Results of LCA with Tally

Generating LCA reports in Tally for Project A and B had no significant difference. One of the reasons for that is that there was no possibility of defining building type.

In both models, the quantity take-offs have shown various component measurement parameters that defined the same indicators. (e.g., Length, Length_, finished Length, etc.). This unclear parameter structure made the control of the elements and quantities more complicated.

At the beginning of the assessment, matching the Revit materials with the tool’s database was necessary. Although this is time-consuming, copying materials from other projects speed up the process. Tally’s interface lets the user select the materials from a well-structured material tree consisting of generic to manufacturer EPDs. Still, some material matching problems were encountered on the assessment process. For example, materials of the case study for interior wall claddings could not be found in the database. Instead of that material as an alternative “Domestic softwood, US, AWC – EPD” was selected for generating the end report. A similar problem happened for roof construction, the layer of gravel could not be found in the material list.

If the component construction is not designed with detail – meaning with correct layers and thickness – adding layers and defining them with thickness or percent of whole material by the user in Tally is possible. This feature was used for reinforced concrete wall construction in Project B to add an insulation layer to the component. Although some differences in the material composition could be adjusted during the assessment, Inventory Data was not editable. Therefore, the model's information, such as material quantity, should be reliable for the assessment with Tally.

As the literature review mentioned, some LCA modules have more influence on prefabricated construction than conventional construction methods. For example, Module A - transportation and manufacturing – has a significant effect on prefabricated buildings, and Module D is mostly overlooked. Santos et al. (2019) pointed out that module D should be included in LCA for prefabricated constructions because the reuse and recycle options of the prefabrication could bring positive impacts.

Tally offers complete building study with Modules A1-A3, A4, B2-B5, C2-C4, and D automatically. The application offers the user the option for defining which materials are existing – reused/salvaged during the material matching. As the case study was designed to disassemble and re-use the structural elements, structural columns are defined as existing for one variant.

The graphics below show the percentage distribution of total environmental impacts of the analyzed Life Cycle Phases for both projects. The assessments illustrate that the negative numbered impacts mostly come from Module D for both projects (Figure 37 & 38).

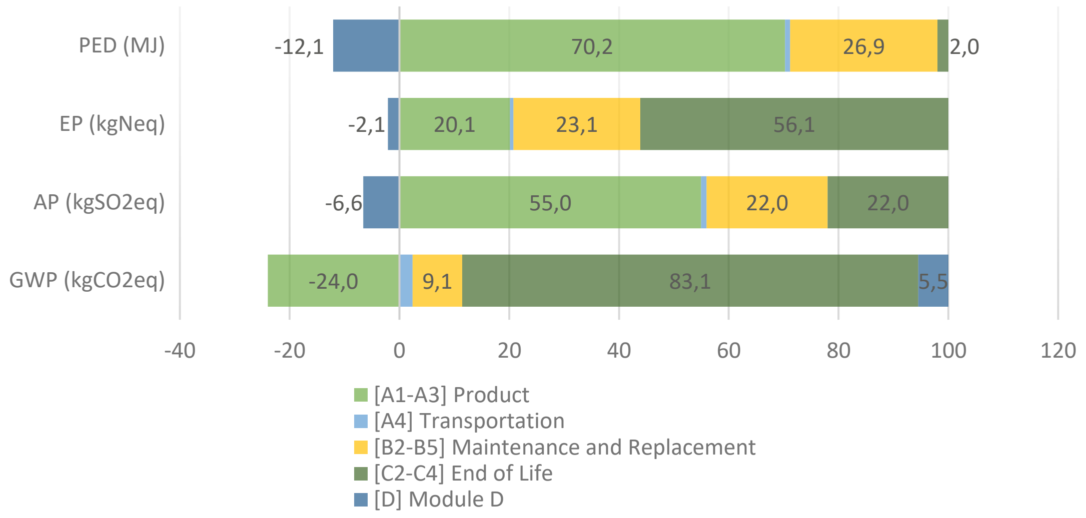


Figure 37 – Project A - Comparison of Environmental Impacts by Life Cycle Phases

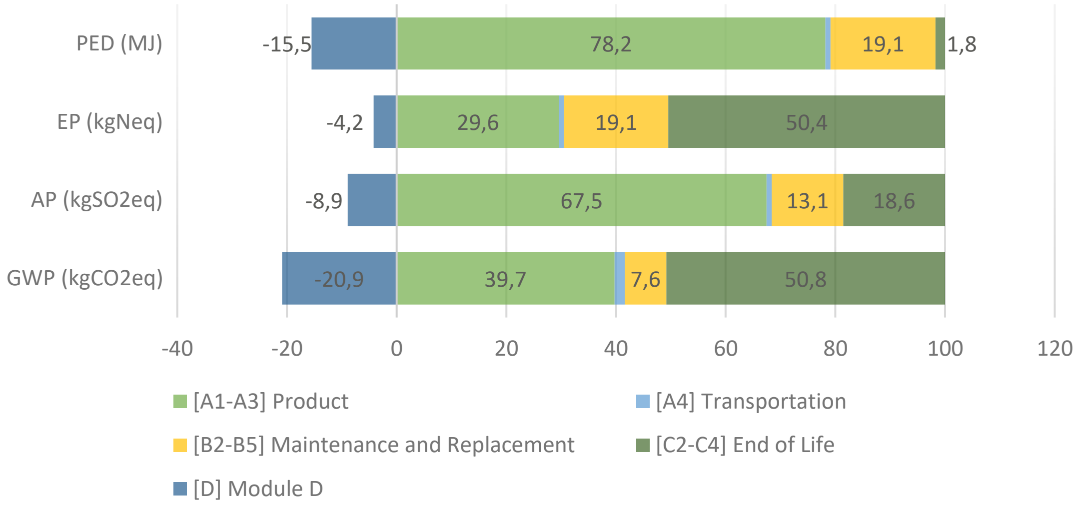


Figure 38 – Project B - Comparison of Environmental Impacts by Life Cycle Phases

Tally provides the assessment results diversely. The environmental impacts could be observed not only by life cycle stage also by material, Revit family and defined Tally material. These subcategories of the results help to understand the results of components easily. For example, the following graphic shows that elements of the models are not correctly defined as interior or exterior in the thermal envelope. Figure 39 explains that most GWP impacts come from undefined building elements.

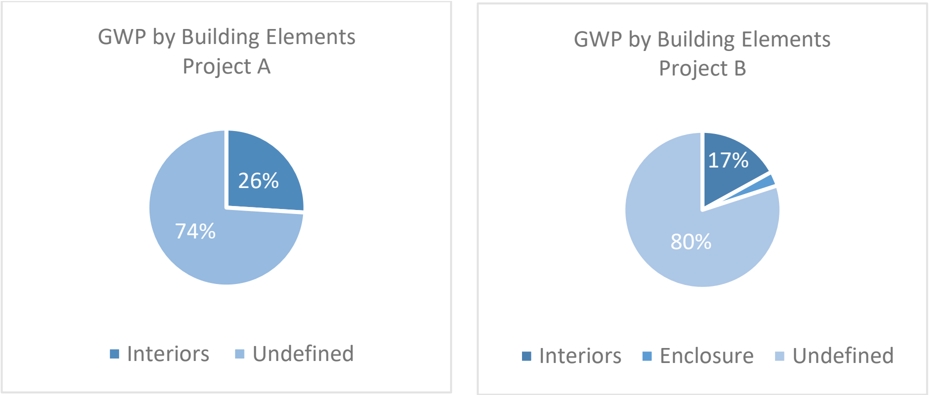
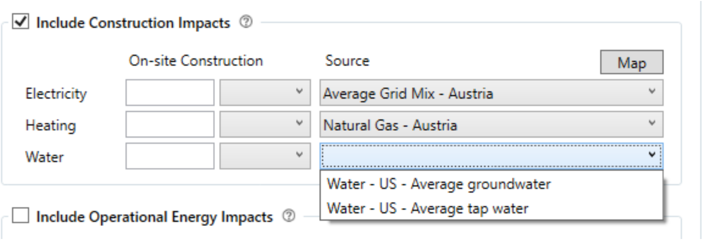


Figure 39 – Distribution of Global warming potential by element position for the assessed projects

The results of the LCAs for both projects showed the most optimization potential by materials for GWP in the category of thermal and moisture protection. Comparisons by the building components showed interesting results. According to the results of assessments, the Project A contributes to the analyzed environmental impacts primarily by its walls. However, the results of Project B show that the most impacts are produced by its floor elements.

Although they were not in the scope of the thesis, also construction impacts of the project are not entirely available for the European region (Figure 40).


☑ Include Construction Impacts

	On-site Construction		Source
Electricity			Average Grid Mix - Austria
Heating			Natural Gas - Austria
Water			Water - US - Average groundwater Water - US - Average tap water

☐ Include Operational Energy Impacts

Figure 40 – Tally Construction Impacts

Additional sustainability parameters, such as LCC or Social aspects of the projects, could not be evaluated through the tool.

5.1.3.3. Detailed Results of LCA with CAALA

Although the methodology steps for preparing the BIM models for LCA assessments were followed, adjustments of the model parameters and new settings in the BIM platform were needed more than once in the assessment processes. For non-experts working with gbXML import and their settings is a challenge in the beginning. Therefore, the tool offers detailed online manuals and video tutorials.

Prefabricated timber construction needs model components that are not standard for system families in Revit. A company with detailed manufacturing models of the components can easily create its own BIM library. However, it is necessary to control and define the parameters needed for the assessments.

The BIM model components were mainly built as a generic family in Revit. For a successful assessment, these component families should be modeled according to the needs and limitations of BIM-based LCA tools; if not, interoperability problems can occur (Figure 41). For example, the facade wall family for Project and Project B were defined false with the interior wall parameter. Therefore, gbXML file identified these elements as interior wall, instead of exterior wall. Similarly, the same floor type was used for the regular and ground floors of the tested models. CAALA needs the setting of exterior and interior for identifying the thermal envelope of the building. Therefore, the floor element of Project B had to be divided in two, and it was ordered to new floor type with the parameter exterior.

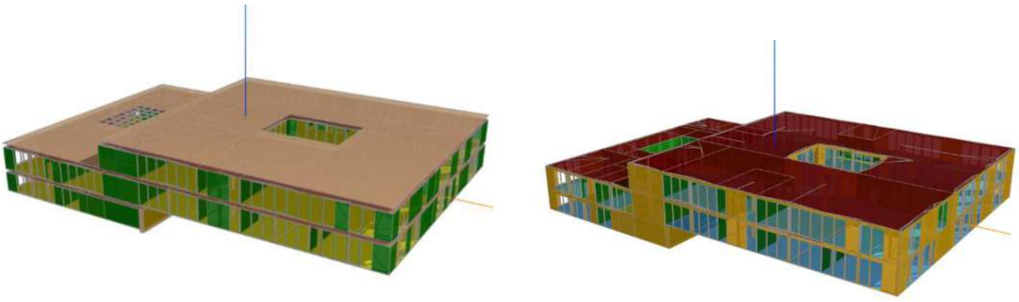


Figure 41 – False recognition of the exterior walls, roof, and false ceiling in gbXML schema (left) and corrected version (right)

Identification issues of the elements also create problems in the project net floor area recognized by CAALA. gbXML schema export made by spaces according to the tool's manual, so it does not recognize the columns in the rooms. Therefore, they were not included in this assessment. The floor area of Project A 13% and Project B 70% were also less than their actual value. For the school building, this could be explained till to 15% with lower LOD level and the rooms not included in the thermal envelope (e.g., Inneryard, Technic rooms). However, after correcting these errors and controlling the gbXML file of Project B, the gbXML file still lacked all the ceiling and floor elements. Control of the file showed that the floor element was recognized with the air parameter and was not included in the area calculations in CAALA. These elements are edited through the gbXML editor and matched with the parameter "interior/exposed floor." In the end, the deviation of net floor area could be reduced to 21,3%.

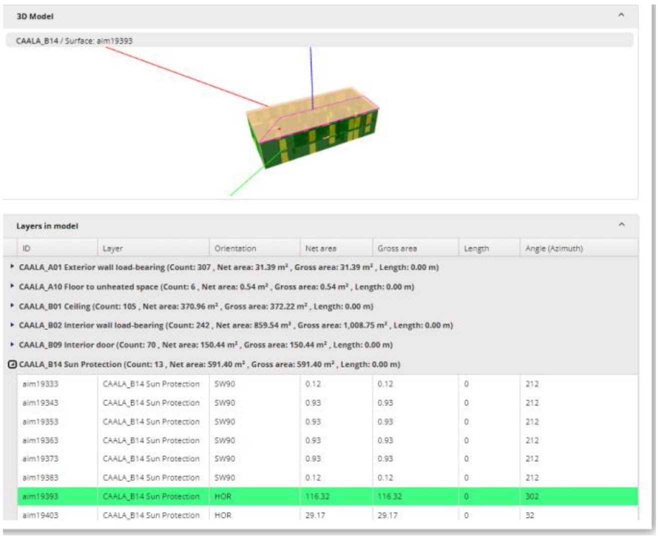
Project A did have all the rooms defined in gbXML and are included in the thermal envelope. However, during the first import, it was also recognized that room height should be adjusted as they did not include the roof and exterior walls.

For the mentioned adjustments and corrections of the parameter and model element identification, gbXML editor and Revit were required for both projects. Some of the errors could be corrected by Revit settings. If the problem continued, a gbXML editor could edit the component parameter. Still, the issue with the exterior facade cladding elements could not be solved with both. These elements were not recognized in gbXML, because they are designed as separate construction elements, and room settings in Revit could be extended maximum to the wall axis/edge.

After the successful import in the CAALA website, the system recognizes the elements and lists as Exterior Wall, Roof, Floor to unheated space, Ceiling to unheated space, Window, Ceiling, Interior Wall, Interior Door. Similar to Tally, assessment units are combined components instead of separate layers. They are grouped under building elements, such as exterior walls, interior walls, etc.

Materials could be matched easily. Materials and their detail construction can also be edited by layers and their measurements. E.g., CAALA_exterior walls consist of three layers; the wall structure, interior, and exterior cladding. These layers should be defined separately by material information. Here, the user can customize the details further and add a new layer. This is an efficient feature for corrections and to easily check the variants.

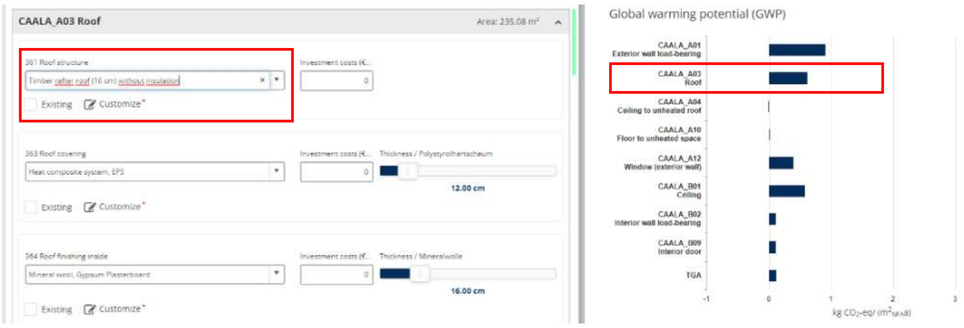
CAALA provides a material list that is linked to the 3D of the project. In this list, elements could be selected and in 3D view highlighted. That offers a quick troubleshooting possibility if the material is right ordered (Figure 42).



ID	Layer	Orientation	Net area	Gross area	Length	Angle (Azimuth)
▸ CAALA_A01 Exterior wall load-bearing (Count: 307 , Net area: 31.39 m² , Gross area: 31.39 m² , Length: 0.00 m)						
▸ CAALA_A10 Floor to unheated space (Count: 6 , Net area: 0.54 m² , Gross area: 0.54 m² , Length: 0.00 m)						
▸ CAALA_B01 Ceiling (Count: 105 , Net area: 370.96 m² , Gross area: 372.22 m² , Length: 0.00 m)						
▸ CAALA_B02 Interior wall load-bearing (Count: 242 , Net area: 859.54 m² , Gross area: 1,008.75 m² , Length: 0.00 m)						
▸ CAALA_B09 Interior door (Count: 70 , Net area: 150.44 m² , Gross area: 150.44 m² , Length: 0.00 m)						
⊟ CAALA_B14 Sun Protection (Count: 13 , Net area: 591.40 m² , Gross area: 591.40 m² , Length: 0.00 m)						
aim19333	CAALA_B14 Sun Protection	SW90	0.12	0.12	0	212
aim19343	CAALA_B14 Sun Protection	SW90	0.93	0.93	0	212
aim19353	CAALA_B14 Sun Protection	SW90	0.93	0.93	0	212
aim19363	CAALA_B14 Sun Protection	SW90	0.93	0.93	0	212
aim19373	CAALA_B14 Sun Protection	SW90	0.93	0.93	0	212
aim19383	CAALA_B14 Sun Protection	SW90	0.12	0.12	0	212
aim19393	CAALA_B14 Sun Protection	HOR	116.32	116.32	0	302
aim19403	CAALA_B14 Sun Protection	HOR	29.17	29.17	0	32

Figure 42 – 3d Model visualization of the elements

One significant feature of CAALA is real-time assessment. Regarding every given information, the assessment on the right side updates itself. This approach helps the user directly check the impact of the selected or designed material. With that feature, the materials of the windows, roof, and interior walls were updated, and the improvements could have been seen on the graphic chart and lists. (Figure 43).



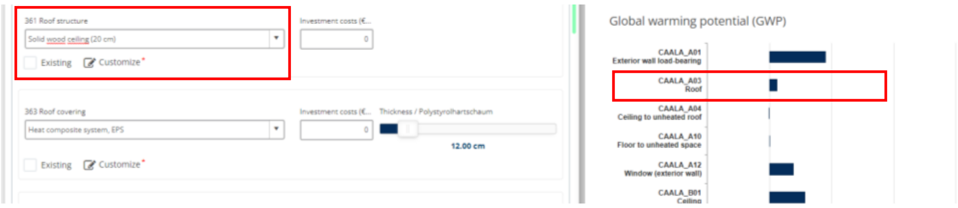
CAALA_A03 Roof — Area: 235.08 m²

361 Roof structure: Timber rafter roof (16 cm) without insulation — Investment costs (€...: 0

363 Roof covering: Heat composite system, EPS — Investment costs (€...: 0 — Thickness / Polystyrolhartschaum: 12.00 cm

364 Roof finishing inside: Mineral wool, Gypsum Plasterboard — Investment costs (€...: 0 — Thickness / Mineralwolle: 16.00 cm

Figure 43 – Roof structure - Variant 1

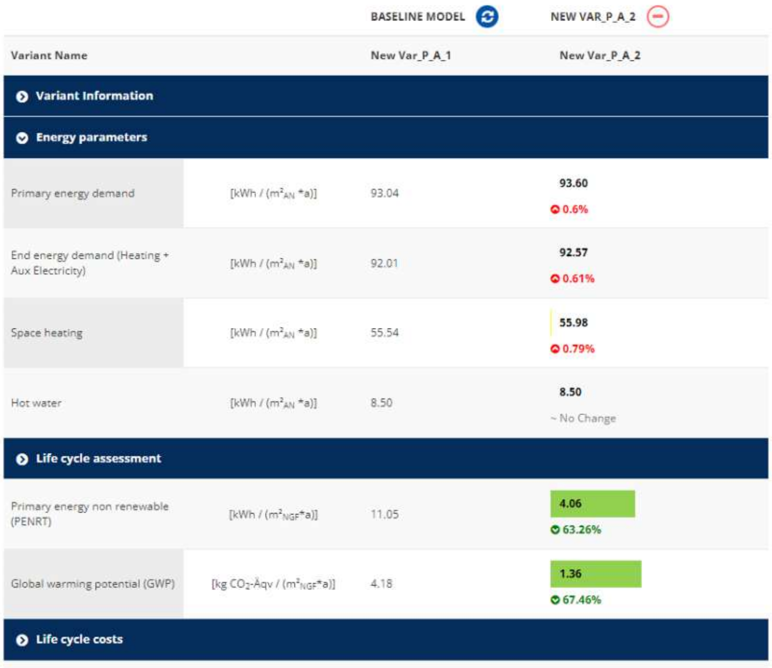


361 Roof structure: Solid wood ceiling (20 cm)
☐ Existing · Customize*
Investment costs (€...: 0

363 Roof covering: Heat composite system, EPS
☐ Existing · Customize*
Investment costs (€...: 0
Thickness / Polystyrolhartschaum: 12.00 cm

Figure 44 – optimized Roof structure - Variant 2

The material optimization is repeated for windows and interior walls as well. The figure below shows the changes between the variants and highlights the improved variant (Figure 45).



		BASELINE MODEL	NEW VAR_P_A_2
Variant Name		New Var_P_A_1	New Var_P_A_2
Variant Information			
Energy parameters			
Primary energy demand	$[kWh / (m^2_{AN} *a)]$	93.04	93.60 0.6%
End energy demand (Heating + Aux Electricity)	$[kWh / (m^2_{AN} *a)]$	92.01	92.57 0.61%
Space heating	$[kWh / (m^2_{AN} *a)]$	55.54	55.98 0.79%
Hot water	$[kWh / (m^2_{AN} *a)]$	8.50	8.50 ~ No Change
Life cycle assessment			
Primary energy non renewable (PENRT)	$[kWh / (m^2_{NGF}*a)]$	11.05	4.06 63.26%
Global warming potential (GWP)	[kg CO$_2$-Äqv / $(m^2_{NGF}*a)]$	4.18	1.36 67.46%
Life cycle costs			

Figure 45 – Improvements through Material Changes

CAALA offers different options for life cycle stage selection for the assessment. This assessment took Module A1-A3 Production, B4 Replacement, C3-C4 End-of-life and D Benefits beyond the system boundaries into account.

The two following graphics show the percentage distribution of total environmental impacts of the analyzed by building layer for both projects. As the environmental impacts of the assessments and visualization of the data are different, it is quite complicated to make a realistic comparison of the values of different tools.

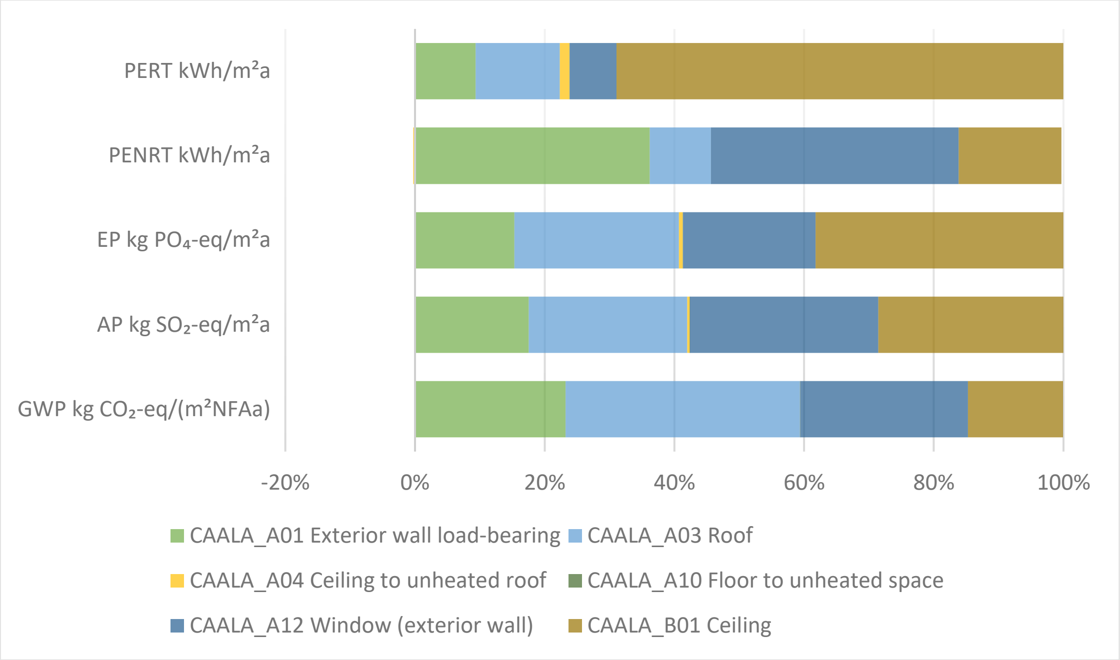


Figure 46 – Project A - Comparison of Environmental Impacts by building layer

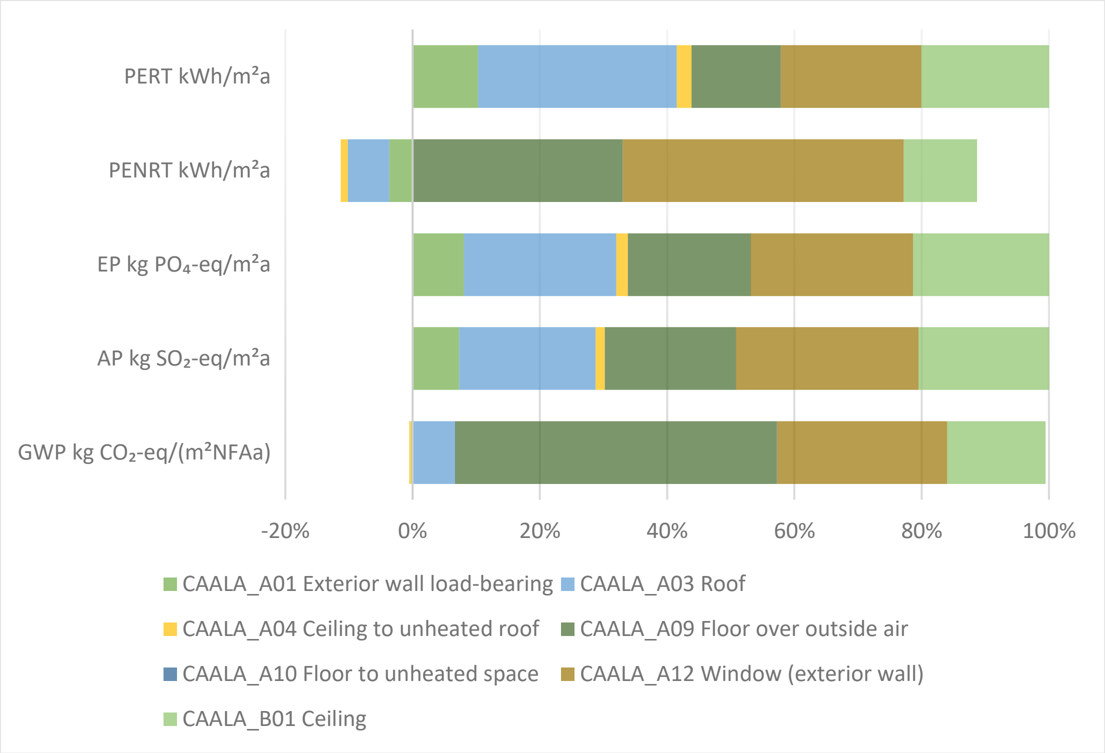


Figure 47 – Project B - Comparison of Environmental Impacts by building layer

5.2. Discussion

This chapter provides a discussion based on the results of two case studies. Moreover, the challenges during the analysis and possible solution proposals to the subjects will be explained here.

5.2.1. Further use cases for BIM Adoption for prefabricated constructions

BIM may not be made explicitly for sustainability, but as a building database, it creates an excellent possibility to reach sustainable projects. Theoretically, BIM provides the essential building data for the life cycle assessments. Still, the efficiency and reliability of BIM-based LCA for prefabricated construction depend on multiple stakeholders during different project stages.

The case studies of building projects demonstrate the applicability of the tools for prefabricated construction models. According to the BIM use case catalog of KIT, the tested BIM models are mainly used for model-based planning, project development, and check purposes. This work focuses on sustainability and its extension on the AEC industry. Therefore, it is essential to list the following use cases for future developments regarding BIM, LCA, and sustainability purposes.

This study analyzes “model-based sustainability and energy management” use cases of KIT (2018) for prefabricated timber constructions, as follows:

- *Creation of early forecasts about energy consumption, energetic life cycle costs, or usage costs*
- *Demonstration of optimization possibilities on the design model in order to reduce the life cycle costs*
- *Carrying out a sustainability and energy efficiency analysis through real data analysis of the energy consumption*
- *Direct evaluation of the model according to, e.g., LEED criteria*
- *Reading out documents and data for certifications*
- *Simulative evaluation and economic optimization*
- *Carrying out various life cycle considerations*

- *Determining the life cycle costs through real data analysis*

However, there is a potential for further use of the analyzed BIM models for sustainability. The following sustainability use cases focus on the project's use and end-of-life stages. It is necessary to have an as-built model; furthermore, it is also possible with a digital twin.

- Model-based strategic property management
    - *Linking the FM model with higher-level asset management tools*
    - *Creation of "what-if" scenarios for strategic planning*
    - *Creation of forecasts for the development of the property's life cycle costs, TGA maintenance costs, service provider costs, etc.*
    - *Networking of sensors, systems, mobile devices, etc. with the model to create a large, evaluable database*
    - *Use of the database for (BIG data) analyzes and forecasting and evaluation of information about temperature, humidity, energy consumption, usage behavior, utilization, failure, lost times, etc. for a state*
- Model-based warranty, maintenance, and repair management
    - *Virtual development of a maintenance and repair concept*
    - *Automated coordination and management of maintenance cycles*
    - *Automated creation of push notifications when maintenance is required*
    - *Model-based coordination of maintenance and repair measures*
    - *Preparation of documentation of maintenance and repair measures*
    - *Provision and dissemination of manufacturer documents via the web and cloud*
    - *Preparation of process documentation for systems and equipment.*
    - *Identification and communication of quality problems.*
    - *Virtual development of a concept for emergency repairs*
- Model-based building automation (intelligent building operation)
    - *Reading out object information for building automation*
    - *Use of model data, e.g., software-controlled room use planning*
- Model-based and creation of the facility management model
    - *Integrating the as-built model into a CAFM system*
    - *Integrating the FM model data into higher-level models (e.g., for traffic planning)*
    - *Updating and managing the building stock model Creating the FM documentation*

- *Creating links in the model with equipment and inventory lists*
- *Creating links in the model with maintenance and care instructions*
- *Dynamic derivation of operating and assembly instructions*
- *Dynamic derivation of CAFM documents* (KIT, 2018).

5.2.2. Improvements for the SWOT Analysis Results

In Chapter 5.1.2, the existent BIM use cases are shown and later summarized under the related sections for the timber construction method. In the following, the obstacles and possible improvement proposals will be explained.

The parameters defined in BIM components provided a basis for the LCA studies of the present thesis. As earlier mentioned, LCC is not taken into account in this study. However, involving more parameters in the model elements is necessary to review the project's sustainability in a circular way. Different phases and departments require a variety of information. For example, Production – manufacturing integration needs, besides usual measurement parameters, at least an article number to be able to link the data from the BIM component. Also, for an automated LCC, it is required to involve the cost and environmental performance of the selected materials. Therefore, parallel to conventional construction, it is necessary to define from the beginning where to apply the cost and environmental performance of the materials and in which phase this information is needed (Kovacic et al., 2018).

According to Aberger (2017), timber construction professionals already use BIM and they plan to continue with the focus of collision control, 3d visualization, and quantity take-off in the future. As mentioned in chapter 4.2.2, here we see the same approach. BIM models are used mainly for planning purposes and clash detection. Further goals such as sustainability or cost management are currently in the planning phase.

The creation of a BIM library is certainly essential for increasing efficiency and reducing errors in design and construction phases for a prefabricated construction company. However, the companies that work with different stakeholders should keep in mind to adopt the Open BIM solutions to empower the strength of their BIM models and to reduce extra separate planning and needed experts.

Using BIM tools for automated collision controls gives a reliable and fast solution for complex projects' data-driven quality checks. On the other hand, the quality tools for these checks require an additional budget. For projects similar to the case studies, simple solutions which are configured in the BIM model itself as special-formatted views and lists could answer the needs of small and middle-sized simple projects.

According to Negendahl (2015), if the designer and expert teams work collaboratively, the highest sustainability performance could be reached. Additionally, this approach combined with integrated dynamic models brings the most flexibility during the project process (Negendahl, 2015). Although this was not the case in this project, creating a collaborative BIM model for different departments to generate and evaluate the model data for economic or sustainability reasons is possible. Therefore, it is required to establish common ground by regulating and defining information management between the parties. Participants will not benefit from collaboration properly without a mutual understanding of standards and workflows (Guinée, 2012; Kloepffer, 2008).

Aberger (2017) mentions that BIM adoption of prefabricated timber construction companies is higher than the conventional ones. Furthermore, these companies hold great potential with their data of various construction phases such as, design of prefabricated elements or integration of manufacturing. As in the results chapter already mentioned, cooperation between industry and researchers should be empowered immediately so that this potential could be a chance for BIM and Prefabrication research.

Concerning BIM adoption, various programs and the necessity of experts could also lead to resistance to change in already working processes. However, no tool provides the need of every department. Therefore, as in the VDC concept described, focusing on the methods and potentials of BIM Model are necessary. Interoperability plays a significant role here to realize these potentials and for interoperability, defining interfaces and file formats in the earlier phases is essential. As Santos et al. (2019) noted, to achieve real-time collaboration based on a BIM Coordination Model between other departments or different software, using Open BIM Standards is required.

Data-driven quality checks with automated collision controls give a perfect solution for more complex projects. As in the case of this thesis, two-story residential and three-story school buildings, these solutions should be reviewed for added value to the project regarding needed cost and time.

Similarly, further BIM use case implementations often result with additional costs and IT requirements. Most of the prefabricated timber companies are small to middle-sized companies, which found these costs of BIM and its further processes critical (Aberger, 2017). Therefore, as long as it is optional and not supported through standards or legal restrictions, BIM will probably stay as "nice-to-have". To increase the BIM adoption and support digitalization in AEC, having support from legal authorities is crucial.

All-in providers in the industry tend to lead into something that Patlakas et al. (2015) mention as a *"closed silo"* mentality. On the other hand, these companies could provide massive information from different phases from manufacturing to construction for future sustainability research. Besides providing better design quality, the amount of data that prefabrication companies hold creates an excellent potential for circular economy research.

5.2.3. Challenges of BIM-based LCA for prefabricated construction

LCA assessments of both prefabricated buildings show that their BIM models – even though they have different LODs and are not designed for LCA assessments- have a high-level information. Although it is a step forward, it is also necessary to examine the future possibilities.

The responses of tools to the different LODs were not easy to compare. CAALA demands the level of detail of the model and gives two options preliminary and blueprint design. In the meantime, LOD selection or definition for Tally is not available during the assessment process because Tally automatically updates all the relevant information of the building element, such as building layers and materials.

As in the literature review mentioned, Lu et al. (2021) show the workflow of the LCA and LCC integration methodology to BIM (see Figure 34). According to that, this study used approaches 2 and 3 of BIM-based LCA studies.

Approach 2 is reviewed in this study with CAALA. This approach uses the BIM model as the data collection platform. Data exchange is managed through gbXML export. The advantage of this approach is that LCA studies could be performed independently from the BIM platform so that different BIM solutions could be used. However, the case studies have shown that this approach needs continuously a new export from the BIM model and upload into the LCA platform in the case of quantity changes or adjustments.

Assesments with Tally used the approach 3. The advantage of this approach is that everything remains in the BIM environment. Therefore, the assessments are faster and usability for non-experts higher. This third approach requires no external data exchange between the BIM and LCA platforms. The case studies of both projects show that this approach brings a dynamic access to the process, if a component or design variant should be checked. As the results chapter mentioned, the tested tool gives a limited possibility to edit parameters and material compositions. For early design phases, this could be enough. However, the editing options were not entirely enough for complicated and detailed component constructions like prefabricated timber.

Although the usability of Approach 3 (e.g., Tally) for non-experts is higher, it is limited for interoperability between BIM tools. On the contrary, the cloud service variations (e.g., CAALA) are getting more common on the market and offer a wide variety of interface possibilities. As Amoah (2019) mentioned, cloud services will play a significant role in BIM interoperability's future. In the case of LCA studies, the same approach is also observed.

IFC and gbXML are two open standards that are mainly used for BIM-based LCA studies. In this study, gbXML schema is tested. The literature mentioned that there were problems with the automatic recognition of the rooms and thermal boundaries while using open BIM standards. Bastos Porsani et al. (2021) notes that when the file was bigger and had more data, more problems were encountered by model creation with gbXML. For both projects, there were geometric issues during the export. Project A shows a floor area deviation of 13% and Project B 70%. To reduce the deviations, extra steps such as corrections in the model as well as editing in the gbXML file itself were necessary. However, they could not be entirely solved. Moreover, these steps create an added load and difficulty to the assessment process.

It was also found out that the gbXML export of the project differed according to the different Revit versions. Export from Revit 2022 provided more similarity to the BIM model.

As in the results already mentioned, the thermal envelope recognition needed extra corrections, such as dividing the floor element and creating new family types. In addition, some elements were not recognized, others were shown under the wrong categories. The various reasons for that in the results are already explained. In the meantime, these issues imply that assessing with open BIM standards – in this case with gbXML – requires extra controls for prefabricated buildings. In consequence, if these errors are not detected and corrected, as Elagiry et al. (2020) also observed in their review, they will be transferred to the assessments and endanger the reliability of the assessments.

Another problem was that if the room height was set on the ceiling level, gbXML model did not include the roof structure and false ceiling and, therefore, was not recognized in CAALA. Because gbXML recognizes the directly contacted model element but not the further ones. As a solution, the room height for top floors adjusted as roof level instead of ceiling level. gbXML exported file by spaces only recognizes the objects touched by the room surfaces. Therefore, if the top floor ceiling is not included in the roof element and is designed separately, either the room height or roof element structure should be adjusted. This issues proves that the prefabricated elements of the case studies were defined and modeled differently from a standard conventional system. If the further use of sustainability tools is decided, defining the BIM model components new is inevitable according to the limitations and requirements of the tools for the assessments. However, potential BIM model users from other disciplines, such as modeling, manufacturing, and procurement, should review the change and consolidation processes regarding which option is the most suitable.

Although the plug-in working directly in a BIM platform has significant usability advantages, testing the workflows with open BIM solutions, such as gbXML or IFC, could provide a better basis to help compare and standardize the LCA parameters and processes.

Two tested tools show that making a successful comparison without the same standards is hard. Two different tools showed that it was not possible entirely to use the same materials without a common database. As Schultz et al. (2017)

noted, this is especially necessary for comparability of the assessments. Also, adding more databases with different LOD information would simplify and fasten the process of BIM-based LCA (Cavalliere et al., 2019; Dalla Mora et al., 2020; Schultz et al., 2017). According to Santos (Santos et al., 2018), the EPD and TRACI method are not similar, so the comparability of the methods is also in question. Therefore, some common database standards are required, for example, selection of primary life cycle stages, impact categories. As seen in case studies, two tools result in different units and have a varied distribution of the environmental impacts. For a realistic comparison, having the same impact units and distribution is equally important to examine the results quickly.

As Hollberg et al. (2020) also stressed, material selection and matching in LCA every tool works with a separate database. Current processes do not include an automatic match between materials of the BIM model with the LCA Database. An additional effort with matching the materials was here also necessary. Hollberg et al. (2020) suggested the material matching recognizition could be solved with a predefined components material list. Another suggestion by Kotula(2020) is using AI and machine learning for matching materials in future projects. Both of the options could offer a solution for prefabricated construction.

Similar standards should be defined in model parameters. CAALA assessment also shows that a detailed LCA assessment needs some additional model parameters. Prefabricated element families should differ according to their thermal envelope role by the parameter exterior/interior. In the meantime, keeping the modeling standards of prefabrication is also necessary. It differs from conventional construction because the components are already defined, designed, and modeled with high-level details. Still, defining model use cases is required so that model elements can be designed according to the common standards and parameters. For example, not including the screws of the components because of keeping the model lean or designing and modeling facade element families separate from walls because of transparency in the bill of quantities.

The analysis of the tools presents that there are no standards again for included assessment phases. While CAALA analyzes according to Module A1-A3, B4, C3-C4, and D, Tally provides the assessment Module A1-A3, A4, B2-B5, C2-C4, and D. The literature review mentioned that construction, end-of-life, and beyond-life phases differ for the prefabricated constructions contrast to the conventional ones. First of all, the challenge for these stages is that the information comes from different stakeholders and requires difficult communication between other departments, e.g., design, construction, and facility management. Second of all, there are technical restrictions. The tested tools present diverse focuses on their assessment phases. Tally and CAALA have varied assessment categories for use and end-of-life phases. Furthermore, CAALA does not include the construction phase in the assessment. The tools should provide a standard with Module A1-A3, A4, B4, C3-C4, and D phases for a holistic approach and further circular economy studies.

The tested tools provided no possibility to include SLCA measures. SLCA is hard to measure, but still, it should be step by step included in the LCA for a holistic approach (Guinée, 2012; Kloepffer, 2008). However, the tested tools presents no option to add or track measures other than already defined in the tool.

5.2.4. Improvements for the tested workflows

After all the given outputs from studies and literature review, the following optimization measures in the workflow of the tools are suggested and shown in Figure 48.

The suggested workflow differs from the tested ones with pre-defined standards and modeling parameters. To define them requires analyzing and determining the use cases of the BIM model **(1)**. The new workflow demands that the model standard and parameters for LCA-ready BIM model should be defined from the beginning according to use cases of the model **(2)**, and these defined standards and parameters should be specified as a project template for the future projects **(3)**. As a result, the quality of the model elements will be increased, and errors will be reduced. For the absolute certainty of the geometry, more tests with different open BIM scheme are required. Tests with gbXML case study models have shown that 100% certainty of geometry is still in question because identification of the model elements and the room-based spaces for Revit are still an issue. Therefore, before the assessment, an extra model check within BIM is required to recognize the issues like deviations in floor areas **(4)**. Using different databases is suggested as a solution to the lack of materials and diverse LODs **(5)**. Here the approach of Hollberg et al.(2020) and Cavalliere et al. (2019) are combined. Having access to various databases gives the possibility to work with different LODs. Also, by creating an upload function of EPDs, the users can create their special construction element layers and save them as pre-defined lists to use later. Both measures help to reduce the lack of material information for assessments and better user experience for repetitive construction elements.

This approach offers a solution to track SLCA impacts. The social impact also can be included to the project databases to track information during the project's life cycle. Information on SLCA impacts is still lacking and SLCAs have a significant problems with data inconsistency. However, examples like *Social Hotspots Database, SocialBIM Cloud* consist of databases with social impact information by regions. Eventually these information could be included in the assessments via predefined templates for solution of the mentioned problems. (Das et al., 2015; *SHSD*, 2019)

Real-time data-driven analyses or improvements (e.g., operation and use phases) are beyond this project's scope. Still, these phases should also be included for realistic assessments. However, as the literature review already mentioned, there is a problem with collecting reliable and enough information from these phases. Because most of the projects in their use phases are not observed. For the case studies, there were similarly no data available from the use/operation phase regarding LCA assessments of the prefabricated constructions in the projects' BIM models. These missing LCA phases also creates a gap for circular economy studies.

Digital twin concepts and their broader use in facility management could be a solution to cover that gap. This issue is not only important in the new construction of projects. The digital twin of a building is essential in the refurbishment processes of the whole cycle process of the building. In these processes, the environmental, economic, and social impact of the current materials can be evaluated, and how much of the materials will be open for reuse or recycling in the event of the destruction of the structure can be quickly revealed with a digital concept that includes digital production and the construction phase. Nevertheless, observing and collecting the relevant data creates added value currently for more complex and bigger projects.

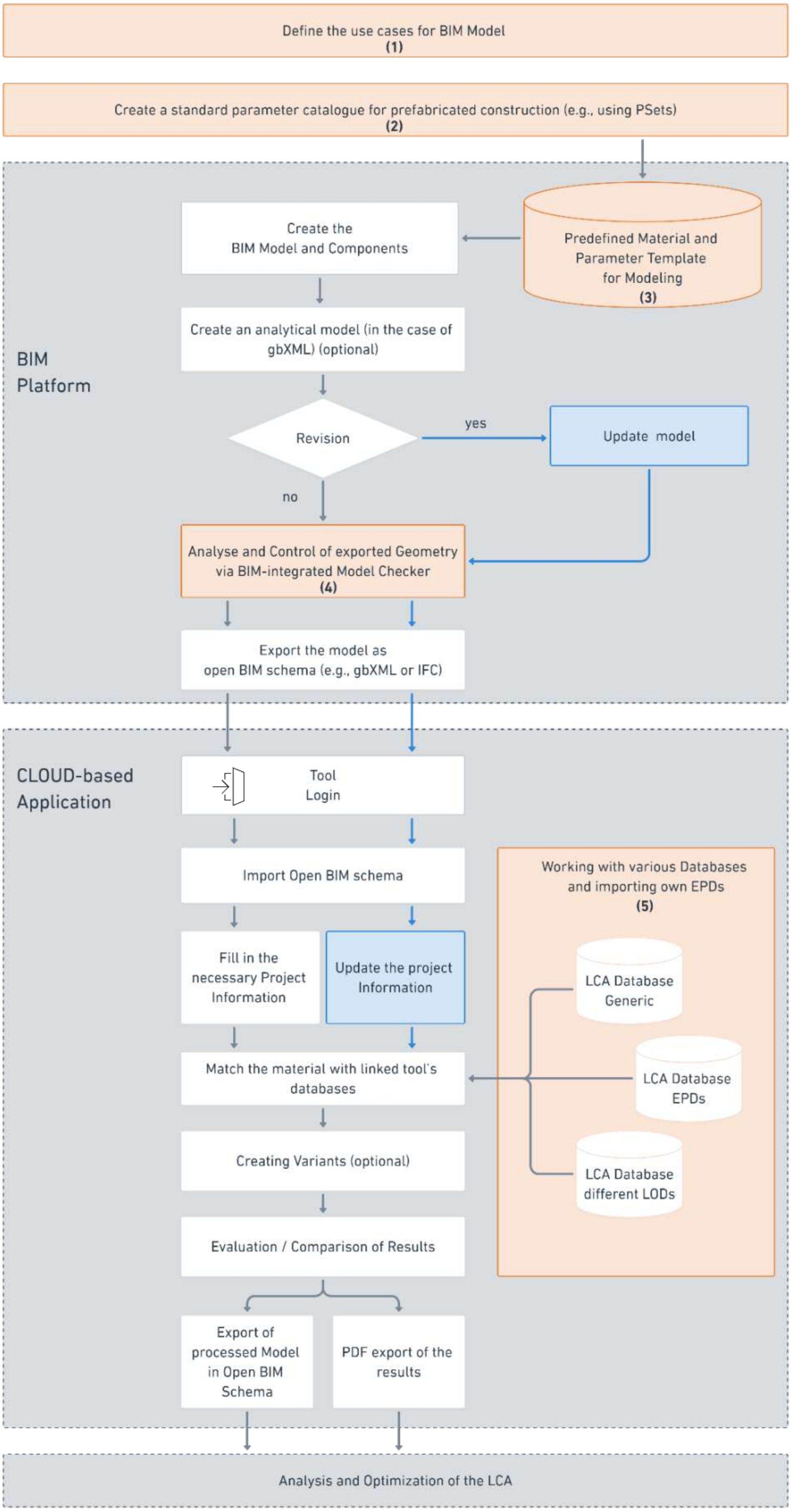


Figure 48 – Optimization proposal of the workflow

6. Conclusion and Future Work

6.1. Conclusion

The present work discussed the differences between prefabricated and conventional construction projects regarding the use of BIM models and BIM-integrated LCA analysis through case study projects. Based on two BIM building models, BIM use for prefabricated timber constructions and their LCA calculations in BIM were examined. Here the aim is to support different design decisions, where the design alternatives can be evaluated quickly.

The main conclusions are summarized as follows:

- BIM is not made explicitly for sustainability or prefabrication, but it creates an excellent possibility as a building database. Theoretically, BIM provides the essential building data for the life cycle assessments. Still, the efficiency and reliability of BIM-based LCA for prefabricated construction depends on multiple stakeholders throughout the project's phases.
- The successful use of BIM-based LCA tools depends on factors such as BIM model parameters, correct designed model families, availability of various databases, and EPD import.
- Prefabricated Construction differs from conventional construction on many levels concerning BIM. Prefabrication needs a more sensitive and detailed planning phase. Therefore, an accurate quantity take-off can be estimated for standard elements at the early design phase. It is advantageous for LCA studies because the BIM model is mainly designed with higher LOD. The literature review suggests that LCAs result in a more realistic comparison to earlier design processes. However, the comparison of the same prefabricated construction projects with different LOD levels should be researched.
- Similar to the conventional construction methods, prefabricated construction needs to define the naming of files, components, or even the

layers in the case of further collaboration with different departments for efficiency and quality of the process. Also, definitions of the "content" are important. As Kovacic et al. (2014) describe, deciding what to include in the model is essential, and this decision involves of views of different stakeholders. However, the primary approach should be keeping data records lean. *"So you model as detailed as necessary - and not as possible (Eichler, 2014)."*

The second part of the analysis chapter shows that using BIM-based LCA tools for prefabricated constructions is possible. However, as in the methodology chapter mentioned, LCA is still a complex task, and these tools still have limitations. The study also found out the following conclusions about BIM-based LCA for prefabricated timber constructions:

- The case studies on real building projects demonstrated the applicability of the tools for the prefabricated construction model. According to the results, BIM-based LCA tools can only be effectively used for prefabricated timber construction projects, if the parameters and standards for assessment process are integrated in model element designs from the beginning.
- The literature notes that prefabricated construction differs from conventional construction, especially in Module A3, A4, C, and D phases, and these should be considered in LCA Studies. Assessment of these two phases was partly possible with both tested tools. Module D was included in both of the tools. However, Module C could be assessed only with Tally.
- The plug-ins that work directly in the BIM environment give the process an excellent advantage for usability reasons. This approach also allows the possibility to control and observe the different variants' environmental impacts quickly. However, as Lu et al. (Lu et al., 2021) also noted, this kind of tool requires more extended and more expensive developments.
- BIM-based LCA analysis may not be necessary for every project for a company that uses the same type of material and has a limited type of construction method because of time and cost-efficiency. However, for a company with various options in its portfolio, these solutions provide a quick analysis for foreseeing the environmental impacts.

- Building type was not relevant to the assessment for Tally. CAALA makes a difference between residential and non-residential projects. Similarly, the only CAALA asks and defines the different level of details of the model.
- Comparison of the tools shows that CAALA is currently not fully integrated into the Revit. The cloud platform uses as an exchange format gbXML. The advantage is that gbXML is an open BIM schema; therefore, it is not BIM software dependent. However, preliminary work and settings are necessary and can be complicated for beginners.
- gbXML export of the projects has shown many undefined parameters for the assessments. The difference to conventional construction methods is that most of the needed families are included in Revit system families, and their parameter definition and recognition works better. Prefabricated constructions require their own families. If these elements are planned to be used in BIM-based assessments, it is essential to define and add the related parameters from the beginning.
- Tally, the plug-in fully integrated into BIM Platform, shows better performance for usability. Giving limited material and software options may be more efficient for early design decisions, but it was not always enough for the prefabricated timber construction (e.g., material selection).
- The deviations between the BIM model and LCA Tools recognitions can be caused by various reasons, such as modeling decisions, model maturity, LOD level, different design phases, and using different open BIM Standards. The literature mentions that using simplified IFC models or different open BIM standards such as IFC or gbXML results in deviation in calculations (Forth, 2018). The tested projects were also varied between 13% and 21% of floor area in gbXML.
- As a solution, open BIM scheme are more suitable for professionals to intervene or compare different options when necessary. However, the deviations make the comparisons not realistic. Therefore, IFC and gbXML as exchange formats must be further studied for prefabrication needs to interoperate between computerized design and manufacture.
- The tool comparison has shown that in the process of BIM-based LCA for prefabricated constructions, it is essential to have the possibility to add new EPDs. The manufacturing and product development environment change

rapidly according to new technological developments, standards, and industry needs. Therefore, it is extremely difficult to include all the product information and keep them up-to-date.

- A realistic LCA requires adjustment of bill of quantities and materials for optimization. Additionally, auto-detection of BIM models does not give completely accurate results. (e.g., the deviation between model and gbXML)
- In LCA tools, the market and databases could be a restriction. For example, Tally focuses on the US market; therefore, material selection is designed according to that region. However, prefabricated constructions mostly needed different elements other than the conventional method. For international and broader availability in the construction industry, addable EPDs are a necessary feature.

6.2. Future Work

The AEC industry has already agreed that BIM is the future, even though there is still a lot to manage. For the development of this work, the following points are proposed to be researched.

- This thesis focused on prefabricated timber constructions. To get a comprehensive view of prefabricated construction, it is necessary to work on other prefabrication systems and analyze them. Moreover, it is necessary to create a test process with different BIM Platforms and Open BIM standards to compare the differences.
- As explained in the methodology chapter, some LCA phases were not included in the study during the assessment. Although it is important, there was a lack of available real-time data from operation phase. Moreover application of all the LCA phases, IoT solutions, and especially digital twins should be included to future work.
- The deviations between the formats and tools should be studied more. For a start, model element-based comparisons of various open BIM standards are required. For LCA studies, deviations could be solved with an adjustable material and bill of quantities. Although for realizing the whole digital assessment process of the manufacturing and supply chain, it should be researched if the gap between the open standards could be weighted or

corrected. Furthermore, the results should also be compared with the dedicated LCA software assessments.

- The expansion of the BIM integration to include further sustainability analysis should be also listed here as an outlook. As Lu et al. (Lu et al., 2021) show in their paper, there is currently a lack of studies focusing on sustainability score and BIM integration. The case studies show the need to add possibilities to track in tested tools for further sustainability studies.
- In both tools automatic material recognisition or matching from BIM model was lacking. Predefined material database in BIM Platform or AI could offer an automated solution to recognize the linked materials based on their structure composition. (Hollberg et al., 2020; Kotula, 2020)

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