CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Civil Engineering
Department of Architectural Engineering

BIM Data Structure in the Building Optimization:
Methodology for Model Development

Standardizace datové struktury BIM modelu:
Tvorba metodiky pro strukturu zadávacích požadavků pro optimalizaci návrhu budovy

DOCTORAL THESIS

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Declaration

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Title of the doctoral thesis: BIM Data Structure in the Building Optimization: Methodology for Model Development

I hereby declare that this doctoral thesis is my own work and effort written under the guidance of the tutors Doc. Ing. Vladimír Žďára, CSc. and Ing. Jan Růžička, Ph.D. All sources and other materials used have been quoted in the list of references.

The doctoral thesis was written in connection with research on the projects:

- TN01000056: BIMIP - Implementation within building's life-cycle;
- FV10685: Flexible hybrid timber-concrete construction system for energy efficient buildings;
- FW03010555: Digitalization and automation of production processes of energy-efficient prefabricated wooden buildings;
- TH02030797: Sustainable and resilient buildings;
- TJ02000086: Library of embodied environmental impacts of building compositions and systems and its application for use in Archicad and REVIT;
- LTT19022: Czech participation on IEA EBC Annex 72 project;
- SGS20/097/OHK1/2T/11: BIM for building optimization in early-design stage with SBToolCZ methodology;
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signature

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Abstrakt

Informační modelování (BIM) již tvoří nedílnou součást stavebního procesu v České republice i ve světě. Hlavní překážky bránící implementaci jsou postupně odstraňovány a tyto modely nacházejí využití ve stále více součástech stavebnictví. Dalším způsobem využití je environmentální analýza, která se postupně dostává z oblasti výzkumných projektů do běžné praxe.

Dizertační práce se zaměřuje na shrnutí problematiky aktuálních environmentálních souvislostí v celosvětovém kontextu stavebního odvětví, analyzuje využití informačních modelů pro tyto výpočty v různých částech životního cyklu a shrnuje potenciál pro optimalizaci návrhu stavby. V textu je proces návrhu stavby rozdělen na tři hlavní etapy: prvotní, pokročilý a detailní návrh stavby. Tyto etapy zhruba kopírují úroveň studie, dokumentace pro stavební povolení (DSP) a dokumentace pro provedení stavby / výrobní dokumentace (DPS/VD). Řešeny jsou také fáze provozní, demoliční a potenciál recyklace.

Stěžejní bod práce tvoří metodický pokyn pro tvorbu informačních modelů pro každou se zmíněných etap, včetně specifikace vhodných environmentálních dat a možností optimalizace návrhu stavby v této etapě.

Teoretickou část doplňuje pro všechny definované fáze návrhu řada českých i zahraničních případových studií z výzkumné i komerční sféry.

Zbytek práce je věnován shrnutím diskuzí nad výsledky případových studií, doporučením do praxe a subjektivnímu výhledu budoucího vývoje v této oblasti.

Klíčová slova: Building information modeling; BIM; informační model; Life-Cycle Assessment; LCA; automatizace, standardizace, metodika

Abstract

Building Information Modelling (BIM) is already an integral part of the construction process in the Czech Republic and worldwide. The main barriers to implementation are gradually being removed, and these models are being used in more and more parts of the construction industry. Another way of use is environmental analysis, which is gradually moving from the field of research projects to everyday practice.

This dissertation aims to summarize the current environmental issues in the global context of the construction industry, analyze the use of information models for these calculations in different parts of the life cycle, and summarize the potential for optimizing building design. The text divides the construction design process into three main stages: initial, advanced, and detailed construction design. These stages replicate the levels of study, construction permit documentation, and construction shop drawing / manufacturing documentation (SD/MD). The operational, demolition and recycling potential phases are also addressed.

The focal point of the thesis is the methodological guidance for developing information models for each of these stages, including the specification of appropriate environmental data and options for optimizing the design of the building at this stage.

Several Czech and foreign case studies from the research and commercial sphere complemented the theoretical part for all defined design phases.

The remainder of the thesis is devoted to a summary of discussions on the results of the case studies, practice recommendations, and a subjective outlook on future developments in this area.

Keywords: Building information modeling; BIM;; Life-Cycle Assessment; LCA; automation, standards, methodology

Table of Contents

List of Figures

Lists of Abbreviations

1	AEC	Architecture, Engineering, Construction
2	AIM	Asset Information Model
3	AIR	Asset Information Requirements
4	BEP	BIM Execution Plan
5	BIM	Building Information Modelling
6	BoQ	Bill of Quantity
7	BREEAM	Building Research Establishment Environmental Assessment Method
8	DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
9	DT	Digital Twin
10	EIR	Exchange Information Requirements
11	EPD	Environmental Product Declaration
12	HVAC	Heating, Ventilation, Air-Conditioning, Cooling
13	IT	Information Technology
14	KPI	Key Performance Indicator
15	LCA	Life Cycle Assessment
16	LCC	Life Cycle Cost
17	LCI	Life Cycle Inventory
18	LEED	Leadership in Energy and Environmental Design
19	MEP	Mechanical, Electrical, Plumbing
20	OIR	Organizational Information Requirements
21	PIM	Project Information Model
22	PIR	Project Information Requirements
23	SBToolCZ	Sustainability Building Tool Czechia

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First, I thank colleagues from Czech Technical University in Prague, the Faculty of Civil Engineering, and the University Centre for Energy Efficient Buildings. Doc. Ing. Vladimír Žďára, CSc. respectively Ing. Jan Růžička, Ph.D. for official leading my work during doctoral studies. Doc. Ing. Antonín Lupíšek, Ph.D., Ing. Martin Volf, Ph.D. and prof. Petr Hájek, CSc. for many opportunities in various research projects I have been involved in. All of them helped me to find the right direction on the way.

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I also thank my grandfather, Ing. Vladimír Bělohubý for proofreading, valuable feedback, and all the other support.

Finally, I thank my dear wife, Lenka, who had patience with me along the long way, especially in the last months of finishing this work.

Foreword

The following thesis summarizes a seven-year journey of doctoral studies at the Department of Architectural Engineering, Faculty of Civil Engineering, Czech Technical University in Prague. During my studies, I worked as a BIM Consultant at cadconsulting, BIM Coordinator for IRIVET Software House in Dubai (UAE), BIM and LCA Consultant for SIEMENS, and finally as a BIM and LCA Researcher at the University Centre for Energy Efficient Buildings of the Czech Technical University. The work is focused on the practical application of BIM models to calculate the environmental performance of buildings.

Continuous reworking of student projects in AutoCAD never made sense to me in my undergraduate or graduate studies convinced me to look for BIM and dig deeper into it early as possible. Simple tasks, such as moving a window, might take hours. And only because each element is in many different places in traditional drawings. If we stick with the window example, we can find it in the floor plans, elevations, and sections. On top of that, we can see the same element in the Bill of Quantity (BoQ) and other related documents.

Traditional workflow is no longer efficient. Of course, BIM is only one of the answers to some problems in the design process. But it can be significantly helpful in particular tasks. The "single source of the truth" principle is the universal principle, valid for many parts of the IT world.

My work on the topic in the following text started with my Bachelor Thesis [1] in 2013. This work was focused on exploring possibilities of using BIM for building physics. In particular, energy and sun simulation, HVAC calculations, etc. After four years of studying architecture, when the most critical class of the semester was building design, this task was sow to me. And probably, the idea of digging deeper into the BIM topic came to my mind.

Another comprehensive work that adjusted my perspective was the Master Thesis [2]. According to the Czech legislation, the main goal was to investigate the potential of BIM in particular building phases; the process was divided into nine different phases (according to the Czech Chamber of Authorized Engineers and Technicians in Construction and the Czech Chamber of Architects "výkonové fáze") in which BIM could be used. Nowadays, the work might look a bit naïve. This was caused in 2015 when BIM was not adequately known today. And, of course, lack of expertise was also an important aspect.

When I started my Ph.D. studies, I still needed to decide which aspects of BIM I would like to explore more. So, the first two years were theoretical. I tried to understand the principles of building optimization, the theory of decision-making, the theory of systems, and advanced energy modeling. It was a good foundation for future work, even though it needed to be clarified how this knowledge could be helpful. Meanwhile, I was working on a part-time job as a BIM consultant. It helped me to gain a valuable understanding of the practical usage of BIM in architectural studios and MEP offices.

After the first two years, I took a year's break from the university. I went to Dubai (UAE) to gain experience in BIM from the massive projects (i.e., airport Midfield

Terminal Building in Abu Dhabi, Al Maktoum International Airport in Dubai, Royal Atlantis Hotel located on the artificial island Dubai Palm, etc.). From a professional perspective, it was an exciting experience for sure. But after a year in the Gulf Area, I did not want to participate in another "useless" building in the desert. Moreover, I saw that the "Dubai paradise" is often built by workers living in deplorable conditions. I wanted to return to Prague and continue my Ph.D. studies.

After the break, I understood BIM on a large scale, design processes, etc. The last piece of the puzzle was the environmental aspect of buildings. I started to work partly at the University Centre for Energy Efficient Buildings on a research project focused on sustainable buildings. My responsibility for such a project was always BIM. I realized that the combination of BIM and LCA is excellent for my work. After two years of research and several projects (described later in this text), I had a chance to go to the research internship in one of the most advanced BIM-LCA working groups in Europe: Chair of Sustainable Construction at ETH in Zurich. Most of this work was written there, and I am grateful for such an opportunity. On top of that, I also had a chance to stay one month in Graz, which was also a great experience.

I hope that this work helps to understand the complex topic of BIM-LCA topic and helps somebody with the transition to start developing better information models.

The following work focuses on a combination of various fields, such as Building Information Modelling (BIM), which and Life-Cycle Assessment (LCA). For the interpretation of both fields, knowledge of Data Analysis is also necessary. Therefore, a basic understanding of Civil, Environmental Engineering, and Computer Science is essential.

1 Introduction

1.1 Thesis Description

The whole thesis is divided into six main chapters. In the introduction part, the broad view of the area is described. Some vital global facts are presented along with possible outlooks for the future. The second chapter is focused on the current state of the art in the BIM-LCA field with various consequences. The third chapter discusses BIM data in multiple project phases and how it can be used in environmental assessment. The fourth chapter is entirely focused on case studies and verifies chapter three. Chapter five presents potential problems, recommendations to the private sector, and current gaps in the knowledge.

The last chapter summarizes all the thesis findings and describes the proposed topic's possible future outlook. The detailed schema of the work is shown in Figure 1.

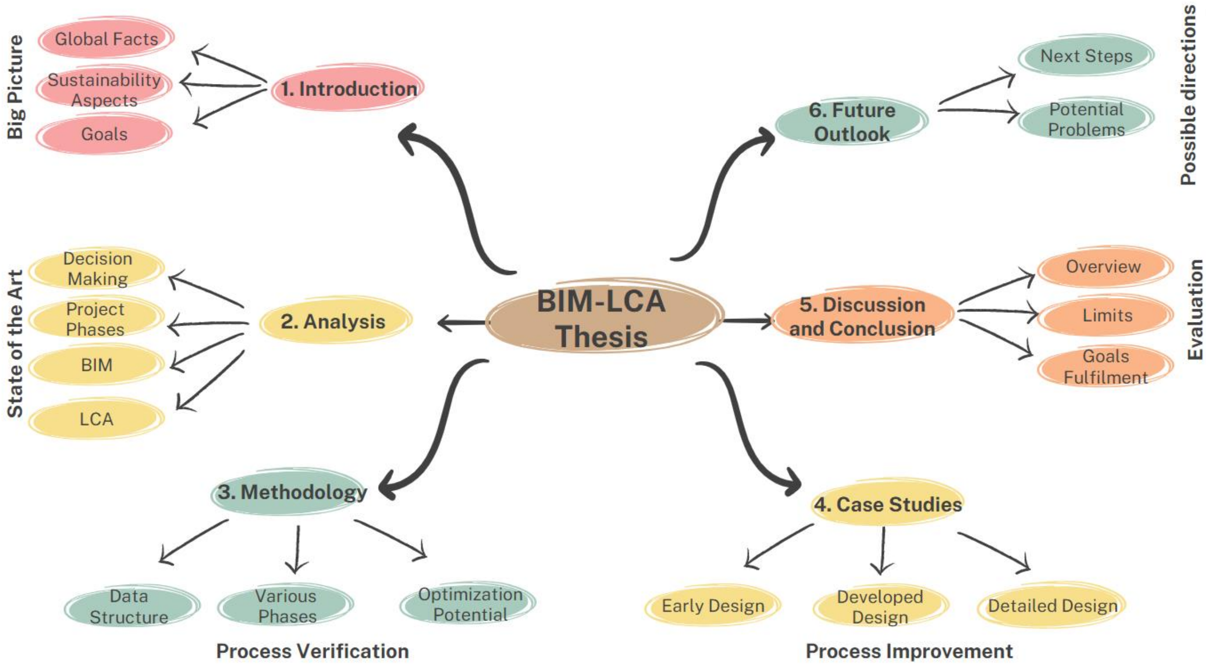

Figure 1 - Focus of the Thesis (author´s archive).

1.2 Global Facts

No era in human history was easy, and a broad and various literature body confirms that. But nowadays, we live in the most challenging time ever. Of course, this is neither political nor socioeconomic work, but presenting facts about the current world is still valuable.

According to numerous sources, such as recent IPCC reports [3], [4] or UN reports [5], [6], the Construction sector is one of the biggest producers of CO2 emissions with its contribution around the world with:

- 40% of the total global CO2 emissions and 11% of total annual global emissions;
- 50-60% raw material consumption;

- 50% water usage;
- 35% waste production.

Scientists have sounded the alarm in this regard for a long time. For example, a professor emeritus at the University of Manitoba (CAN), Václav Smil. This interdisciplinary scientist with a background in energy, environmental and population change, food production, history of technical innovation, risk assessment, and public policy, and author of more than 40 books, is exceptional in linking different disciplines [7]–[10].

In the context of the Czech Republic, for example, Bedřich Moldan, a professor at Charles University, is active in this respect. He draws attention to the environmental problems of today's world in his book Conquered Planet [11] (Podmaněná planeta in Czech).

Scientists and public figures are in the business of drawing attention to the world's current environmental problems. For example, Bill Gates and his book How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need [12] accurately describes the current state of the world and shows possible directions for future development.

By the nature of its production, concrete, or its bare component cement, has a significant negative impact. Therefore, if we want to reduce the impact of the proposal significantly, it is advisable to optimize the quantity of this material. This can be achieved by appropriately setting the building on the site, which minimizes excavation and the amount of concrete in the foundations. Reducing the amount of cement in buildings (especially in cities) can also be very helpful in the future by reducing the number of parking spaces underground. These are both financially and environmentally burdensome for projects. This solution would require a comprehensive review of the functioning of cities, the behavior of its users, the depreciation of individual traffic in the inner city, etc.) There is neither the social atmosphere nor the political will for these changes, so the rest of the paper does not deal with these aspects.

The Paris Agreement has been broadly discussed among professionals and in public news recently. An ambitious goal is limiting global warming to below 2, preferably 1.5 degrees Celsius, compared to pre-industrial levels. To achieve that, it is necessary to massively reduce the amount of carbon in the atmosphere and take a path to carbon neutrality ("annual carbon balance") by 2050. To fulfill that, the action plan Fit for 55 is not being discussed in the European Parliament and elsewhere. Except mentioned public commitments, the also private sector makes its commitments. E.g., Siemens: carbon neutrality by 2030[1]; Skanska: 50% emissions by 2030[2], neutrality by 2045; Volkswagen: carbon neutrality by 2050[3]. The direction is clear, and we as a society should try our best to achieve as much as we can. Possible reports in this regard are adverse. The tremendous

[1] https://new.siemens.com/global/en/company/sustainability/carbonneutral.html

[2] https://group.skanska.com/sustainability/net-zero-carbon-emissions-to-2045/

[3] https://www.volkswagenag.com/en/news/2021/04/way-to-zero--volkswagen-presents-roadmap-for-climate-neutral-mob.html

development of technologies such as renewable electricity shows the decreasing kWh price from these sources. It should be borne in mind that the graph is from before the war in Ukraine, so energy prices have had a turbulent time over the past year. However, the trend of dramatically lower electricity prices from solar and wind is clear. In this respect, the influence of buildings is also quite significant, as they can, for example, serve as carriers for PV panels. The trend is shown in Figure 2.

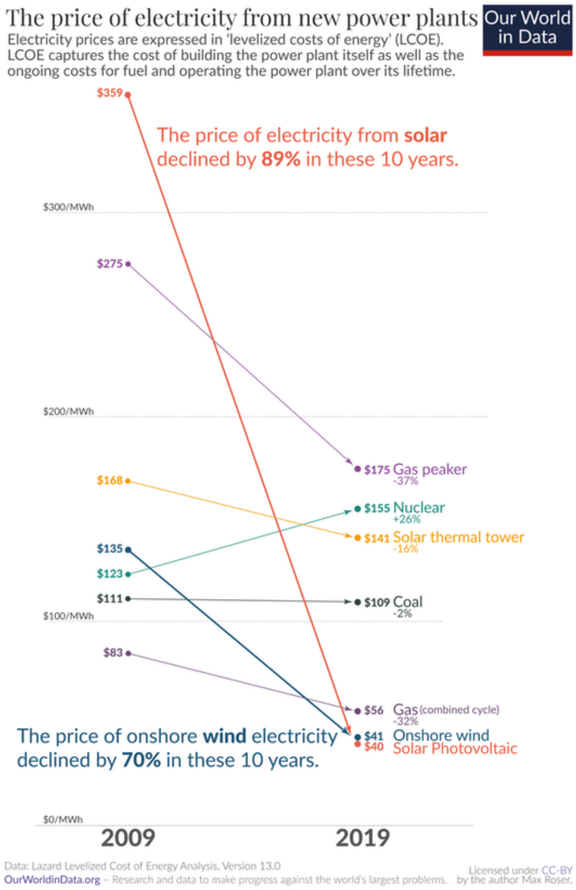

Figure 2 – The price of electricity from new power plants [13].

1.3 Digitalization and relation to BIM

The construction sector is the only sector of human activity in the last 70 years in which efficiency has grown slowly. Unlike the others, it has been stagnant or even slightly declining for a long time. This is due to the specific position of this sector, in which the complexity of construction is constantly increasing. Comparisons of industries are shown in Figure 3.

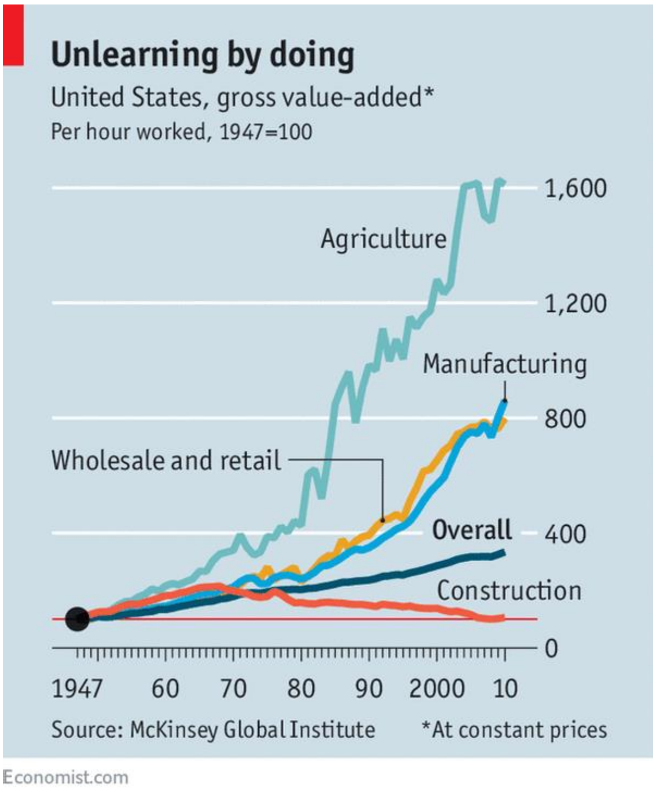

Figure 3 - The effectivity of specific sectors according to The Economist [14].

According to the consulting company McKinsey & Company and its Global Digitalization Index [15], the construction industry has long been one of the least digitalized sectors of human activity. Figure 4 shows the index from 2015; however, it is clear that according to even more recent McKinsey & Company studies conducted between 2016-2021 in different parts of the world: China [16], USA [17], Australia [18], Europe [19], the trend is changing only very slowly.

The digitization of the construction sector has received considerable attention in recent years, so the values in this index will likely increase in the coming period. One of the tools for the development of this trend is BIM. The National Centre for Construction 4.0 has been established in the Czech Republic for these activities. Digitization is one of the key parameters leading to the streamlining of the sector.

Figure 4 – Industry Digitalization Index [15].

Building information modeling (sometimes management) has been established as the leading platform for building design and leads the effort in the digitalization of the construction industry. There are many definitions; within the scope of this thesis, it is considered as a guiding principle that BIM is primarily a process, changing the relationships within the design, delivery, and management of buildings (not just buildings). BIM is embedded in the ISO 19650 [20] standard, which contains all the details regarding the relationships between the various stakeholders.

This standard also specifies the information BIM models should contain concerning the project phase, their intended use, and their flows. To use the data from these models for the environmental performance analysis of the buildings, the model requirements need to be inserted directly into these documents. A schematic of the information flows described in Figure Figure 5. The topic is described in more detail in chapter 2.3.

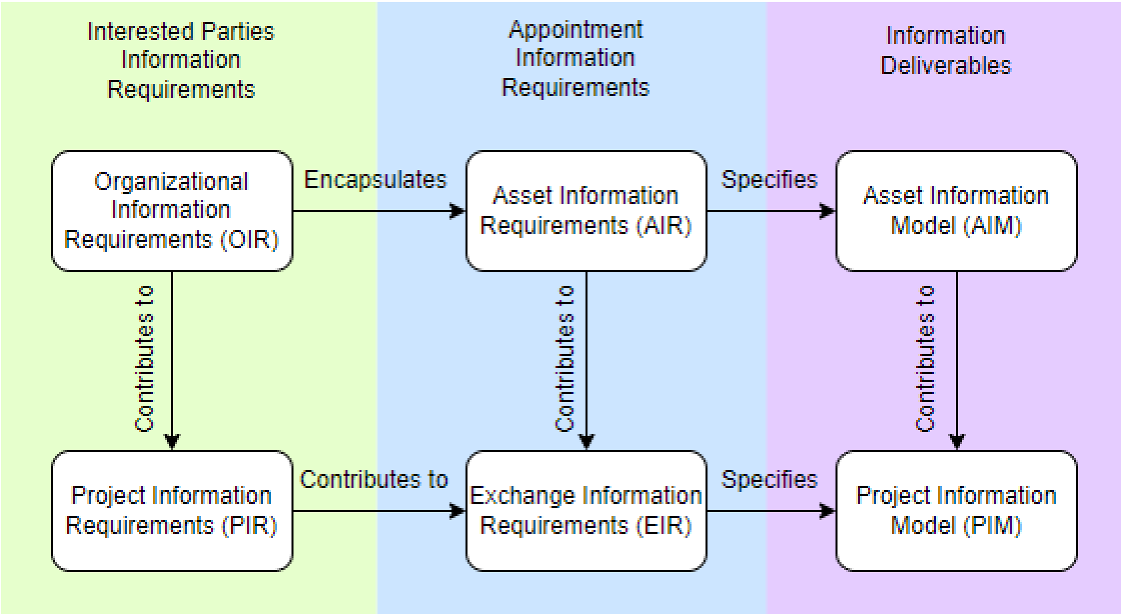

Figure 5 - Hierarchy of information requirements (author´ s archive; [20]).

1.4 Sustainability aspects

This proposed work deals with official terms and expressions. Therefore, it is valuable to define the most important ones. Sustainability is a broad topic that includes all the other following chapters. The definition is that the current generation can leave the planet Earth and its environment in the same (or better) condition than when it took over control. Sustainability consists of three pillars: environmental, economic, and social. Only when all of them are considered sustainability principles can they be fulfilled. The design quality can be expressed exactly by means of a so-called comprehensive building quality assessment, in which all these pillars are assessed.

Life Cycle Assessment (LCA)

Life Cycle Assessment is a widely accepted methodology for assessing materials, products, and buildings. It became the most used methodology for evaluation building and in the context of the Architecture, Engineering, and Construction (AEC) industry. This method is used to quantify the embodied and operational environmental impacts of a building over its entire life cycle. The LCA method is standardized [21] and, therefore, replicable. A simple schema of the process is shown in Figure 6. Detailed information and relation to BIM are described in 2.5.

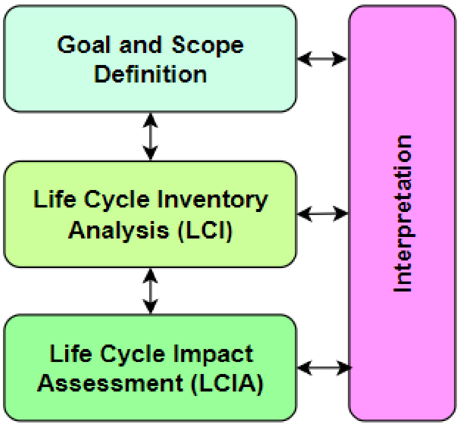

Figure 6 - LCA principle according to ISO 14044 [21].

Green Building certifications

Building projects are specific because they are unique, extremely long-term, complex, and highly resource-demanding. Along with nature, buildings are changing the environment more than anything (products, etc.). On top of that, some certification systems also add the perspective of the development's location. There are many different certification systems on the market. In the context of Central Europe, the following certification systems are the most relevant:

- UK: BREEAM (Building Research Establishment Environmental Assessment Method),
- USA: LEED (Leadership in Energy and Environmental Design),
- DE: DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen),
- CZ: SBToolCZ (Sustainable Building Tool Czech Republic).

Figure 7 shows the overview of the certification systems mainly used in the Czech Republic, including covered LCA phases (modules) and indicators. It is taken from the published paper Recommendations for Developing a BIM for LCA in Green Building Certifications [22].

Evaluated aspects	BREEAM	LEED	DGNB	SBToolCZ
Life cycle phases				
A1-A3 - Production phase	●	●	●	●
A4 - Transport to the construction site		●		
A5 - Construction process				
B1 - Use		●		
B2 - Maintenance		●	○	
B3 - Repair		●		
B4 - Replacement	●	●	○	○
B5 - Repair	●	●		
B6 - Operational energy use	●		●	●
B7 - Operational water use	●	●	●	
C1 - Deconstruction, demolition	●	●		
C2 - Transport	●	●		
C3 - Waste processing	●	●	●	
C4 - Disposal	●	●	●	
D - Reuse, recovery, recycling	●		●	
Mandatory elements to be included				
Load bearing structures (walls, columns, floors, roofs)	●	●	●	●
Foundations and basement walls	●	●	●	●
Windows and doors	○	●	●	●
Non-loading walls	●	●	●	●
Other non-load bearing structures (coatings, coverings, finishes, cladding)	●	●	●	●
Building installations (heating, cooling, air-conditioning, PV panels etc.)			●	
Indicators				
Global warming potential	●	●	●	●
Ozone depletion potential	●	●	●	○
Photochemical ozone creation potentials	●	●	●	○
Acidification	●	●	●	●
Eutrophication potential	●	●	●	○
Primary energy, non renewable			●	●
Primary energy total			●	
Abiotic depletion potential			●	
Non- hazardous waste			●	
Others				
Reference study period (years)	60	min. 60	50	50
Benchmarks for LCA result			●	●
Mandatory databases or tools for LCA	●		○	
● Relevant				
○ Partly relevant				

Figure 7 - Summary of the certification systems [22].

The current situation in Europe

In 2012, the European Union issued the Energy Performance of Buildings Directive (EPBD) [23], a framework that all EU Member States must implement in their national legislation. The objectives include:

- long-term renovation strategies,
- minimum energy performance requirements,
- net-zero-energy buildings,
- fulfill the EU Green Deal commitments.

The EPBD is currently being updated, and from the new version, in addition to the energy analysis (in the Czech Republic, the Energy Performance Certificate of the building - PENB), the calculation of the environmental impact of the planned (reconstructed building) is to be added. Due to the increasing penetration of BIM in the markets, there is a natural demand for the use of models in calculating the environmental impact of buildings.

1.5 Research questions

Research questions have been developed since the beginning of the Ph.D. study. The following research questions were proposed:

1) How can BIM help to reduce the carbon footprint the buildings?
2) How to use BIM for design optimization?
3) In which project phases is BIM beneficial for building design?
4) Which possible BIM-LCA workflows are available?
5) Is the current market ready for a massive expansion of BIM models and LCA?
6) Is the current market ready for the increased time commitment associated with the application of data standards?
7) Which construction companies (typologically) have already entered the BIM-LCA segment, and what is their motivation?

Working hypotheses

- A data standard that will benefit all participants in the construction process can be defined.
- There is a growing demand for creating a methodology describing how to work with data.

1.6 Goals of this Thesis

This thesis has a following list of goals:

1) To raise awareness in the professional community of the importance of environmental calculations of buildings and to demonstrate the possibilities of using building information models.
2) Summarise foreign methodologies, practices, and approaches.
3) Analysis of current practice and definition of the most common problems in information models.
4) Definition of project phases (so-called Performance Phases according to ČKAIT vs. internationally recognized LOD).
5) Propose a methodology for model development in various project phases
6) Demonstrate the possibilities through case studies.
7) Summarize opportunities for the automation of the process.
8) Suggest the possibility of integration into the Czech environment.

2 Theoretical Analysis

The following chapter summarizes recent findings in several areas: BIM, LCA, standards, project phases, and the situation in the Czech Republic. The chapter includes a range of sources, mostly research papers, books, insights from practice, personal interviews, and experiences. The components build on and complement each other, as shown in Figure 8. The theoretical part concludes with a SWOT analysis.

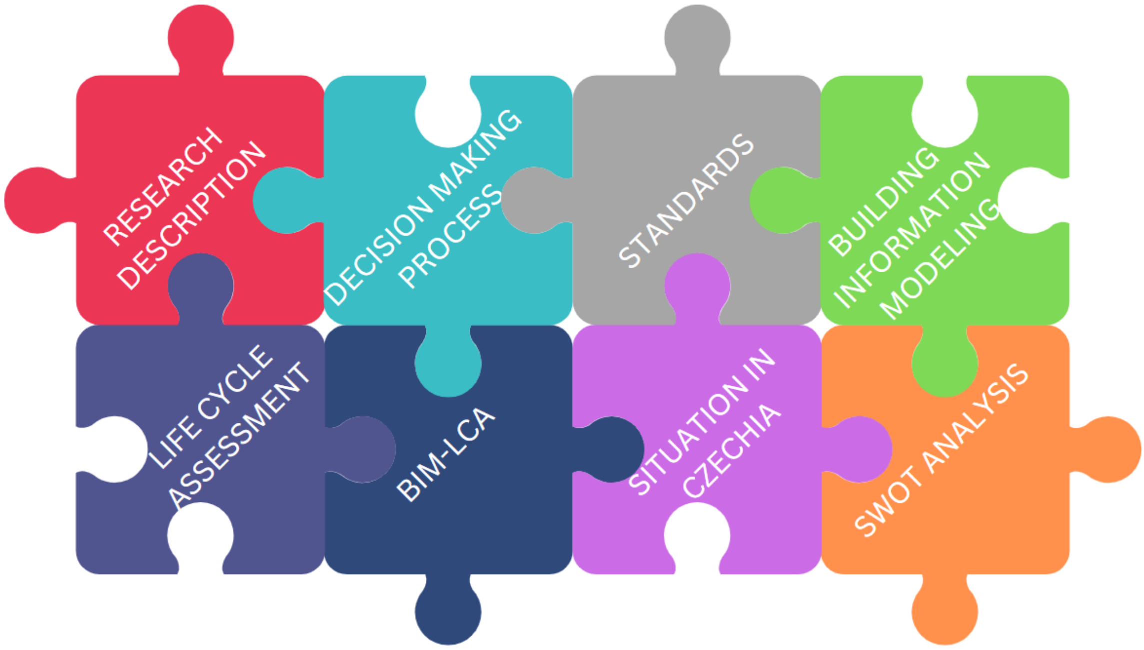

Figure 8 - Schema of the Theoretical part (author´ s archive).

2.1 Research Description

At the beginning of this research, it was necessary to find relevant literature and articles. For these purposes, literature was drawn from the literature that had already been used for the diploma or bachelor thesis, in which partial parts of the problem were addressed, and these sources were supplemented by other, especially other books and professional articles published on available sources, through the metasearch engine available at CTU - SUMMON. The results were mainly from the Science Direct website.

Keywords: BIM (building information modeling); Building orientation; Energy; Green Building; Small-scale construction; Sustainability; Visual Programming; Dynamo; LCA, Optimization; Power BI.

Around a hundred articles were found, with the number dropping to about 60, according to a cursory look at the abstracts. While going through them, additional articles were analyzed to a total of 56.

The first pattern among the papers and the most fruitful studies were those that recorded various research trends everywhere, for example, Yalcinkaya [24], who analyzed 975 articles containing BIM methodology using semantic methods. Similarly, applicable, less extensive research has been conducted by Wong [25] and Oti et al. [26]. These three studies were fundament providing an overview of the research topic. The last article examined was written by Evins [27]. Here, he analyses the optimization methods most used in y efficient buildings. It is not without interest that the most used algorithms are genetic algorithms. Another comprehensive work was published by Santos et al. [28], in which they summarized the finding of 291 papers.

The second trend was focused on topics that have been more depth, which is the use of visual programming and especially data handling, which will become increasingly necessary in the context of working with building models. This topic has been addressed, for example, by Khaja et al. [29], who embedded the data needed for Facility Management into the model. However, this method, coupled with the aforementioned genetic algorithms, is also used by Asl et al. [30], which here presents a multicriteria optimization of window size and glazing type, where, on the one hand, the requirements are the daylight factor and on the other hand the lowest possible heating demand. This optimization algorithm is undoubtedly worthy of closer analysis.

The third investigated area was the environmental calculations and how BIM can benefit this process. Initial research on the topic was conducted from the proceedings of Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Design [31]. This book contains the abstracts of nearly 400 papers from the IALCCE2018 international conference. Sections MS5: Early BIM for life-cycle performance; MS8: IEA EBC Annex 72: Assessing life-cycle related environmental impacts caused by buildings; MS19: Circular economy to improve the sustainability of infrastructure; SS18: The impact of BIM and web technologies in the life cycle of our built environment; and GS8: Life-cycle assessment provided a several of suggestions for papers for further study.

Another valuable resource was the book Embodied Carbon in Buildings: Measurement, Management, and Mitigation [32]. This contains 22 articles related to the topic, and in particular, the issue of uncertainty is discussed in great detail. This area of literature points included an overview of the top-down or bottom-up approach [33], an overview of the workflows [34], a systematic literature review that compares results [35], and data analysis of the different design phases [36]–[38]. The remaining literature body was also helpful and served for a better overall understanding of the problem. This research provided valuable information regarding the further direction of the thesis and helped to define the following areas of interest:

- Life Cycle Assessment,
- Visual programming,
- Generative design,
- Dynamo,
- Data Visualization,
- Power BI.

2.2 Decision-making process and potential for BIM

This chapter was added according to the discussion at Doctoral State Exam. It helped to define the following work on the topic.

First of all, it is necessary to clarify several terms that are often misused in practice. This is the inequality of the terms Data, Information, Knowledge, and Wisdom, which also appear in a pyramid. In particular, data and information often need clarification, but there is a significant difference between them. Only when data (or signals) are organized are they become information. These can then be translated into decisions and experiences through knowledge and wisdom.

It needs to be made clear when this hierarchy was first used. According to Wiki, it is the first half of the 20th century. The concept was then popularised in the 1980s by Milan Zelený [39], an economist from Czechoslovakia who worked at universities in the USA. Although a graphical version of the pyramid was not yet used, the expressions "__know-nothing__, __know-what__, __know-how__, and __know-why__" were very close to the later graphical form.

In the case of BIM, this hierarchy can be expressed by an n-dimensional model of the building that is created continuously as the project progresses (data), which is enriched with several parameters (information), e.g., quantities, reports, etc. Based on which (knowledge) management decisions can be made based on the analysis. All this is intended to reduce the environmental impact of buildings on the living environment.

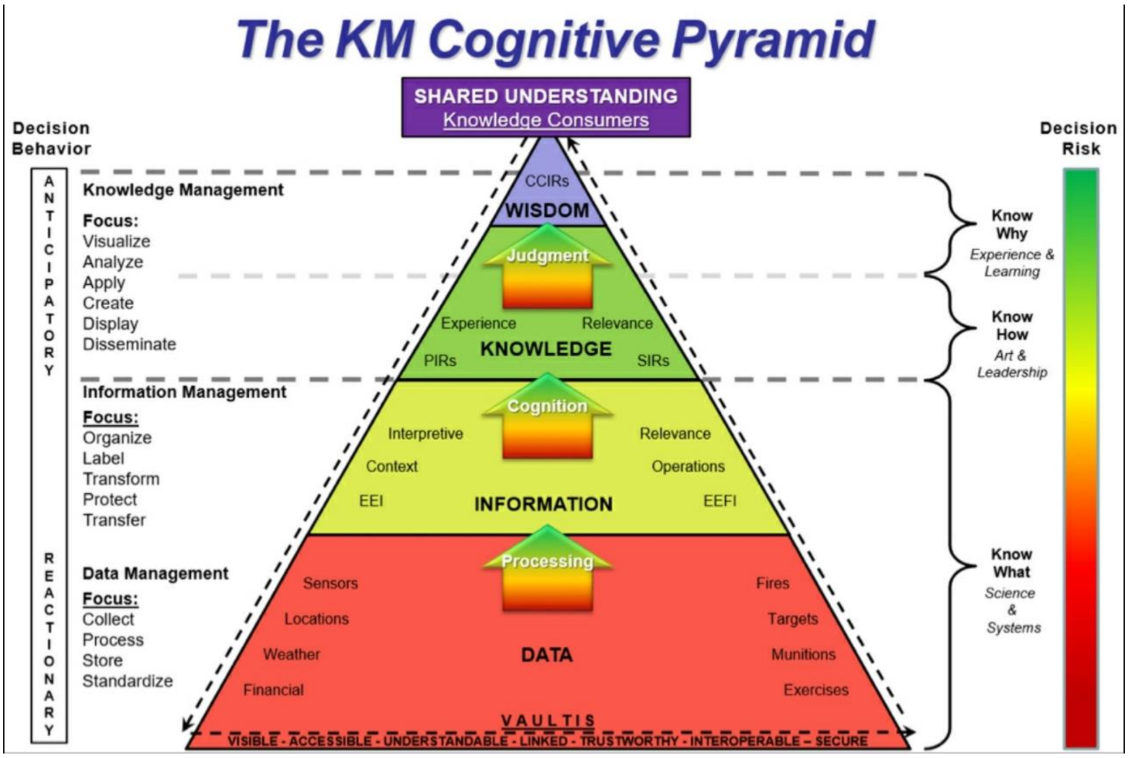

Figure 9 - Example of DIKW Pyramid [40].

A fundamental argument for using BIM is the ability to analyze models. There are many possibilities of use; it depends only on the technical maturity of the application. First, it is necessary to define whether the model contains all the required information or needs to be supplemented with parameters. These can carry several data types (generic, e.g., boolean, string, number, integer, or building specific, e.g., velocity, current, and many others).

This thesis included an analysis of the effectiveness of the floor area design. The result was performed over an information model in Autodesk Revit software at the LOD 300 (Building Permit) level of development. From the model, the total Gross Floor Area (including vertical structures) was obtained, from which the floor areas of the vertical structures were subsequently subtracted, resulting in the Net Floor Space. A parameter was then added to the model dividing all rooms into different groups to determine the project's efficiency in terms of space utilization. The project was, therefore, further divided into Rentable Area, Usable Space, and Primary Usable Space. Subsequently, it was possible to compare the achieved values with the defined Key Performance Indicators (KPIs). The visualization was done in Microsoft Power BI software, and a Dynamo script was created to export the data from the model. This semi-automates the whole process, and after subsequent updating of the model, it is possible to update the analysis in (literally) 5 clicks.

This example is shown in Figure 10 and serves as an example of how model analysis can aid in decision-making.

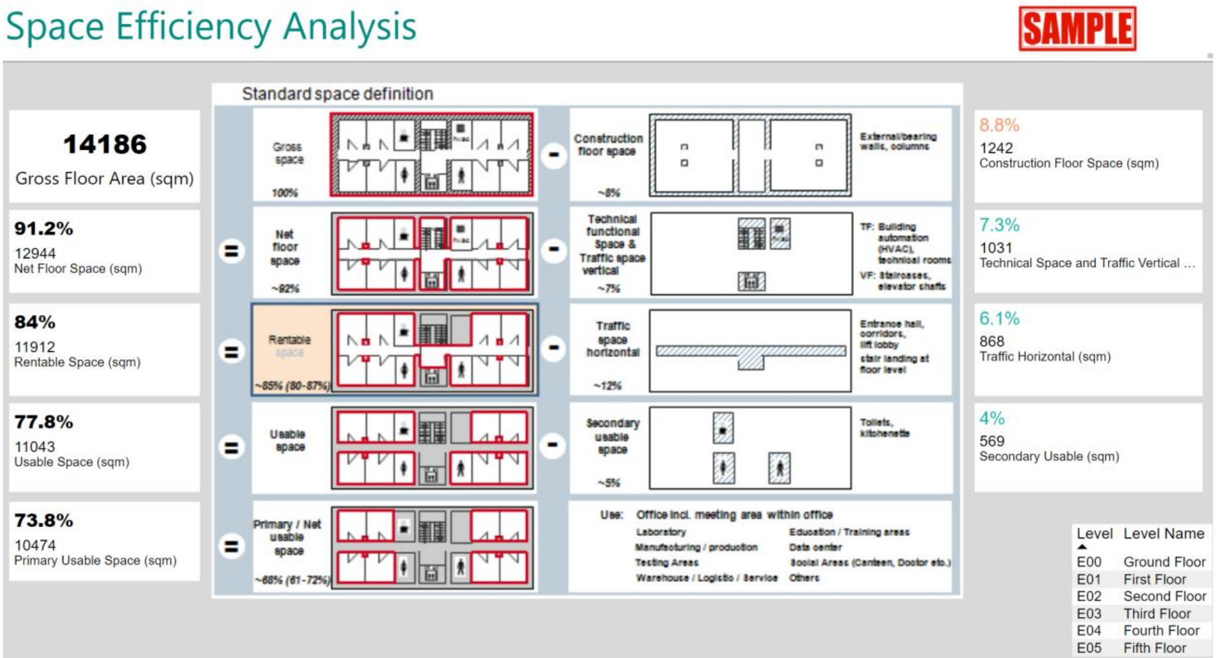

Figure 10 - Model analysis in decision-making (author´ s archive).

2.3 Standards

Currently, no data standard in BIM provides a uniform data structure and the possibility of more complex analyses across projects. Everything is handled in design offices, so the much-touted "efficiency of BIM" is often not demonstrable. As the sources in the research shows, there is a market demand for such a data structure of models and implementation methodology from both government and the private sector.

This thesis aims to develop a standard implementation methodology, BEP document annex, and supporting applications.

Exchange Information Requirement (EIR)

A key document in which the investor defines the information requirement. It is a part of the contract between the investor and the contractor of the project documentation. It represents the use of BIM models throughout the construction life cycle. This is the place to start if the use of BIM models for calculating the carbon intensity of the construction is envisaged.

A typical requirement in this respect might be: The BIM model will be used for environmental analysis. This will be done at different project stages (early, developed, and detailed design). The analysis's conclusions will be considered in the following design steps. The aim is to minimize the environmental impact of the construction by 30% compared to the standard condition.

BIM Execution Plan (BEP)

BEP is the answer to the EIR mentioned in the previous chapter. Here, the demanding party comments on the defined requirements and describes the pathways to their fulfillment in detail. Two different types of this document are distinguished: Pre-contract BEP and Post-contract BEP. The former is usually between the investor and the supplier of the project documentation. The latter is between the investor and the leading construction company. If more than one entity is requested, it is usual for the investor to send all parties its BEP template. This is mainly because these documents tend to be very comprehensive, and although they may have a similar structure, they can be very different. If completed in a single template, the subsequent comparison is much easier.

A practical example: The model will contain all the layers, and the materials will be described in detail, including the bulk masses. The model will also have lists of these materials. For infills of openings and façade elements, the groups of the sub-frame materials and glazing areas will be directly listed, including their detailed description). These steps will allow the pairing with environmental data from the generic, and EPD databases. The analysis can be performed with a commercial tool (e.g., One Click LCA) or otherwise. All materials will be mapped for export to the IFC format so that the exported model contains all the values mentioned.

Common Data Environment (CDE)

A common data environment is a virtual space in which models and other project-related information are exchanged between all stakeholders. It can be imagined as a standard cloud-based file-sharing service with several extra functionalities (e.g., detailed access management, integrated protocols, file browsers, communication channel, notification platforms, revision capability, history, advanced security, etc.). No special requirements for this environment are necessary for environmental calculations.

Some CDEs collaborate with commercial environmental analysis tools (for example, Autodesk Construction Cloud allows direct integration of One Click LCA).

2.4 Building Information Modelling (BIM)

The main advantages include the constant updating of the model, not only in standard outputs (drawings) but also in reports and other tables, which are also an integral part of the project documentation. For example, a newly created window will not only appear in all drawings where it should be visible (floor plans, sections, views) but also in the window report. At the same time, the volume of the wall material is automatically reduced. This contributes to lower error rates and, thus, higher efficiency in the creation of project documentation.

Ideas about a new way of designing are from the late 70s. The first product on the market was Graphisoft` s ArchiCAD. The expression itself (BIM) was invented and popularized by Autodesk in the 90` s. In the last decades, both platforms have been (along with others) developed. BIM is not just a 3D model. It is a parametric database model with riched of physical, energy, environmental, and many other types of data. Therefore, the 3D view is only one perspective of how the user can read the model. Other options are Floor Plan views, Reflected Ceiling Plan (RCP) views, schedules, models, or any other type of perspective.

BIM is a process or method of dealing with data throughout the life cycle of the building.

The information model is always up-to-date and thus helps to fulfill an idea originally taken from the field of information technology, namely that information should be kept in one place, the so-called "single source of truth." Building information modelling is an intensively emerging trend in the construction industry, which aims to streamline the whole sector to the level of the engineering sector. This is done both through 3D modelling of the building and especially the information value of the entire model.

As with any model, it is, of course, a matter of information representation and, to some extent, a simplification of reality to the level of a computer model. This should help us, among other things: (1) increasing the quality of the project, detecting most of the errors during the design phase; (2) increasing the accuracy of the reports; (3) providing the analytical basis for correct decision-making; (4) optimizing the proposed solution.

Due to the above-mentioned reasons, it is very important to have the information we need in the model at each given stage of its life cycle. It is not advisable to have not enough information in the model that we need (otherwise, we are not able to use the model realistically and effectively), but neither is it advisable to have an excess of information that we do not need. This often makes the model unnecessarily complex and opaque.

Another advantage of modeling that is often mentioned is the reduction of the cost of project documentation and the speeding up of its production. These are neglected for the moment because, due to the complexity of implementing BIM solutions in practice, we have not yet been able to demonstrate these savings. The purpose of the model is, among other things, that we can analyze it and then make decisions based on this analysis leading to a more efficient building design.

Information modelling should thus be seen in a number of different contexts, each of which is at a different stage of implementation in the market. The traditional division is represented by the project phases (the so-called performance phases described by CKAIT[4]). The classical forms of project documentation valuation are linked to this view. These phases of development are followed by the so-called Level of Development (LOD), i.e. the Levels of Model Development defined in a document managed by BIMForum [41]. This document is usually part of the contractual relationships within which it is referred to. The LODs are called Graphical (what the model looks like at that stage) and Non-Graphical (information defined in parameters within the model).

However, this approach has many limitations: (1) it focuses only on the preparation and construction phase, not on the operation and subsequent demolition of the structure, although these phases are important in the whole life cycle; (2) it is very rigid and does not take into account the different uses of the information model, which evolve dynamically over time.

Therefore, the second approach, using the so-called Labels, seems to be better for this purpose. This principle is used by the Czech Agency for Standardization (CAS) in the preparation of the Data Standard for Construction (DSS). The principle is that in the preparation of the tender documentation with the requirement for BIM, the so-called Model Requirements are defined. Each requirement has defined parameters in the individual model stages. This means that based on the required "use scenarios" of the model, specific requirements (also graphical and non-graphical) for the model are defined. This approach better reflects the fact that each stakeholder has different requirements for the model.

One of the key issues we face not only in the design of building units (civil, civil engineering, and other structures) is making the right decisions based on relevant information.

The Building Information Model (BIM) contains a significant amount of data. We can take advantage of the fact that this model is a database with which we can perform arbitrary operations. In this way, we can organize seemingly disorganized data in such a way that it provides us with the right information that can serve as a basis for more informed decisions, especially managerial decisions.

A new trend that is emerging in the world is linking building models with Business Intelligence software, which can help us not only "comb" the data but also visualize it in a form that is easy to grasp, even for people who are not experts in the field (but are also often so-called Decision Makers).Risksk related to implementation BIM are described by Petr Matějka [42].

The uses for Business Intelligence in information modelling are numerous. One of the areas where this method can find application is data visualization based on a volumetric feasibility study of a construction project. Every developer has to deal with this problem and data visualization using BI software can make this decision very easy.

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[4] https://www.ckait.cz/

Within the BIM model, different types of operations for given parts of the project can be modelled very easily in the conceptual phase. The project can thus be divided into:

- residential,

- office,

- manufacturing,

- services,

- leisure.

At the moment the developer is trying to optimize the project costs. Each of the mentioned facilities has a different sale (rental) value, but at the same time it is not possible to design only one-sided usability in the project. It is therefore necessary to decide what percentage of the floor area will be dedicated to which operation. This is where applied statistics in the form of Business Intelligence software can help. From the BIM model, we can easily get information about the areas, volumes, etc. of the plants based on the different architectural design options, and in the BI software we can link this information with information about the value of the individual plants and very clearly compare the different design options.

At the same time, we can also take advantage of the fact that there is a live link between the BIM model and the BI software, so any change (change in the number of floors of the apartment building, etc.) is immediately reflected.

2.4.1 Parametric Design

At this stage, we have to make the most important decision - how we will proceed in building our own model. Among other things, we have to determine which software platform to choose, which is a very complex decision in itself. The experience with the software packages in question (itself complicated to define) will play a role here, but also the price of the software, or the supply of the market, which must be able to meet our needs and create the model.

A multi-criteria analysis can help us here, by using appropriately chosen parameters and weighting them to convert them into a single-criteria solution to the problem. This will allow us to select one of the software platforms quite easily. Although this is a simple matter at first glance, the reality is not nearly so simple. Since the information contained in the model is important for its further use, populating the model with the right data is crucial. At each stage of the project documentation, we have clearly defined (via LOD) which information and how structured to put into the model at that stage.

A document that clearly defines the information to be included in the project documentation, including the exact definition of each parameter and the formatting of the information, is called a BIM Execution Plan (BEP). Improving the quality of the project, detecting most errors during the design phase

Having spoken to a number of BIM managers from different companies, I consider this point to be the primary reason why individual companies are switching to

BIM solutions, even though the market is often not yet pushing them to do so. Although this is a very important issue, we are not able to help ourselves with any technique or method from the field of management theory. All that can be argued (without longer-term statistics and experience) at this point is theoretical values and the "belief" that this is the right direction. The decision-making apparatus is of no help at this point either. It is only necessary to focus on increasing the accuracy of the statements (which, of course, goes hand in hand with the aforementioned increase in the quality of the model or project documentation as a whole). However, this point (if done technically correctly) can be used very successfully throughout the entire preparation and construction phase of the actual building. In particular, it is necessary to use the correct dial systems so that the building can immediately take over all the data from the model. In contrast, this point offers literally endless possibilities for the use of decision-making and optimization methods, where we can take advantage of the fact that we have a model and can analyze it very easily and efficiently and continuously adjust it according to the results of the analysis.)

2.4.2 Generative Design

This is an open-source graphical programming software available in two variants, as a native Dynamo Studio application or as an add-on to other software, such as Autodesk Revit. The main advantage lies in the possibility of (semi-)automating some processes, creating complex geometry, or working with data (data analytics) of the model. This online superstructure allows to generate any number (thousands) of design variants and work with them in a user-friendly way after connecting a project from Dynamo. This process allows the user to select the most suitable variant, which can be re-entered into Dynamo and then exported to Revit for detailed development.

If we have several designs available, it is relatively easy to determine the optimal solution. However, the problem arises when we have several variables, each of which can take on different values. The number of possible solutions increases exponentially, and it is no longer humanly possible to try out thousands of options and choose the best one.

This option generates a pre-selected number of values in each "slider" and then combines them randomly. This solution is the most computationally intensive, as it can easily generate thousands of variant solutions.

As the name suggests, this option allows us to generate random variants based on values from a preset range. This setting generates interesting and novel designs, but because of the randomness, it also generates a large number of nonsensical variants.

This last option for generating designs allows you to choose parameter values up to 20% different from the current variant based on the current variant. This algorithm is suitable for final tuning of the final design. For a successful application of Generative Design, it is first necessary to focus on the possibility of algorithmizing of the design, so some knowledge of mathematical logic is required. The values that we want to change using generative design need to be mathematically linked so that changing one parameter dynamically changes the others that are linked to it. As in the case of using any other software solution that enables (semi) automation of design, it is of course not possible to rely entirely on a computer program, but human reasoning and an engineering approach must also be involved. Example is shown in Figure 11.

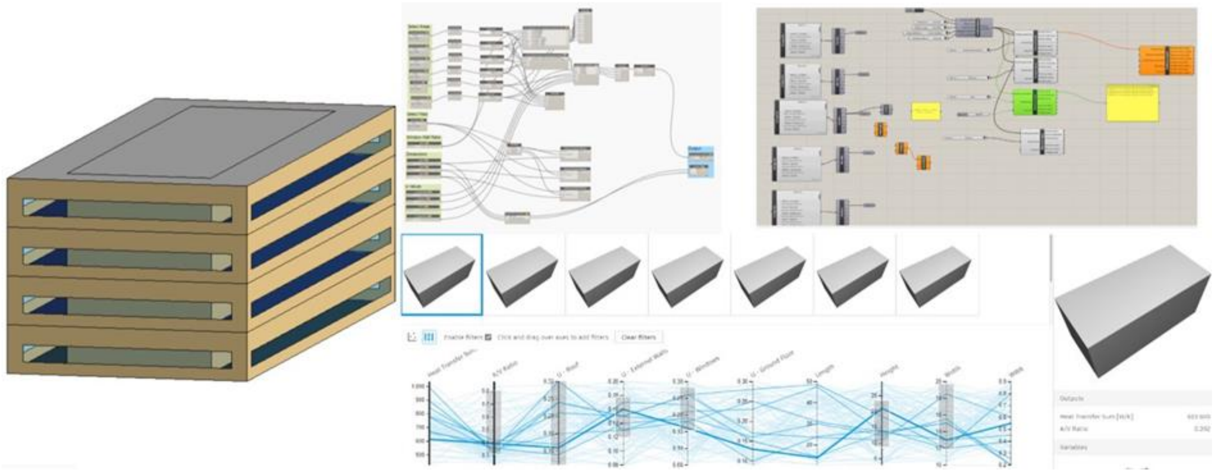


Figure 11 – Variants which combine various imputs (author´ s archive).

By transferring this Dynamo script to Generative Design, we can inversely determine which of the preset parameters will be variables and let a large number of different designs be generated. We can easily navigate between these designs to determine the quality of the design based on our requirements. When there are a large number of variants, sliders are used for better orientation, which allow us to filter the individual variants according to the selected parameters (for example, only variants that have a length of 30-50m can be displayed in this way and all others are ignored).

2.4.3 Digital Twin (DT)

The situation with a Digital Twin (DT) term is even more difficult and it has not been stabilized yet. Probably the most accurate current definition is BIM-based model showing the real time data from other inputs (e.g. sensors). The point is to combine rigid model with current inputs. The principle is shown in Figure 12

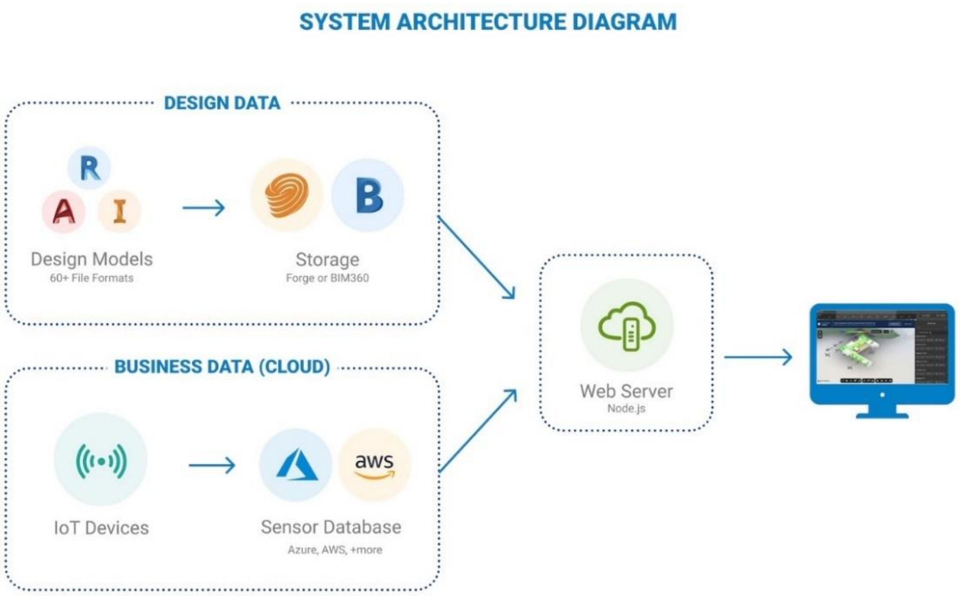


Figure 12 - Principle of the Digital twin based on Autodesk platform (source: https://aps.autodesk.com/blog/forge-data-visualization-components-early-access)

In the BIMIP research project (details in the chapter 8.3) created such a model was developed. First mockup and proof of concept was based on the Autodesk Tandem and Hyperion tools on the Autodesk Forge platform and it was developed as a Master Thesis of Filip Chrást (under supervision of doc. Ing. Michal Kabrhel, Ph.D. and author of this Thesis). The model with data from the sensors is shown in Figure 13. Second version was based on a platform BIMPOINT in a copoperation with a project partner di5 architekti inženýři, s.r.o..

The purpose is higher clarity and thus added value of the models during building management. The models can therefore serve as a basis for analyzing the behavior of the building and be linked to its management, in which they can thus participate.

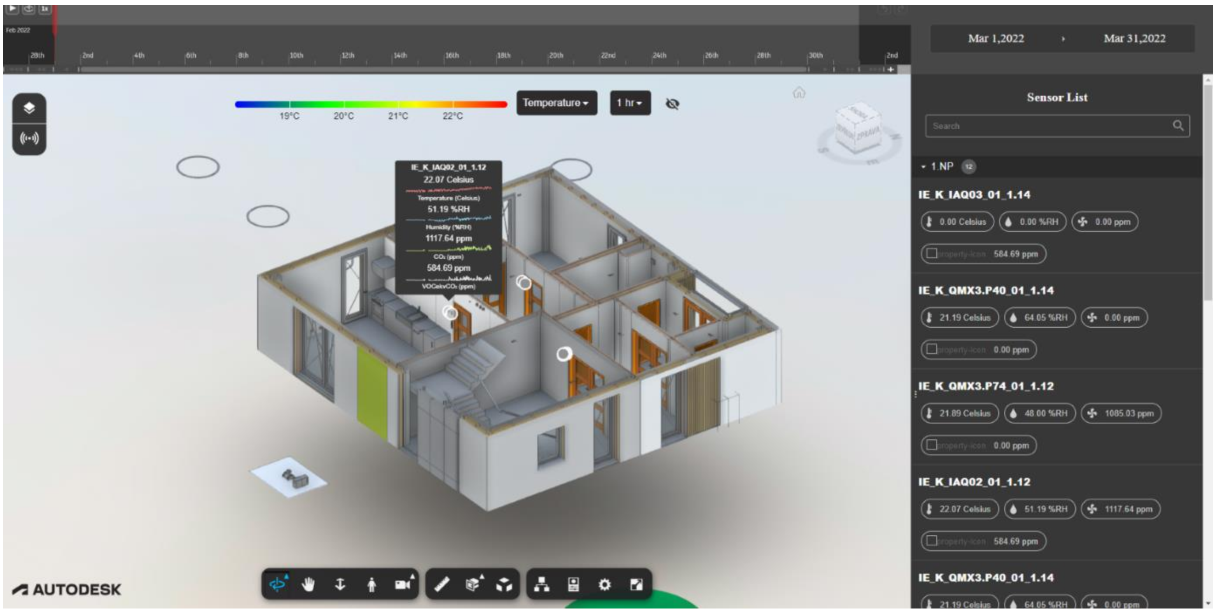


Figure 13 - Example of the Digital Twin from the BIMIP project based on the Autodesk Forge platform (author of the model Filip Chrást).

2.4.4 BoQ

The bill of quantities is an integral part of all construction projects. Due to the aforementioned uniqueness and complexity of all construction projects, high demands for accuracy are placed on these statements. The information model is a useful tool for the production of these statements. In order to use the models effectively, it is necessary to have set rules between all parties involved as defined in the contract documents.

In the following chapters of the, the pitfalls of information models will be discussed in detail, as they are always simplified to some extent. It is therefore not possible to use the statement of estimates for environmental assessment purposes directly.

Bill of Quantity (BoQ) is a list with all the materials, products and other elements related to the building. Quality of BoQ is a key part and BIM in order to calculation environmental impact of the building. It takes benefits out of the fact that model is still updated and therefore [43]–[45].

Life Cycle Inventory (LCI)

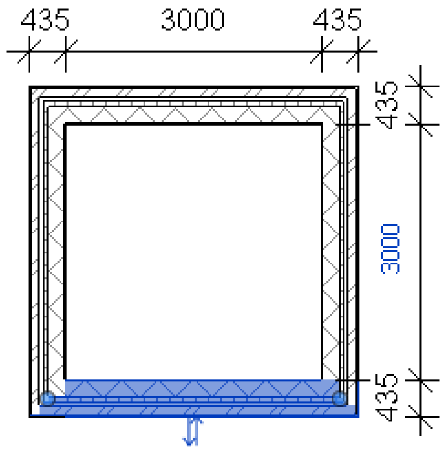
This term is often mixed with previously mentioned BoQ, therefore, it is important to clarify the difference. The Life Cycle Inventory can be considered as a superstructure to the aforementioned Bill of Quantities. The generic databases required for the calculation of the LCA are usually calculated per kilogram of materials, so that in addition to typical quantities such as volumes, areas and pieces of individual materials, it is the kilograms that need to be determined. Again, information models can be used to great advantage, but only if each material also contains information about the bulk mass.

Another non-negligible parameter for the LCA calculation is the expected lifetime of the material, structure or element. In addition to the material itself, the location within the structure must be considered in this estimation, as the same material in a different location may have a radically different service life.

Both of these parameters are used to calculate the built-in environmental impacts (A1-A3), but also to take into account the replacement of components or the modification or improvement of the building (indicators B4-B6).

When using Building Information Models (BIM) for Life Cycle Inventory (LCI), we encounter the problem of different reporting across software platforms. We can report the materials of flat building structures by area or volume. However, a complication arises in the linking of building structures. If the information models are created using a partitioned approach (structure, insulation, finishes), the area and volume calculation is more accurate. This procedure of separate modeling is also recommended by the Czech Agency for Standardization (CAS) in the emerging Data Standard for Construction (DSS) framework. However, when structures are modeled as a whole layer, inaccuracies in the reports occur because they are calculated from the same wall axis (centerline). Other minor differences may arise due to different wall connections, including but, miter or rectangular terminations.

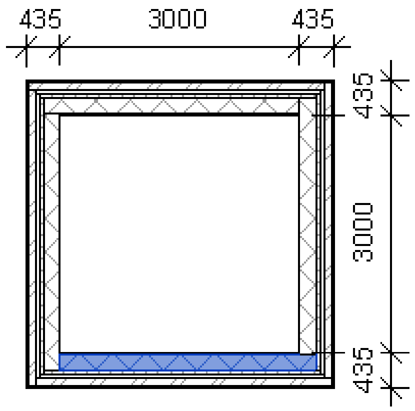
All modeling or connection options are shown in the following examples. Autodesk Revit 2022 software was used for the demonstration.



<Wall Material Takeoff>

A	B	C	D
Material:	Material: Name	Material: Area	Material: Volume
1	Gypsum Wall Boar	54.96 m²	0.55 m³
2	Concrete Masonry	54.96 m²	10.99 m³
3	Vapour Retarder	54.96 m²	0.00 m³
4	Cavity Fill	54.96 m²	2.75 m³
5	Air	54.96 m²	2.75 m³
6	Brick, Common	54.96 m²	5.50 m³
7	EIFS, Exterior Insul	54.96 m²	1.37 m³
Grand total: 28		384.72 m²	23.91 m³

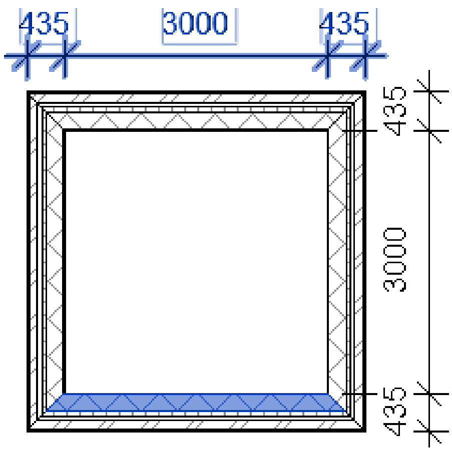
Figure 14 – Joint „Butt“, multi layers (author´ s archive).



<Wall Material Takeoff>

A	B	C	D
Material:	Material: Name	Material: Area	Material: Volume
1	Gypsum Wall Boar	54.96 m²	0.55 m³
2	Concrete Masonry	54.96 m²	10.99 m³
3	Vapour Retarder	54.96 m²	0.00 m³
4	Cavity Fill	54.96 m²	2.75 m³
5	Air	54.96 m²	2.75 m³
6	Brick, Common	54.96 m²	5.50 m³
7	EIFS, Exterior Insul	54.96 m²	1.37 m³
Grand total: 28		384.72 m²	23.91 m³

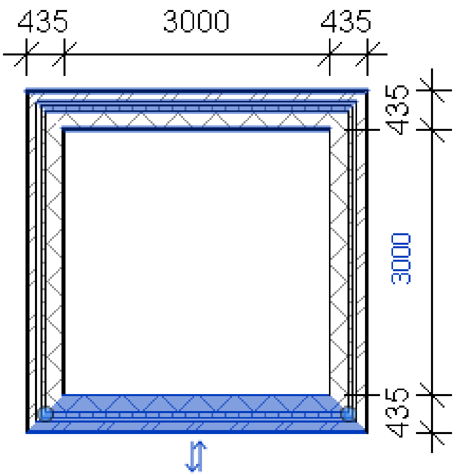
Figure 15 - Joint „Butt“, separated layers - parts (author´ s archive).



<Wall Material Takeoff>

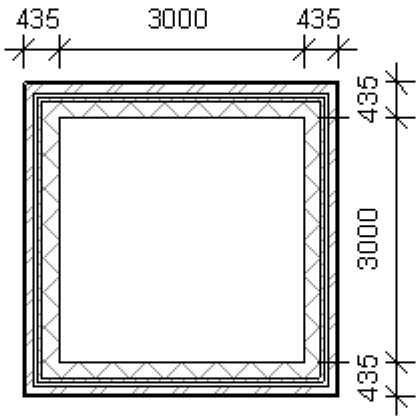
A	B	C	D
Material:	Material: Name	Material: Area	Material: Volume
1	Gypsum Wall Boar	48.32 m²	0.48 m³
2	Concrete Masonry	54.72 m²	10.30 m³
3	Vapour Retarder	61.92 m²	0.00 m³
4	Cavity Fill	56.32 m²	2.78 m³
5	Air	57.92 m²	2.86 m³
6	Brick, Common	61.12 m²	5.95 m³
7	EIFS, Exterior Insul	61.92 m²	1.54 m³
Grand total: 28		402.24 m²	23.91 m³

Figure 16 - Joint „Miter“, multi layers (author´ s archive).



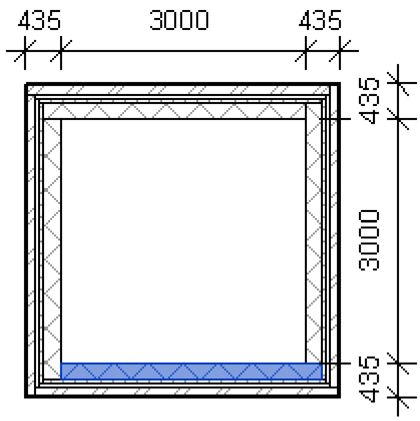
<Wall Material Takeoff>			
A	B	C	D
Material:	Material: Name	Material: Area	Material: Volume
1	Gypsum Wall Boar	48.32 m^2	0.48 m^3
2	Concrete Masonry	54.72 m^2	10.30 m^3
3	Vapour Retarder	61.92 m^2	0.00 m^3
4	Cavity Fill	56.32 m^2	2.78 m^3
5	Air	57.92 m^2	2.86 m^3
6	Brick, Common	61.12 m^2	5.95 m^3
7	EIFS, Exterior Insul	61.92 m^2	1.54 m^3
Grand total: 28		402.24 m^2	23.91 m^3

Figure 17 - Joint „Miter“, separated layers - parts (author´ s archive).



<Wall Material Takeoff>			
A	B	C	D
Material:	Material: Name	Material: Area	Material: Volume
1	Gypsum Wall Boar	54.96 m^2	0.55 m^3
2	Concrete Masonry	54.96 m^2	10.99 m^3
3	Vapour Retarder	54.96 m^2	0.00 m^3
4	Cavity Fill	54.96 m^2	2.75 m^3
5	Air	54.96 m^2	2.75 m^3
6	Brick, Common	54.96 m^2	5.50 m^3
7	EIFS, Exterior Insul	54.96 m^2	1.37 m^3
Grand total: 28		384.72 m^2	23.91 m^3

Figure 18 - Joint „Square off“, multi layers (author´ s archive).



<Wall Material Takeoff>			
A	B	C	D
Material:	Material: Name	Material: Area	Material: Volume
1	Gypsum Wall Boar	54.96 m^2	0.55 m^3
2	Concrete Masonry	54.96 m^2	10.99 m^3
3	Vapour Retarder	54.96 m^2	0.00 m^3
4	Cavity Fill	54.96 m^2	2.75 m^3
5	Air	54.96 m^2	2.75 m^3
6	Brick, Common	54.96 m^2	5.50 m^3
7	EIFS, Exterior Insul	54.96 m^2	1.37 m^3
Grand total: 28		384.72 m^2	23.91 m^3

Figure 19 - Joint „Square off“, separated layers – parts (author´ s archive).

Overall, using volumes that vary less by wall connection settings for LCA reporting purposes is preferable. If wall area reporting is chosen for calculation purposes, it is necessary to use the miter connection throughout the model. Otherwise, there are relatively large inaccuracies in the area reporting. This is the reason for the inaccuracies in the LCA calculations.

Native formats

Software developers prefer to use their own closed formats. This has a number of advantages for them, the most important being that "their" file cannot be easily opened, understood and edited, for example in a note editor. BIM software is no exception to this, and the vast majority of programs use their own formats.

However, the advantage for the developer (and, to some extent, the user) can be a disadvantage for other participants in the construction process. In order to open the models and then work with them fully, a license for the software is required.

Industry Foundation Classes (IFC)

In the context of the development of software platforms, the development of the open IFC format, which aims to freely view and work with models, has been ongoing. This format is developed by the international organization buildingSMART, based in Switzerland, and is described in the ISO standard [46].

The IFC format is also currently approved as an exchange format for use in the Czech Republic [47].

Given the direction set to digitize the construction procedure and permits, the use of the IFC format is envisaged in great detail. Regarding the issues presented, the models must be exported with the correct settings to have all the properties needed for their environmental analysis (volumes, pieces, material properties, etc.). The Czech Standardization Agency is currently working on the preparation of these materials.

2.4.5 Project phases in relation to BIM

In the context of design practice, the critical decision is at what stage of the project the environmental analysis should be carried out. The primary division of construction projects is early, developed, and detailed.

The earlier this calculation is carried out (early design; LOD 200), the greater the uncertainty associated with such a calculation. Only the material studies and initial designs of the individual buildings are created. This phase is specific because a higher level of uncertainty has to be taken into account as all design details have yet to be discovered. On the other hand, several changes can be made at this stage of the project to optimize the design and the resulting reduction in embodied energy and emissions. This undoubtedly has a positive effect on the environmental quality of the overall project. To have a "reasonable" calculation accuracy, however, aggregated data for the most commonly used building structures are needed. With this data, it is possible to perform the environmental calculation with satisfactory results at this stage. On the other hand, even an inaccurate analysis can be a valuable basis for subsequent project optimization. Another obstacle may be the quality of the so-called aggregated data (environmental impacts calculated, for example, per square meter of a given structure). Such a database is available in Switzerland but not in the Czech Republic. It is, therefore, only sometimes possible to get reliable results.

At a later stage of the project is the developed design (e.g., building permit; LOD 300), a lot of precise information (dimensions) can be extracted from the model so that BIM can be used to calculate environmental impacts. At the same time, the availability of environmental data is higher, making the calculation easier. Due to the advanced elaboration of the model, it is generally possible to count on a higher level of accuracy of the results than in the early phase of the project. On the other hand, it should be taken into account that any changes leading to higher design efficiency are enforced in the late stage of the project. Design and material changes are already practically impossible.

In Detailed Design, the high information value of the whole project is guaranteed so that very accurate calculations of the environmental impacts of the building can be achieved. On the other hand, this calculation is the most time-consuming and without the possibility of fundamentally influencing (optimizing) the design.

Whether in complexity or duration, everything plays an essential role in the entire construction life cycle. When considering using an information model for environmental calculations, it is necessary to consider the phase in which the user wants to apply these calculations. A comparison of the different stages of the project across the member countries was carried out in the Annex 72 project [48]. In other countries, the various project phases and the resulting requirements for project documentation vary in detail. This document shows that projects in the participating countries proceed very similarly, with each stage having specific information requirements and not all being suitable for BIM-LCA implementation. The division into the three steps mentioned above (early, developed, and detailed) is sufficient for environmental calculations. The comparison is shown in Figure 3. Conclusions, including this figure, can be found in [48].

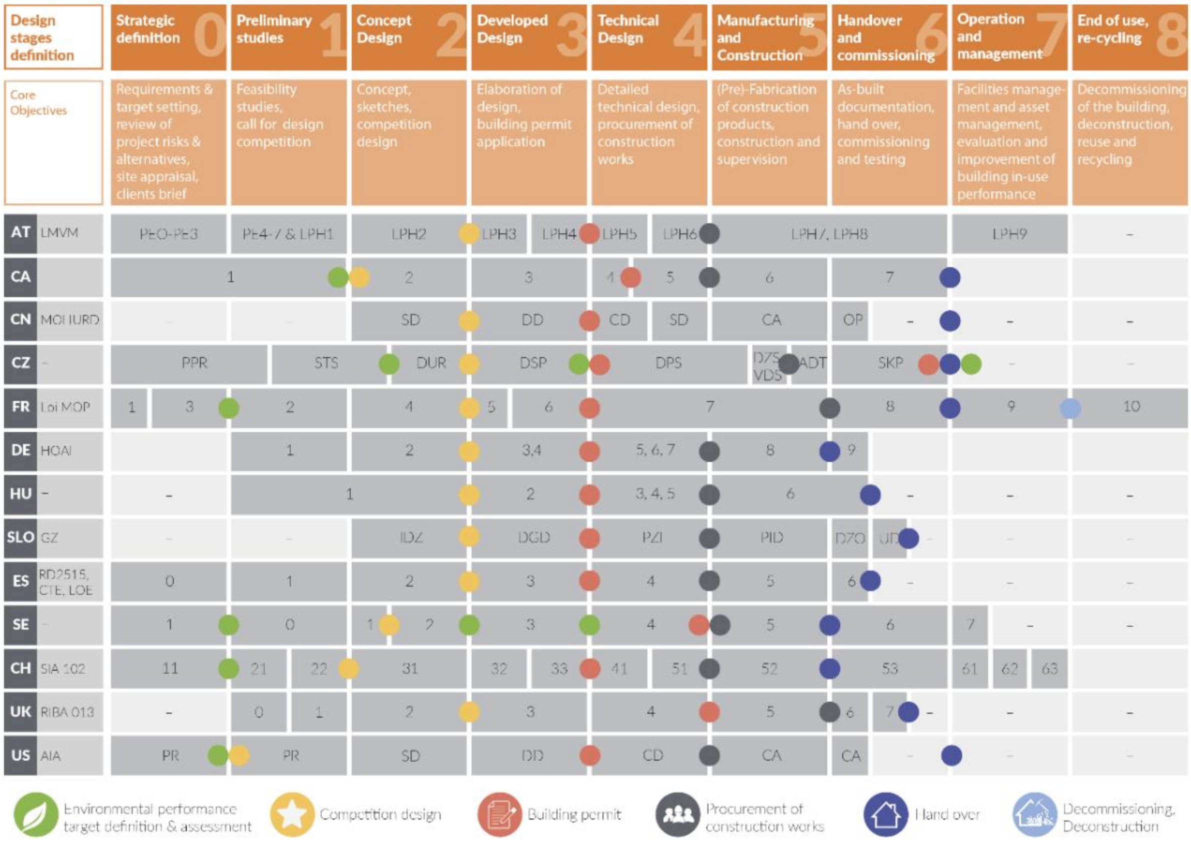


Figure 20 – Project phases definition in various countries [48].

Level of Development

To work effectively with models during the construction life cycle, it is necessary to be able to describe them graphically and non-graphically. For this purpose, the Level of Development (LOD) publication is used globally. Previously, Level of Detail was used, but this name evoked only the graphical aspect of the model, so the process replaced it. LOD is maintained by the non-profit organization BIMforum[5] from the USA. The purpose is to describe the level of detail of models about the project phase. The basic breakdown is LOD 100-400, with a higher number indicating greater model detail. A take LOD 500 is used for building management, so its value lies not in graphics but in-information extensiveness.

The LOD Spec publication [57] describes the whole principle, which is regularly updated. It breaks down the different components of information models (walls, columns, technical equipment, etc.) according to the different phases of LOD. This document is referenced by several other documents mentioned later in the text (Exchange Information Requirement, BIM Execution Plan, etc.). For example, building permit documents will be in LOD 300 detail, with some components in LOD 350. An example of a particular element in various LOD is described in Figure 21.

[5] https://bimforum.org/

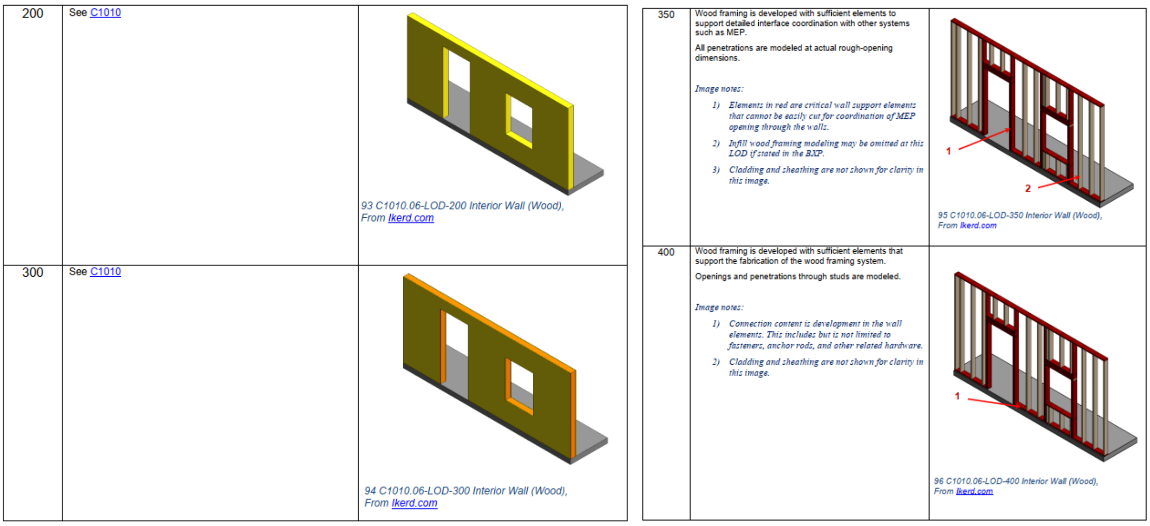


Figure 21 - Internal wall in various LOD [41].

2.5 Life Cycle Assessment (LCA)

LCA Methodology is currently established as the leading methodology for the environmental assessment of buildings. LCA is described in detail in ISO and EN [21], [49]–[51] standards and is used in many fields of human activity, such as manufacturing, engineering, chemical, and, last but not least, the construction industry. The first publication in the Czech Republic on using LCA in the construction industry dates back to 2012. Life Cycle Assessment is a widely accepted methodology for assessing materials, products, and buildings. It became the most used methodology for evaluation building and in the context of the Architecture, Engineering, and Construction (AEC) industry. The LCA method is standardized [21], [50] and, therefore, replicable. The schema of the process is shown in Figure 6 - LCA principle according to ISO 14044 [21].

Phases

The principle of LCA is that the object under study (product, process, or construction) is divided into life cycle phases called modules. These can be divided into (A) production, (B) operational, (C) demolition, and (D) recycling potential. The individual modules are further subdivided into subgroups dividing the whole life cycle process into more complex parts. A detailed description of the modules based on EN 15978 is given in Figure 22.

Data for the calculation of environmental impacts are relatively easy to obtain for some modules. In particular for the production part (A1-A3) and the operation modules (B5-B6). Since production and operation have the highest share (around 90% of the total), the remaining modules often need to be addressed.

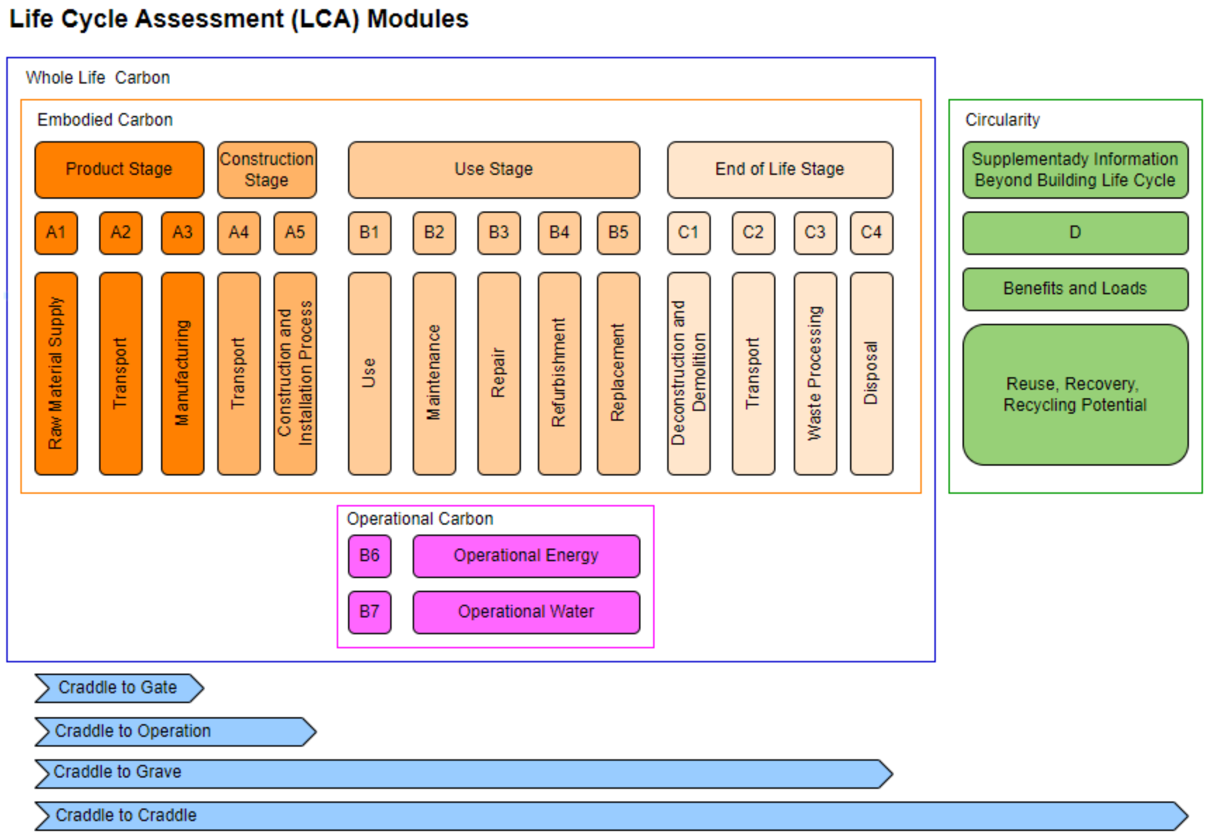


Figure 22 - LCA Modules according to EN 15978 [21].

Indicators

Within the framework of LCA, it is possible to examine several parameters (indicators). Among the most well-known are Primary Energy Intensity (PEI) and Green House Gas Emissions (GHG). There are many of these gases, so for simplicity, they are converted to kilograms of carbon dioxide equivalent (kg CO2eq). In addition, one can encounter, e.g., Primary energy consumption, Environmental acidification, etc. For some specific locations (e.g., affected by mining), it makes sense to use these indicators. However, the reduced primary energy demand and greenhouse gas emissions are mainly used for most cases.

Embodied and Operational consumption

Energy and emissions are divided into two components, (1) embedded and (2) operational. Embodied is contained in the materials and products contained directly in the final product or building. These are modules A1-A5, and the values include energy and emissions associated with the extraction of primary materials, transport to production, subsequent production, transport to the building, and the building itself. Operational energy and emissions include modules B1-B7 and are thus associated with the longest time period, as the long life of a building project (usually at least 50 years) is specific to building projects, with individual components becoming technically or morally obsolete. This means that they have to be replaced during this period, or the building has to be revitalized in other ways.

In older literature, the ratio between embodied and operational energies and emissions was stated to be about 20:80[52]. With the increasing demands on technical quality and the consequent high operational efficiency of buildings, this ratio is changing, and now the influence is leveling out to about 50:50 [53].

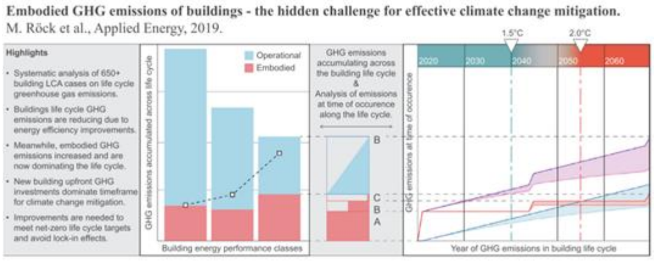


Figure 23 – The increasing ratio of embodied emissions [53].

System boundaries

For the reasons described above, any calculation of environmental impacts must first determine the so-called system boundaries. This means selecting the modules to be included in the analysis. Due to the mentioned long lifetime of buildings, it is also necessary to take into account the replacement of components that no longer technically or morally meet the current requirements during their operation. It follows that even during the operational phase of the building, the built-in emissions will continue to increase due to the replacement of the component units. Typical examples are the various re-cladding of spaces according to the requirements of the current tenant or the replacement of façade elements to meet current thermal engineering standards.

In addition, it would be best to consider the easy accountability of these components. This saves labor during the actual implementation (and ultimately finances), and the undamaged elements can be used elsewhere or recycled for further use.

Uncertainty

Working with uncertainty is an integral part of this theme. It is present in all calculations and thus must be considered. The amount of uncertainty depends on many factors, for example:

- The stage of the project and the resulting level of development of the model,
- The accuracy of the model,
- The quality of the environmental data,
- The quality of the processes to avoid human error as much as possible.

2.5.1 Environmental data

The essential part of the environmental analysis of buildings is the environmental data. It is their quality that determines the accuracy and reliability of the calculation. Three types of environmental data can be distinguished: aggregated, generic, and specific (EPD).

Aggregated database

The aggregated database is suitable for the early design phase of the project when only the areas and primary volumes of the individual structures are known. Its purpose is to estimate the environmental impacts of structures. As this database needs to reflect national building specifics and energy mix, it is country-specific. Unfortunately, such a database has yet to be available in the Czech Republic. However, it is possible to use, for example, the database within the Bombyx tool [54], which was developed at ETH Zurich and thus contains Swiss data. With a certain degree of imprecision, it can also be used in the Czech Republic.

Generic Databases

These environmental data sources find use in all phases of the project but are most relevant to the Developed phase of the project. In this phase, the construction principles and main material solutions are known, but not the detailed specifications of all products are not. These databases should be country-specific to include the energy mixes of the countries. These databases can also be used to produce EPDs that are modeled in detail in sophisticated LCA software such as SimaPro.

Among the best available databases is Ecoinvent[6], which is the most consistent environmental database in the world today. It contains several datasets for different parts of the world, making its use possible everywhere. In the Czech Republic, this database is widely used. Due to its robustness, it is used for the construction industry and all other sectors of human activity, and it is implemented in various other software[7]. The database is paid.

Okbaudat[8] is a database managed by the German government focused on construction production. It contains more than 1400 datasets and complies with EN 15804. Within the Czech Republic, this database is usable without significant problems.

The last database mentioned is the Czech Envimat[9]. It was developed in 2011 by colleagues from the Faculty of Civil Engineering of the Czech Technical University in Prague. Many are now working at the University Centre for Energy Efficient Buildings there. This database is based on Ecoinvent but contains datasets valid for the Czech Republic. After registration, the database is available free of charge, but its disadvantage is that it is not up-to-date. Efforts are currently underway to update it.

Environmental Product Declaration (EPD) Databases

EPDs, specifically building materials and products, are regulated by EN 15804+A2 [49] and are linked to a specific building product or material. These documents

[6] https://ecoinvent.org/

[7] https://ecoinvent.org/the-ecoinvent-association/software-tools/

[8] https://www.oekobaudat.de/en.html

[9] http://envimat.cz/

consist of a textual part describing exactly the process leading to producing a particular material or product. It also explains the Reference Unit (RU), usually kg of material, but other units (m2, m3, etc.) may be chosen. Another integral part is a table describing the life cycle's different stages (modules) and the relevant indicators, both according to the LCA methodology. The user can thus choose the exact values he needs. Recently, the standard ISO 22087:2022 Sustainability in buildings and civil engineering works — Data templates for the use of environmental product declarations (EPDs) for construction products in building information modeling (BIM) [55], has also been published, which regulates the details regarding the use of EPD within BIM. An example of an EPD is shown in Figure 24.

LCA: Results

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED)

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	X	X	MND	MND	MND	MND	MND	MND	MND	X	X	X	X

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT: 1 m² URBANSCAPE Extensive Green Roof System

Parameter	Unit	A1-A3	A4	A5	B1	C2	C3	C4	D
GWP	[kg CO_2-Eq.]	3.97E+0	6.68E-1	2.02E+0	-1.50E+1	5.33E-2	1.96E+1	5.03E-1	-1.78E+0
ODP	[kg CFC11-Eq.]	3.74E-10	3.07E-12	1.41E-10	0.00E+0	2.45E-13	1.01E-11	4.32E-10	-3.20E-10
AP	[kg SO_2-Eq.]	2.44E-2	1.65E-3	6.64E-4	0.00E+0	1.31E-4	1.94E-3	4.29E-5	-2.63E-3
EP	[kg $(PO_4)^{3}$-Eq.]	3.86E-3	3.81E-4	1.14E-4	0.00E+0	3.04E-5	5.12E-4	7.62E-6	-3.17E-4
POCP	[kg ethene-Eq.]	1.51E-3	-4.62E-4	5.30E-5	0.00E+0	-3.69E-5	2.88E-4	4.34E-6	-2.67E-4
ADPE	[kg Sb-Eq.]	1.35E-6	4.45E-8	4.46E-8	0.00E+0	3.55E-9	2.97E-7	2.36E-9	-4.32E-7
ADPF	[MJ]	7.80E+1	9.20E+0	1.78E+0	0.00E+0	7.34E-1	5.73E+0	7.65E-2	-2.23E+1

Figure 24 - Example of an EPD (author´ s archive).

There are several international EPD databases. Among the most comprehensive currently in this wrapper is the EC3 database from the Building Transparency tool[10]. This freely available platform contains a large amount of data and a straightforward interface that offers many settings (for example, comparisons in a boxplot diagram). The direct link to the Tally tool is also an advantage. The disadvantage is that most of the EPD focus on the North American region, which is only partially suitable for Europan conditions. An example is shown in Figure 25.

[10] https://buildingtransparency.org/

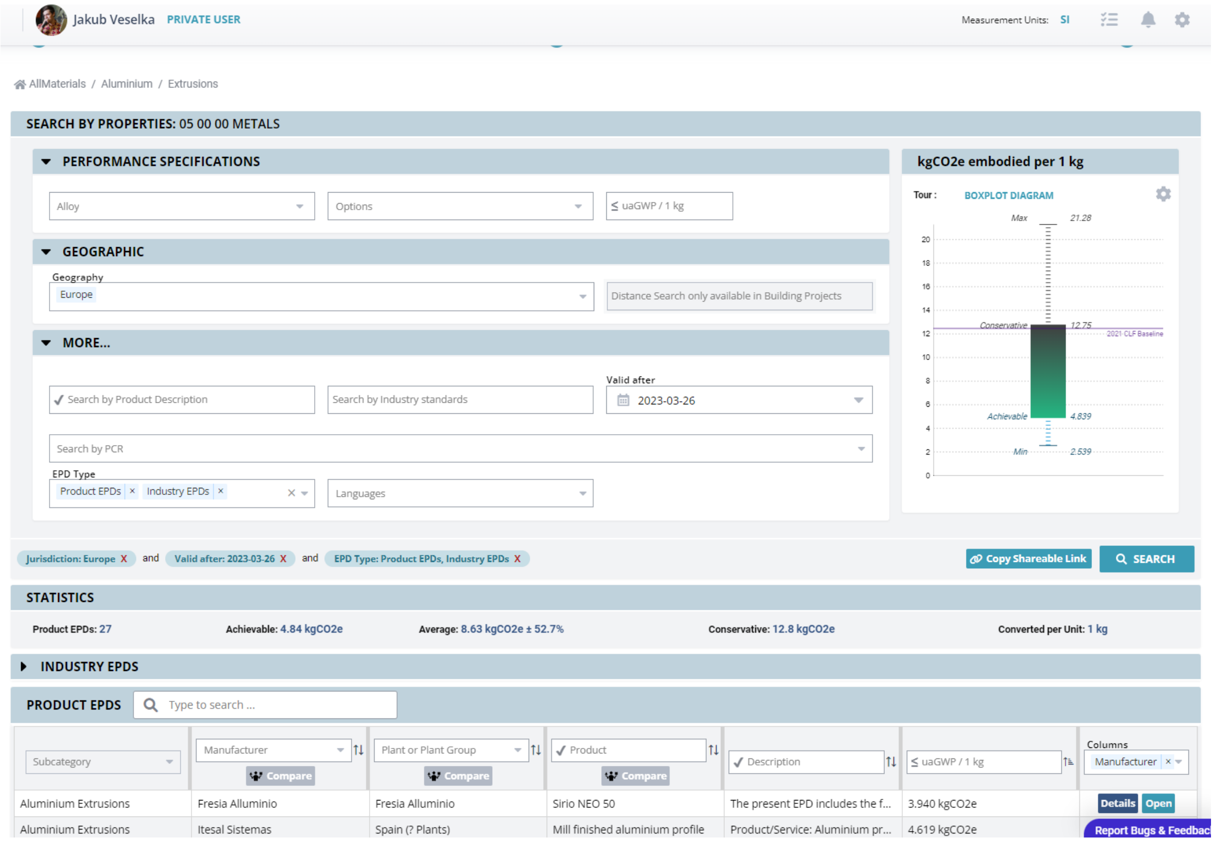


Figure 25 - Building Transparency EPD database (author´ s archive).

Another interesting database is IBU.data[11]. This is created and maintained by the German Institut Bauen und Umwelt e.V and is also freely available. It contains mainly German EPDs, which are more suitable for use in the Czech Republic. The disadvantage is a worse user interface.

The last mentioned database is the Czech database managed by the Czech Environmental Agency[12] (CENIA), which is part of the Ministry of the Environment. This database brings together Czech EPDs and is also freely available. The advantage is the localized data for the Czech Republic; the disadvantage is the poorer user-friendliness.

Some software, such as One Click LCA (more in 2.6.2), integrates these (and other) databases into each other, offering quick use.

Several institutions specialize in producing these certificates, for example, the University Centre for Energy Efficient Buildings, CTU in Prague. To be considered conclusive, they have a limited validity (usually five years) and should be audited by an independent third party. The production of such certificates is thus very laborious and expensive. At the moment, it is possible to trace most building products for the Czech Republic, but the situation is still poor for Building services, and not many EPDs are available yet.

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[11] https://ibu-epd.com/en/

[12] https://www.cenia.cz/spolecenska-odpovednost/epd/databaze-epd/ (in Czech only)

2.5.2 Advanced LCA Tools

Due to the poorer readability of environmental data, databases are usually worked with in specialized software. The primary purpose is the detailed calculation according to the LCA methodology, and the most common use is the creation of EPDs. Therefore, the input to the analysis is data from the environmental database, and all processes are modeled in the software according to defined modules. Commercial and free solutions are available on the market. The best-known alternatives include the Dutch SimaPro[13], the American Sphera[14] (formerly GaBi), or the German Umberto[15]. All have been on the market for over a decade and are available worldwide. As a result, they have a broad portfolio of users and a friendly user interface. A non-commercial alternative is, for example, openLCA[16]. This alternative is freely available, allowing the same outputs as commercial solutions.

LCA tools are also currently being developed in the research sphere. Advanced tools include the Belgian TOTEM[17] (Tool to Optimise the Total Environmental impact of Materials), the German eLCA[18], and Brightway[19]. These tools are characterized by accurate environmental data and are free of charge. Their disadvantages are poorer readability, low technical support, and the need for more advanced IT skills, such as programming in Python.

2.5.3 Life Cycle Cost (LCC)

Life Cycle Cost is a method, in a way, a similar concept to LCA, but instead of environmental impacts, the focus is on life cycle costs.

This method is embedded in the standards ISO 15686-5:2017 [56] an EN 16627:2015 [57]. It is also described in foreign and Czech literature. Heralová et al. [58] published an LCC methodology that allows the direct use of the software. A valuable source of information is the work of Stanislav Vitásek [59], who maps the possibilities of using BIM to evaluate buildings within their life cycle. The LCA and LCC methods are very closely related and are often integrated so that both the environmental and the economic evaluation are carried out within the same analysis [60]–[63].

Specific databases include, for example, the Swiss Baukosten Kochbau (eBKP)[20], which, in addition to a pricing database, also contains a methodology for use within BIM using a software add-on.

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[13] https://simapro.com/

[14] https://sphera.com/

[15] https://www.ifu.com/umberto/

[16] https://www.openlca.org/

[17] https://www.totem-building.be/

[18] https://www.bauteileditor.de/

[19] https://brightway.dev/

[20] https://www.crb.ch/Normen-Standards/Baukostenplaene/eBKP_H.html

2.5.4 Building Services

All the aspects mentioned above of LCA calculation are valid, especially for the civil engineering part of construction projects. The situation in Building Services is more complex for several reasons. In principle, the problems are the same as for the rest of the construction, but they are more fundamental.

In Early Design, only the principles of the individual systems are apparent, not any details. Therefore, analysis at this stage is complicated. In the Developed Design phase, the technical information (routes, principles of operation, etc.) is already clear so that calculations based on BIM models can be carried out with a certain degree of imprecision. Only in the Detailed Design phase are all the technical details known to perform the calculation. However, this phase allows for more optimization of the design.

Even in Detailed design, the situation is complicated because environmental data for many products is unavailable, either from the generic database or the EPD. In the literature, it was sometimes stated that Building Services impacts are estimated to be +10% of the environmental effects of the construction part of the project. This proved inadequate, and Kiamili et al. [64]. used a case study that calculated effects in detail for an office building. This work suggests that the environmental impacts of a modern building can be more than 30%.

In the paper, a summary of the current knowledge regarding building services was developed with colleagues from TU Munich and TU Wuppertal [65].

2.6 BIM-LCA

As is clear from the previous text, the principle of using the BIM-LCA process is to link BoQ with environmental data. This may seem like a trivial task at first glance; however, several rules need to be followed due to the nature of construction projects and their complexity and evolution over time. Many of the problems and bottlenecks mentioned in the previous chapters can be minimized by using a building information model. These qualities can only be exploited if several procedural measures are followed (in particular, the use of a classification system) so that the elements in the model are identifiable and duplication and inappropriate inclusion of materials is avoided in a comprehensive bill of quantities. For example, the same material at different construction sites has a different service life and thus has to be accounted for more than once in the life cycle.

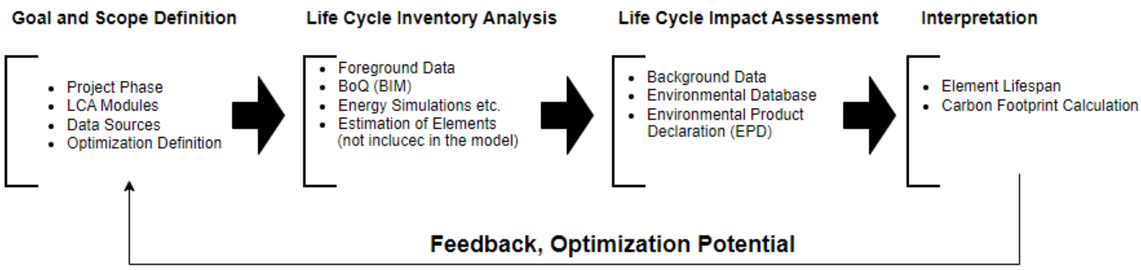

Figure 26 - LCA BIM schema (author´ s archive).

2.6.1 Data export

In case of a requirement for (semi)automation within a process, it is necessary to have a model prepared in a standardized form (classification system). At the same time, there are a number of approaches to creating this BIM-LCA process based on Wastiels et al [34], and further developed by Potrc et al [35].

Creation of reports from the model and subsequent export from the native model

Although this is the least advanced way of working, it is probably the most common at present. The model can be user edited if necessary. The actual environmental calculation takes place in an external environment (Excel or specialized software).

Exporting data from the IFC model

The user can no longer edit the IFC format. The actual environmental calculation takes place in an external environment (Excel or specialized software).

Automated export using visual programming

The actual environmental calculation takes place directly in the visual programming environment or in an external environment (Excel or specialized software).

Automated export via addon

It works similarly to the previous case, but instead of developing an own script, the extra function is added to the BIM software. Not user-editable, only with the help of a programmer. The actual environmental calculation takes place directly in the visual programming environment or in an external environment (Excel or specialized software).

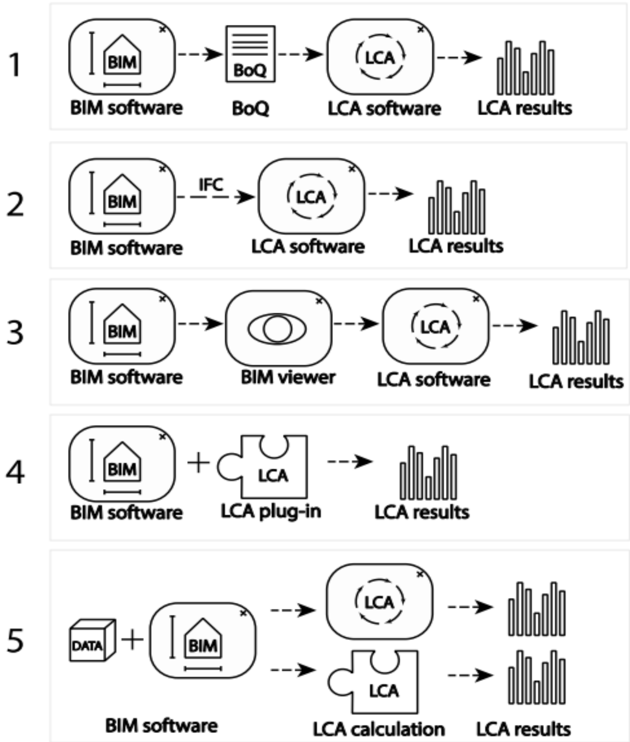

Figure 27 - BIM-LCA workflow comparison [35].

2.6.2 BIM-LCA Tools

It is a dynamically developing industry, and new software solutions are created yearly. This overview is, therefore, limited and mentions the leading platforms or otherwise exciting solutions. The software is divided into commercial and research.

In Europe, One Click LCA[21] is the most widely used commercial solution. This Finnish software allows connection to several environmental databases and is thus very comprehensive. It consists of an online platform in which the BoQ is inserted and paired with environmental data after the project is set up. Insertion is possible in several ways, manually (laborious), by importing from Excel, or by linking to BIM. The actual linking is again possible in several ways, via the Autodesk Construction Cloud online CDE platform, via an add-on to the BIM software, or the IFC format. The next step is to pair this BoQ with the environmental data. This can be done partially automatically (as long as the materials are logically and correctly named). However, meticulous user control is required. Also, more variants of the design can be compared. This tool is functionally very advanced and user-friendly and allows considerable extensibility according to the methodology used (LCA, LCC, Level(s)), etc. It can also work with complex building quality assessments (BREEAM, LEED, DGNB, etc.). The disadvantage is the higher price, so processing small projects (family houses) here is unrealistic. The example of mapping materials is shown in Figure 28.

[21] https://www.oneclicklca.com/

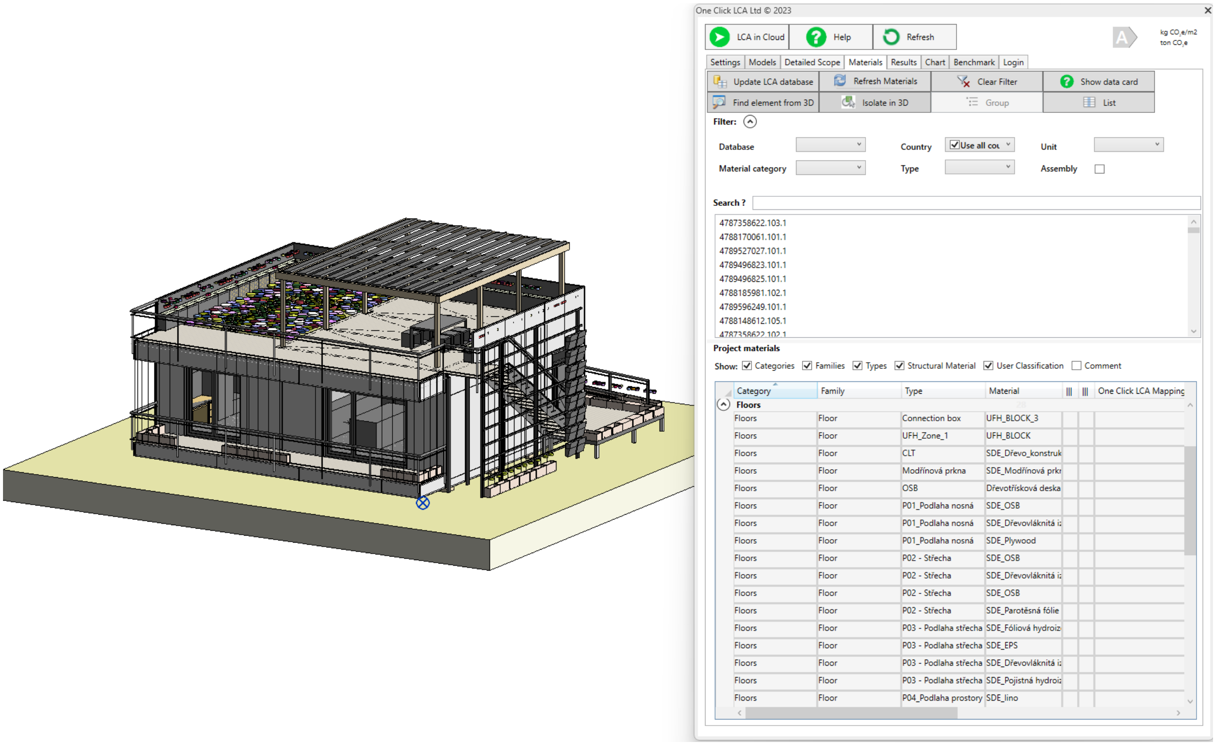

Figure 28 - Mapping materials from BIM in One Click LCA tool (author´ s archive).

Another option is the American Tally Climate Action Tool (CAT)[22], which works similarly and allows direct connection to the EC3 database. However, this contains data from North America, so its use in Europe is limited. The tool is currently in Public beta and is freely downloadable. Third example suitable in Europe is a French CoconBIM[23]. This tool can work directly with IFC format.

The German software CAALA[24] allows for design optimization at an early stage of the project. It specializes in shoebox models and links them to conceptual design, for example, using Rhinoceros. In the early design phase, the Cove.tool[25]. This tool is used, which enables design optimization based on embodied carbon.

2.6.3 Process Automation

Following on from the previous chapters, a significant potential to make the process of using BIM models for the environmental analysis of buildings more efficient lies in the automation of the whole process. To achieve this, it is first necessary to standardize the process and develop a methodology for subsequent reuse using computational algorithms. This thesis should lead to this goal. At the same time, the methodology must include the use of a classification system so that the different parts of the model can be uniquely identified to aid in the automation itself. The automation process can consist of matching the database

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[22] https://www.buildingtransparency.org/tally/tallycat/

[23] https://www.cocon-bim.com/

[24] https://www.caala.de/

[25] https://cove.tools/

from the model with the environmental database. This process can be structured in various ways from low structured (manual workflow) to highly structured data which brings possibility of automation. The schema of highly structured is shown in Figure 29. The figure is taken from the paper BIM and Automation in Complex Building Assessment.

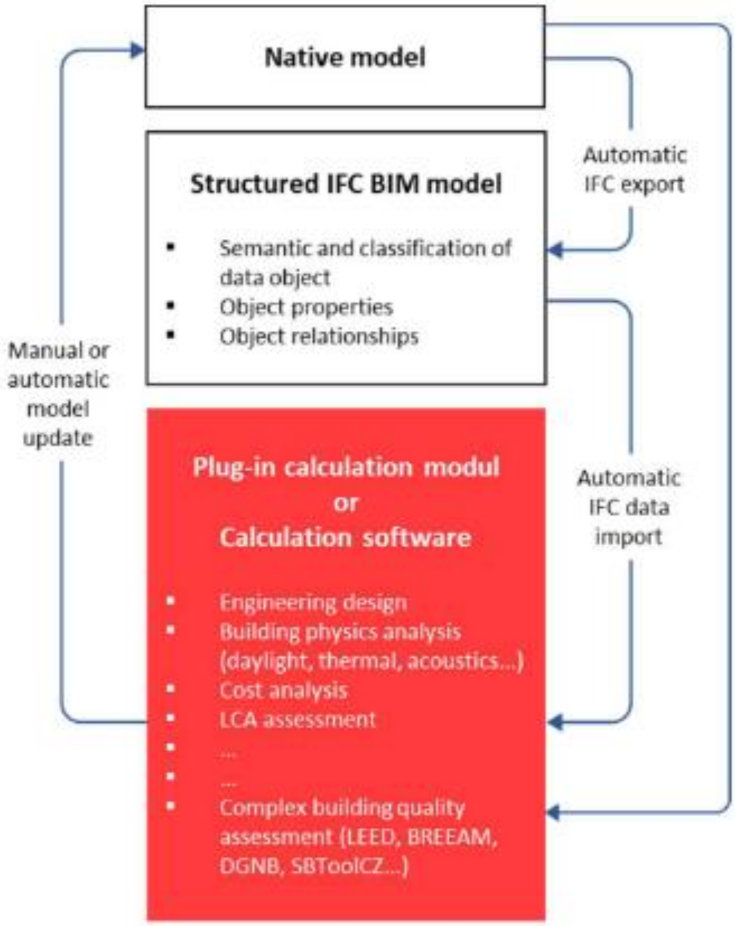

Figure 29 - Schema of highly structured data [66].

The One Click LCA (described in 2.6.2) software partly uses these principles, but the results are still sporadic. Of the few projects counted, 5-10% of the materials have been recognized, so a considerable number of manual steps are still needed.

The next logical step is to simplify the described processes using the software. This should have the following features:

- The ability to import a database of environmental impacts.
- The possibility to work with different types of statements of dimensions (volumes, areas, weight).
- Compliance with the standards that LCA specifies [21], [50], [51].
- Transparency of the calculation process.
- Understandable user interface.
- During the design process of a building using BIM, the model can be used for environmental analysis of the project. However, it is necessary to prepare the model for these purposes. The most important requirement for the

model is the Bill of Materials (BoQ), which is used to calculate the Embodied Carbon values [67].

2.7 Situation in the Czech Republic

The first discussions about BIM in the Czech Republic started before 2010. One of the first Czech-language publications was *Foundations of BIM Implementation on Czech Construction Market*, written by Petr Matějka et al. at Czech Technical University in Prague in 2012 [68]. The authors describe general principles of BIM process and its benefits in various use cases along the construction process. The topic of sustainable construction and potential benefits which could be taken out of the BIM process are already mentioned in this publication. The next important milestone was publication written by Martin Černý et al [69]. Today, both publications are no longer actual and relevant. But almost 10 years ago, they were important foundations for the discussion. Especially the second cited one. Another publications describes BIM from the perspective of the investor in the Czech building environment. BIM Příručka pro investory (BIM for investors) [70] and BIM pro veřejné zadavatele (BIM for the public investors) [71].

Building information modelling is an intensively emerging trend in the construction industry, which aims to streamline the entire industry to the level of the mechanical industry (so-called Construction 4.0). This is done both through 3D modelling of the building, but especially the information value of the entire model.

As with any model, it is of course a matter of information representation and to some extent a simplification of reality to the level of a computer model. This should help us, among other things, in:

- increasing the quality of the project, detecting most of the errors in the design phase;
- increasing the accuracy of the reports;
- providing an analytical basis for decision-making;
- optimizing the proposed solution.

Due to the above-mentioned reasons, it is very important to have the information we need in the model at each given stage of its life cycle. Logically, it is not advisable to have a lack of information in the model, but an excess of information can cause problems (computing power, comfort of work ...) and we are not able to use the model realistically and effectively. The model thus often becomes unnecessarily complex and opaque. Another advantage of modelling that is often mentioned is the reduction of the cost of project documentation and the acceleration of its production. Given the complexity of implementing BIM in practice, it is still too early to objectively assess these savings across the industry. The point of the model is, among other things, that we can analyze it and then make decisions based on that analysis leading to more efficient design, construction and later operation of the building. This is the direction in which the work will continue.

In each phase of the project documentation, we have clearly defined, using LOD (sometimes also referred to as eLOD or iLOD for geometric or informational accuracy) and in which we define how structured and detailed information is to be inserted into the model in that phase.

A document that clearly defines the information to be included in the design documentation, including the precise definition of the various parameters and formatting of the information, is called a BIM Execution Plan (BEP). Based on a number of interviews with BIM managers from various companies, it was concluded that this is the main reason why individual companies are switching to BIM solutions, even though the market is often not yet pushing them to do so.

It is only necessary to focus on increasing the accuracy of the reports (which of course goes hand in hand with the aforementioned increase in the quality of the model or project documentation as a whole). However, this point (if done technically correctly) can be used very successfully throughout the entire preparation and construction phase of the actual building. In particular, it is necessary to use the correct classification systems so that the building can immediately take over all the data from the model.

This is where the untapped potential in the field of information modeling lies. The market is now at a point where it is possible to model seamlessly (this applies to both building and occupational models) and the time is coming when models will need to be 'mined' and the knowledge gained used to make effective decisions across the building lifecycle. However, in order to do this, a systematic approach is needed to prepare the models for such data analysis.

Based on the previous analyses, it will be easier to design an optimal solution, but the optimization itself is not a planned part of this work. Based on the previous paragraph, we can very easily make a decision that is consistent with the objectives (e.g., saving money, material, or environmental optimization). It is therefore necessary to write a methodology for data analytics of information models according to general practice and current legislation.

Czech BIM Council

Established in spring 2011. The main purpose of the organization is to spread awareness within the professional community by bringing together experts, publishing and organizing professional conferences BIM DAY, which has been running since 2013. Part of the Building SMART organization, collaboration with foreign partners.

Classification system SNIM

Other important activities of this association include the development of the SNIM (set of non-graphical information model) classification system. This was developed with the support of several commercial entities and is currently used in a number of projects. This classification system is aimed primarily at the design practice. From 2022, the licenses for loading and further development are transferred to the Czech Agency for Standardization. It is no longer being developed.

Czech Agency for Standardization

On 11 September 2017, the Government of the Czech Republic approved the Concept for the introduction of the BIM method in the Czech Republic and thus made it clear that it is counting on the introduction of the BIM concept.

This concept directly mentions the problematic nature of the ambiguous data structure of the model: "Standardization of the data content stored within the BIM model is much more complex. There is no uniform standardization within the EU, so Member States have to address this issue at national level. The defining input for this standardization is the detail of the model, i.e. the exact project phase for which the model is being developed. Above all, it is necessary to determine the purpose of the model. At present, due to lack of standardization, it often happens that models are required in too much detail in relation to the intended use of the model, which may have a negative impact on the spread of the use of BIM in the Czech Republic."

From the above mentioned documents it is clearly evident that there is a need in the market for the development of a data structure in an information model and also for the development of a methodology that would help in the successful application of this structure with emphasis on comprehensive building quality assessment The author believes that this dissertation could contribute to the solution of this issue.

The BIM concept in the Czech Republic was approved by the Government of the Czech Republic in 2017. Since then, the agenda for the preparation of the legislative framework has been directed by the ČAS agency, specifically the BIM Department. This agency operates within the ÚNMZ, which is responsible for the development of standards for the Czech environment. Both institutions operate under the Ministry of Industry and Trade (MIT). The agenda of ČAS overlaps to some extent with the czBIM organisation. In addition to the above, ČAS also organises conferences for the professional public and the state administration.

Classification system CCI

This classification system Construction Classification International (CCI) is aimed primarily at building managers, which implies that the structure of the classification system contains more levels than the SNIM system mentioned above. The application possibilities are therefore wider and it is more suitable for machine processing. On the other hand, the longer structure makes the system more difficult to read by humans.

This classification system describes various entities of the building project:

- Class;
- Subclass;
- Type;
- System;
- Element.

It can describe all the elements, processes, and other project entities that must be classified in great detail. The system is freely available on the Czech website.

Data Standard for Construction

In addition to the above-mentioned classification system, the Czech Agency for Standardization is responsible for the development of the so-called Data Standard for Construction (DSS). This activity aims to digitalize the construction process, including the Building Permit. Currently under review and expected to be issued in the near future.

Methods of use

The so-called Usage Modes are a concept of work that is widely used within the data standard. It is based on the fact that each construction project is inherently complex and unique, so each builder may have different intentions with the project (and therefore with the information model). These intentions should be defined in the initiation phase of the project by selecting from a predefined list prepared by the Czech Agency for Standardization, with each selected use bringing with it requirements for the graphical and non-graphical aspects of the information model. The aim of this thesis is to show the possibilities of use in the Czech Republic, which includes the definition of one of the uses of the models for environmental calculations.

2.8 SWOT Analysis of BIM-LCA

Strenghts

- Project accuracy (fewer errors, consistent outputs, uniform reporting).
- Integration of information into the digital model and resulting greater project utility. If I have a model full of information, I can also use the data during construction and in the operational part of the building.
- Clarity, unambiguity, and speed of incorporating changes, elimination of duplication, also more visual and understandable for the layperson.
- Easier communication between all participants in the construction process.
- More comprehensive information (shape and attribute).
- Possibility of analytical work with information thanks to its centralisation.
- Complexity of changes, where the change is always addressed with all the continuities (not only the change in the floor plan is addressed, but also the change in the downstream structures, leading to a safe design).

Weaknesses

- Implementation required, which costs money, training people and process changes.
- If people learn BIM and it doesn't suit their corporate environment, they can easily find employment elsewhere.
- Higher time requirements for initial input in creating the base model.
- High expectations due to marketing especially by software vendors. Often 100% cross platform compatibility is expected but is not and the IFC format is also not ubiquitous.
- The need to learn to think and reason in 3D is not easy. BIM places higher demands on both spatial imagination and analytical thinking.

- Changes and their speed - due to the complexity of dealing with changes, it takes longer.
- Current tools - none of the tools available are full BIM because BIM is not about creating a model, it is about the whole process. BIM should be equal to PLM in engineering, but so far we are only addressing the design part.

Opportunities

- Competitive advantage (there is a demand for companies and people who know BIM, which will continue to grow).
- Marketing, PR ("BIM Ready" sells).
- BIM model is more open to external collaboration and teamwork as such.
- BIM is leading to the progressive automation of the construction industry.
- Greater efficiency with respect to safer budgeting and planning.
- More effective communication if the "BIM language" is well defined (now a large number of "dialects").
- Social aspect, there are many designers in practice who have started to enjoy designing again thanks to BIM. It also happens that younger (and often therefore more technologically savvy) people are forced to collaborate more with older, more experienced ones and there is a valuable transfer of experience.

Threats

- Technology has outpaced legislation; for example, the fee schedule does not meet the requirements for model making.
- The investment may be recouped in the longer term (or not at all if there is commitment during implementation).
- Inconsistency of elements, significant differences in libraries, inconsistency of information contained in libraries.
- Expected equivalent of graphical outputs as in 2D. Examples are e.g. developed sections in BTI. Not everything done in 2D is needed. The habits and thinking in 2D, where a company is using BIM to try to achieve the same outputs as it was used to in 2D, can make a project unnecessarily expensive and/or put people off.
- The discipline required of people working on one project, or the way it is easy to incorporate changes into all related parts, can easily breed mistakes if the team is not sufficiently aligned.
- People and their generally low appetite for change.

3 Proposed methodology

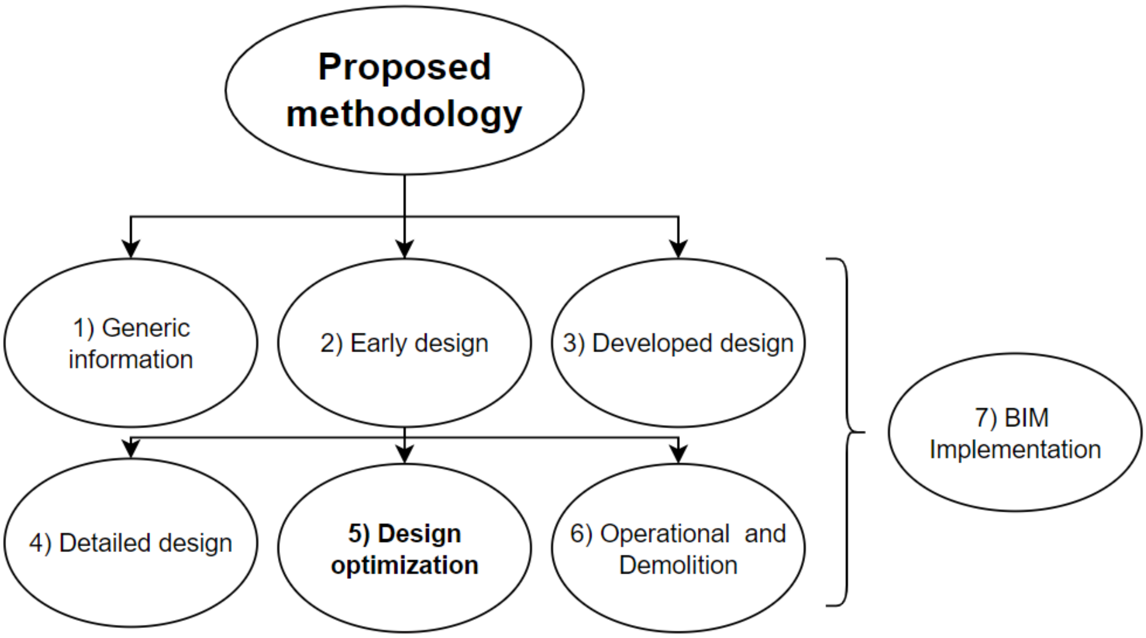

Figure 30 - The methodology overview (author´ s archive).

The following chapter describes the use of BIM models in different phases of the project (early, developed, and detailed design), the information requirements in each phase, the possibilities of using them for project optimization, the possibility of automating the processes and the possibilities of implementation in a commercial environment by implementing the requirements in the prescribed documentation.

3.1 Model for purposes of the environmental assessment

3.1.1 Generic overview

The calculation of the environmental performance itself is simple. The quantity in the reference unit (usually kg, or m, 2, or even m3) of the material is multiplied by the environmental impacts of the material for the selected LCA modules. The difficulty of this task lies in the following:

- Estimating the uncertainty in the model, which varies according to the project's phase and the project's quality.
- Model simplification in each proposed phase (including the detailed one).
- Consideration, which LCA modules supposed to be in the assessment.
- The quality of the environmental data used and included in the calculation and select the proper source for generic data (Ecoinvent, Envimat, etc.) or EPD.

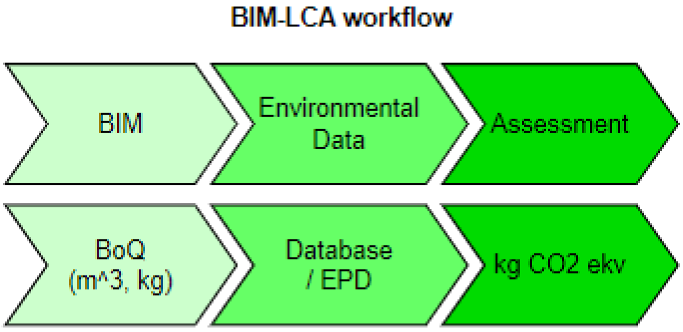

Figure 31 - Schema of the BIM-LCA workflow (author´ s archive).

A comparison of the different phases is shown in Figure 32.

Project Phases			
	Pros	Cons	Environmental Data
Early Design Architectural Study (LOD 200)	• Fast Results • High Optimization Potential • Potential for BIM	• High Uncertainty • Programming Skills Required • Aggregated Database Needed	• Aggregated Database
Developed Design Building Permit (LOD 300)	• Highest Potential for BIM • Lower Uncertainty • More Reliable Results • Automation Potential	• Specific Assessment of Certain Elements (e.g. Windows)	• Generic Database • Environmental Product Declaration
Detailed Design Shopdrawing Phase (LOD 350-400)	• Lowest Uncertainty • Precise Results	• No Optimization Potential • Time Demanding • Low Potential for BIM	• Environmental Product Declaration • Generic Database

Figure 32 – Comparison of possibilities of using BIM in environmental assessment in various project phases (author´ s archive).

3.1.2 User parameters

Depending on the project phase (early design, developed, and detailed) and the considered LCA life cycle modules, the basic information already contained in the BIM model can be supplemented with additional information using so-called parameters. These include many generic data types, e.g., boolean, string, number, integer, or building specific, e.g., velocity, current, and many others. So it is up to the user to decide what information, or parameters, to put into the model.

The essential requirement for calculating embedded CO_2 emissions is to know the quantity of each material according to the so-called reference unit. It means the unit for which the user obtains reliable environmental data. It is often the kilogram, volume, m^2, m^3, or number of pieces of a certain element. It is, therefore, necessary to integrate as many physical properties of all materials as possible into the model to calculate these reference units.

Suppose the user decides to include LCA modules of type B (operational part of building's life cycle). In that case, it is necessary to integrate parameters describing the lifetime of individual materials, building products, and other elements into the model.

3.2 Early Design

At this stage, the exact technical specifications are not yet available in the project, on the other hand, it is easiest to make any decisions about the project. Therefore, it is important to have the most accurate estimates, which is not only true in the context of environmental assessment, but in general. The aim of this phase is to make decisions about the project. Some of these decisions may be guided in the future, but many are irreversible. It is therefore important not to underestimate this phase of the project and to pay maximum attention to it.

Similarly to the monitoring of financial flows and cost estimates, the environmental assessment makes use of so-called aggregated items, which are derived from detailed specifications and the values can be converted into variables that are already known at this stage, such as basic information about the project (typology, floor plan, location, structural system, etc.). And volumes, areas (built-up area, construction areas), are available.

3.2.1 Model Requirements

In this part of the project, there are two types of models: the shoebox model (LOD100), or the element-based simplified model (LOD200). In both cases, however, the exact compositions of the individual structures and other structural, and technical details are unknown. Both types of models are shown in Figure 33. From the model, it is thus possible to export basic information such as the volumes of the individual construction objects, the gross floor areas, the areas of the translucent and opaque parts of the façade, and the resulting Window Wall Ratio (WWR). This information is in the model by default, therefore there is no need to add any information.

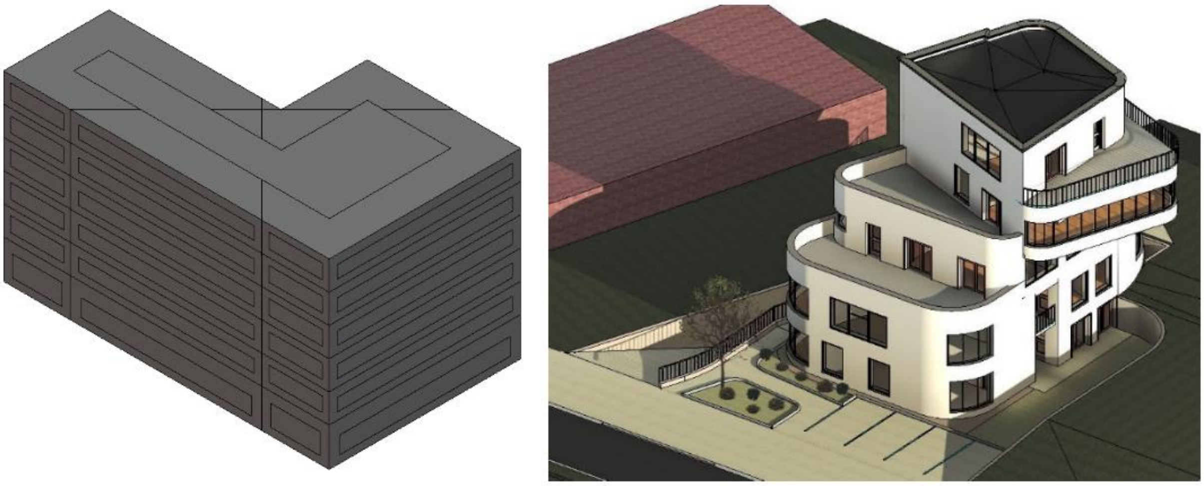

Figure 33 - Two possible types of the model in early design phase [72].

3.2.2 Environmental Data Requirements

A key factor determining the calculation quality at this stage of the project. Exact material and structure design is unknown, therefore, generic data such as Ecoinvent are not possible to easily use. It is necessary to have an aggregated database of the construction compositions used so that the environmental impacts can be calculated not as the sum of the individual elements, but in the aggregate, for example, per square meter of the structure or cubic meter of the built-up area. This system is similar to that used for building valuation, except this data is not widely available.

Within Central Europe, the Bombyx tool [54] developed at ETH Zurich can be used. It is based on data for Switzerland, so accurate results cannot be assumed. Thus, in addition to the uncertainty given by the early design, additional uncertainty is automatically added to the calculation. These results cannot, therefore, be reasoned with precisely. Still, for example, for comparing variants (e.g., different types of facades, structural systems, or building shapes), this tool can be used without any problems.

3.2.3 Design Optimization

This phase of the project provides the most significant potential for optimizing the design of a given proposal. Optimization can be divided into material optimization (using materials with a lower environmental impact on production or, conversely, with a longer lifetime to compensate for these negative impacts) and spatial optimization (adjusting the shape of the building and the resulting potential for using less material. For these requirements, boundary conditions need to be defined, and an algorithm developed.

For these purposes, an iterative process consisting of a number of sub-steps should be used. A parametrich design in visual programming environment (Grasshopper, Dynamo) can be used to great advantage, which can "translate" these algorithms into a BIM environment. Modules for Generative Design (Chapter

2.4.2) are now available, allowing direct optimization based on user requirements. The success of such optimization is conditioned by higher requirements on programming knowledge and especially on the aggregated environmental database. With the latter, spatial optimization can be performed, but the environmental impacts of a given project can be determined.

3.3 Developed Design

At this stage, a number of details regarding the construction and technical design and other details of the building are already available.

The basic definition of any model is that it is a simplification of reality. Although at a more detailed stage of the project (in the Czech Republic, the level for building permits or shop-drawing documentation), which in the level of model development (LOD) corresponds to details 300-350.

3.3.1 Model Requirements

This is the most frequently used phase of project documentation based on a BIM model, so the experience with creating such models is the greatest. If there is a requirement to use it for environmental analysis, the model must be prepared. To make the workflow as smooth as possible, it is necessary to have as much detailed information as possible about the individual materials and their quantities in the structures. In particular, the reference unit for calculating environmental impacts is kilograms, so it is advisable to include volumetric masses in the model to calculate the mass as accurately as possible.

Suppose it is envisaged to use the model for the LCA modules B (operation phase of the building). In that case, it is also necessary to include information on lifetimes in the model at the level of individual materials or building products.

Despite this higher level of detail, many parts of the model are still greatly simplified. The most significant are façades. This part of a building is one of the most important for the architecture and the most expensive part. In addition to helping to shape the architectural expression of the entire building, it is a complex skeleton that must meet several conflicting requirements (thermal, structural, etc.). At the same time, it is one of the most significant investments in the entire construction. The number of panels, their areas and lenghtsa of the frames can be used. But the critical simplification is related to frame profiles, because they are always simplified and profiles neglect bearing frame in it (steel, aluminium, etc.). Example of commonly used window is shown in Figure 34.

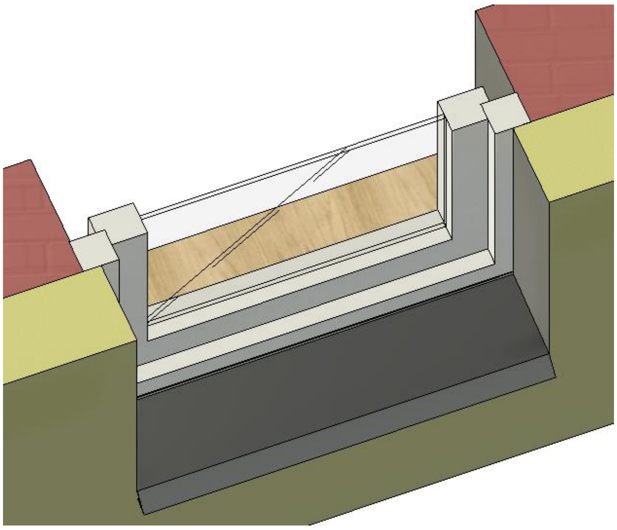

Figure 34 -Typical window in the BIM model in developed phase of the project (author´ s archive).

For an accurate calculation, it is advisable to use the production documentation of a specific part of the façade (module) with detailed drawings, based on which the environmental impacts are determined for the entire façade.

Other the most typical simplified elements which need a special effort are:

- Timber structures – missing elements (two by four system etc.);
- Installation drywalls - missing profiles;
- Façade - glazing, frame;
- Ceilings - missing elements
- Air gaps in walls - framing system;
- Windows - glazing, frame;
- Doors – frame;
- Installation layers, aluminium or wooden profiles, insulation layers.

Another category with high uncertainty are building services (MEP). These elements are partly simple (duct and pipes) and partly complicated elements which consist of many materials and parts.

- Equipment – unknown details about materials;
- Accessory – unknown details about materials;
- Duct – impact per length of certain dimension;
- Pipes - impact per length of certain dimension.

Preparation of the models in developed phase of the project needs some extra effort, but it can be very beneficial.

During model building, it is essential to use a classification system to help organize the model according to its parts. This is important for assigning partial lifetimes (the same material in a different location has a different lifetime). The specific type of classification system does not matter.

3.3.2 Environmental Data Requirements

At this stage, the possibilities regarding the use of environmental data are the most comprehensive. Both generic databases (Ecoinvent, Envimat, etc.) and EPDs can be used. The environmental analysis should include an item-by-item summary so that it is possible to trace back which values for specific impacts have been used, and the combination of generic data and EPDs should always be adequately justified.

Data for the Czech Republic are also available, often freely. The database of available EPDs is maintained by the Ministry of the Environment of the Czech Republic through the Czech Environmental Information Agency (CENIA). The Envimat[26] database is freely available (although already somewhat outdated) and freely accessible after registration. If it is necessary to model a material or product for which data are unavailable, specialized software (e.g., SimaPro) can be used. In design practice, commercial solutions such as One Click LCA can also be used to advantage. However, the disadvantage is the low control over the calculation details and the high cost of this product. Extending this solution massively, for example, in the single-family home sector, is unrealistic.

3.3.3 Design Optimization

At this stage of the project, it is possible to create different design variants to optimize the entire design, especially from a material point of view. This can be done either directly in the BIM by changing individual parts of the model or editing items in the environmental database. The first option is more accurate because if the structural system is changed, for example, the individual cross-sections of the elements and the resulting material volumes should also be changed. On the other hand, this solution is more labor intensive, so it is always necessary to define meaningfulness. The principle is always the same, i.e., the multiplication between quantity (volume, area, weight, etc.) and environmental impact (materials). Another option is to use the tool directly. For example, the One Click LCA software allows the creation of several variants within which both options, i.e., volumes and materials, are varied. By successive iterations, the material design of the building can thus be optimized.

3.4 Detailed design

3.4.1 Model Requirements

The design aspects are known at this project stage, and the last technical details are being worked out. These are the shop drawing or production documentation. This area of the project is specific to BIM models. Although it is a very detailed level, it is often simplified in the models. This is mainly due to the high modeling effort (workload), the computational complexity of working with these models (computer performance), and the low efficiency of using these technical details in later phases of the construction life cycle. These models are generally much more po-detailed than the previous phases of the project are so often. The example is shown inFigure 35. Yet they tend to be simplified, and details are only solved in 2D. Therefore (as in the Developed design), it is not possible to use volumes, pieces, and another Reference unit to match with environmental data

[26] http://envimat.cz/

automatically. Exporting data from a model should always be approached with discretion, carefully weighing all potential problems. The exact requirements of the model vary from project to project. They are always described in the contractual relationships between stakeholders in documents EIR (Requirements) and BEP (Description of achieving those requirements).

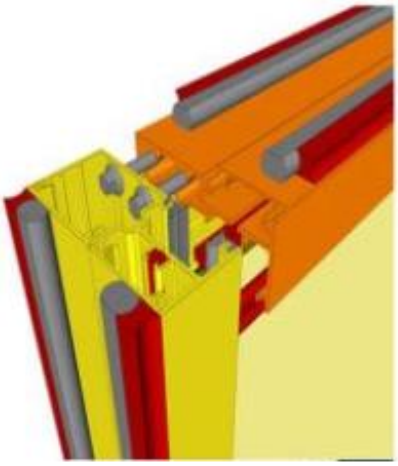

Figure 35 - Model in LOD 400 [73].

3.4.2 Environmental Data Requirements

Due to the knowledge of all the technical details of the design, the environmental impacts can be calculated very accurately. However, the usefulness of such a detailed calculation has to be weighed up, as it can appear to be very time-consuming.

The Environmental Product Declaration (EPD) is a crucial source of environmental data for this project phase. Due to the rapidly increasing number of these documents on the market (companies are starting to see EPDs as their competitive advantage), tracking down the vast majority of building materials and product elements is not a problem.

Due to their structure's standardization [49], [55], these data's rapid expansion can be expected. For example, the commercial software One Click LCA uses this database (including data for the Czech Republic) regularly.

If the required EPDs cannot be traced, a generic environmental database can be used, or specific environmental impacts can be calculated using specialized software (e.g., SimaPro).

In some special cases, a special solution is available for various applications. For example, façade manufacturers such as Saint-Gobain of Wicona offer special software in which details can be designed and production documentation generated. This software also offers a feature for calculating the environmental impact of a specific element (glazing, aluminum alloy, etc.). This workflow can be very valuable for practitioners, but of works as a Blackbox without complete control of the assessment.

3.4.3 Design Optimization

The optimization possibilities are from all the phases the lowest, but even in this case, the construction project can be influenced in a very positive way. All details of all components of the building are known so that the focus can be on material optimization. Manufacturers of building products and materials are currently focusing on this issue, and, for example, EPD certificates are becoming a standard part of the available documents. The client can thus focus on environmental aspects in the procurement of specific materials and products. Thanks to competition in the market, savings of tens of percent can be achieved in this area for individual building materials. For example, aluminum producer (very energy-intensive to produce) Wicona [74] (see in Figure 36) has recently streamlined its production process and launched innovative products that use recycled aluminum and thus achieve a fraction of the environmental impact compared to conventional aluminum.

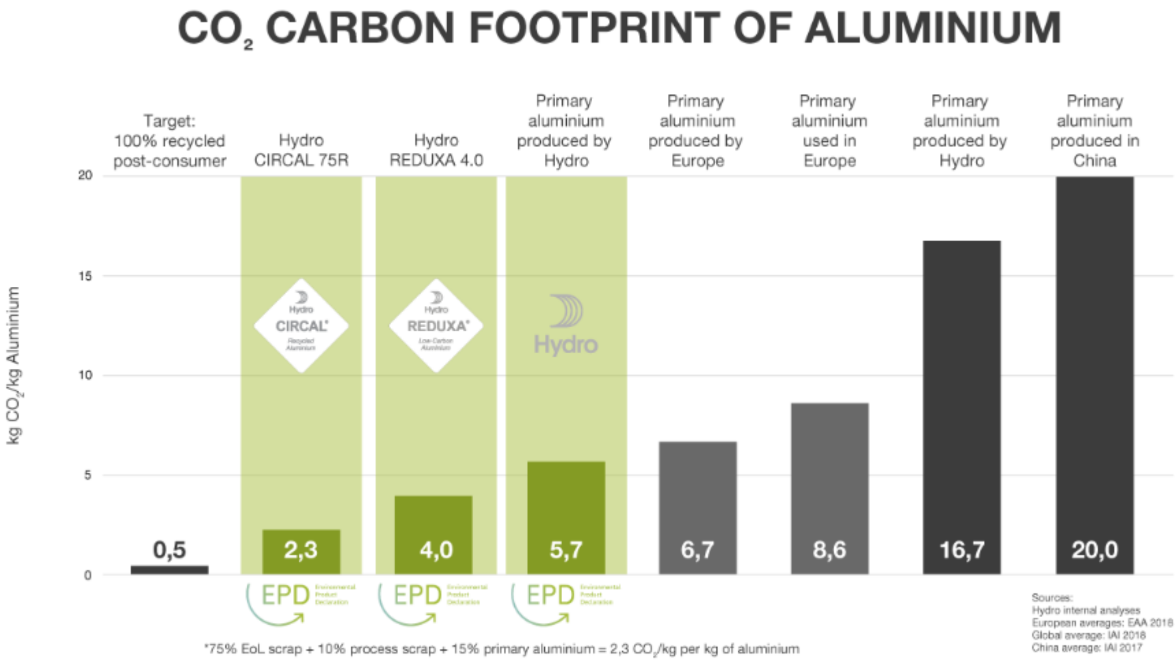

Figure 36 - Comparison of aluminium production [74].

3.4.4 Unit control

The last point that needs to be addressed is the project units; in Czech conditions, they should be derived from the SI system. The units, if inappropriately chosen, or if, for example, the project is transferred across countries, can cause significant problems or inaccuracies in the process. The basic units are usually fine (length, area, volume), but the project also contains many derived units (volume mass, heat fluxes, etc.). It is advisable to check all units (automated or manual) before using the model for environmental calculations.

3.5 Operational Phase

According to the LCA methodology, this project phase is discussed in Module B and divided into two parts. In the first one, the operational energy (emissions) associated with creating a favorable indoor environment of the building, i.e., its heating and cooling, are calculated. These are given, for example, from an energy calculation (PENB in the Czech Republic). These are multiplied with a specific coefficient to obtain these LCA modules' environmental impacts quickly. BIM models are of no help in this part.

In the second phase, the embodied emissions and those associated with the replacement, modification, or improvement of the parts of it are again counted. The principle is very similar to that of Modules A1-A3. The only difference is that the structure or product's lifetime must be estimated. This can be based on the manufacturer's documents, the assessor's professional estimate, or other sources. BIM models are used the same way as for designing a new building. Only information on the structure's service life, material, p, or product must be included.

The moral lifetime should also be considered; this is particularly important for shopping centers, office space, etc. These can change very frequently, for example, every five years. Depending on the nature of the building, this fact should be considered. The relevant parts of the building (structures, products, etc.) should be estimated accordingly and then fed back into the model.

This part of the life cycle is the longest, so it should be considered.

3.6 Demolition, Recycling, Circular Building Industry

The last phase of the life cycle involves demolition (modules according to LCA methodology C) or recycling potential (D). This phase is currently at different stages of development in other countries, and this topic is addressed in the circular economy framework. An international comparison within the Annex 72 project found that Module C was addressed in approximately half of the 21 countries. The redistribution sub-potential (Module D) has only been discussed b China, Denmark, the United Kingdom, New Zealand, and France. In the Czech Republic, the methodology for this phase is still under development in several research projects. University Center for Energy Efficient Buildings (UCEEB) is involved in this development.

Suppose the BIM models contain all the parameters and information needed for the previous phases (modules according to the LCA methodology). In that case, they can also be used for this demolition or recycle potential phase. It is therefore considered necessary that the models contain information on the materials used and their quantities even during the operational phase of the building.

There is a research project involving the UCEEB to develop a tool to predict building quantities for me if their BIM model is unavailable.

4 Case Studies

4.1 Early design phase

In early design phase all decisions having a significant impact should be taken within various stakeholders and based on reliable data. This creates a significant demand for simplified (aggregated) databases which are based on volume or area. Due to the fact that countries have various energy mixes and LCA databases, this data should be national based as well.

4.1.1 Building Mass Optimization using Generative Design

This project was developed during a study internship at ETH Zurich under the supervision of Prof. Guillaume Habert, Deepshi Kaushal, and Alexander Hollberg. The purpose was to investigate the use of generative design in building optimization from a sustainability perspective. A combination of Revit, Dynamo, Generative Design, Grasshopper, and Bombyx was used for this process.

In Revit, a simple volume was created and assigned the parameters Length, Width, Height, Window/Wall Ratio (WWR), then the thermal engineering parameters of the individual structures. The floor area of the whole building was also developed. Based on these parameters, a script was created in Dynamo to allow editing them, and a connection to the Generative design tool was made. Based on this, several hundred design variants were created that meet the edge subconditions. The goal was to maximize the floor area while efficiently using the given mass. A sample of the generative design is shown in Figure 37

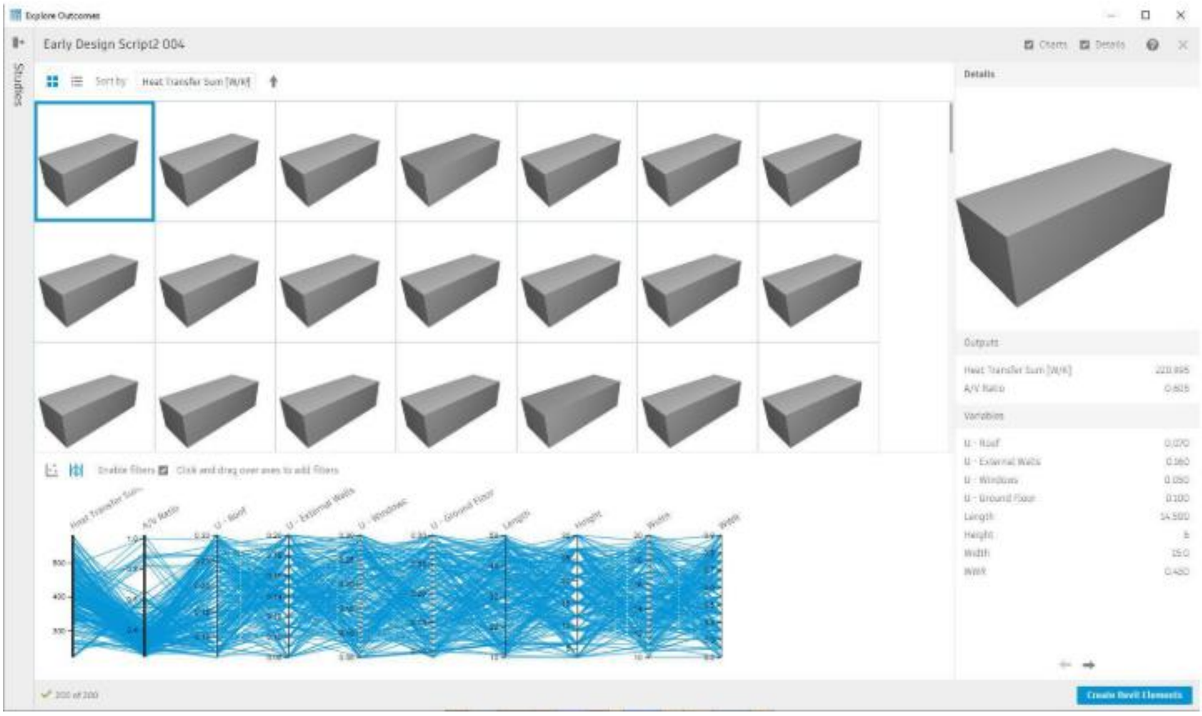

Figure 37 - Generative design tool (author´ s archive).

The next step was manually selecting the five variants that best met the user requirements for all input parameters (shown in Figure 38). These few variants were then sent for environmental analysis to Grasshopper, a tool created in this software: Bombyx. This tool was developed at ETH Zurich and contained aggregated environmental data for typical structures. A script was created for this study that qualitatively evaluates the whole building and includes the calculated areas of the individual systems. This enabled an environmental analysis of all five options and the most appropriate one to be selected. Example of such evaluation is shown in Figure 39.

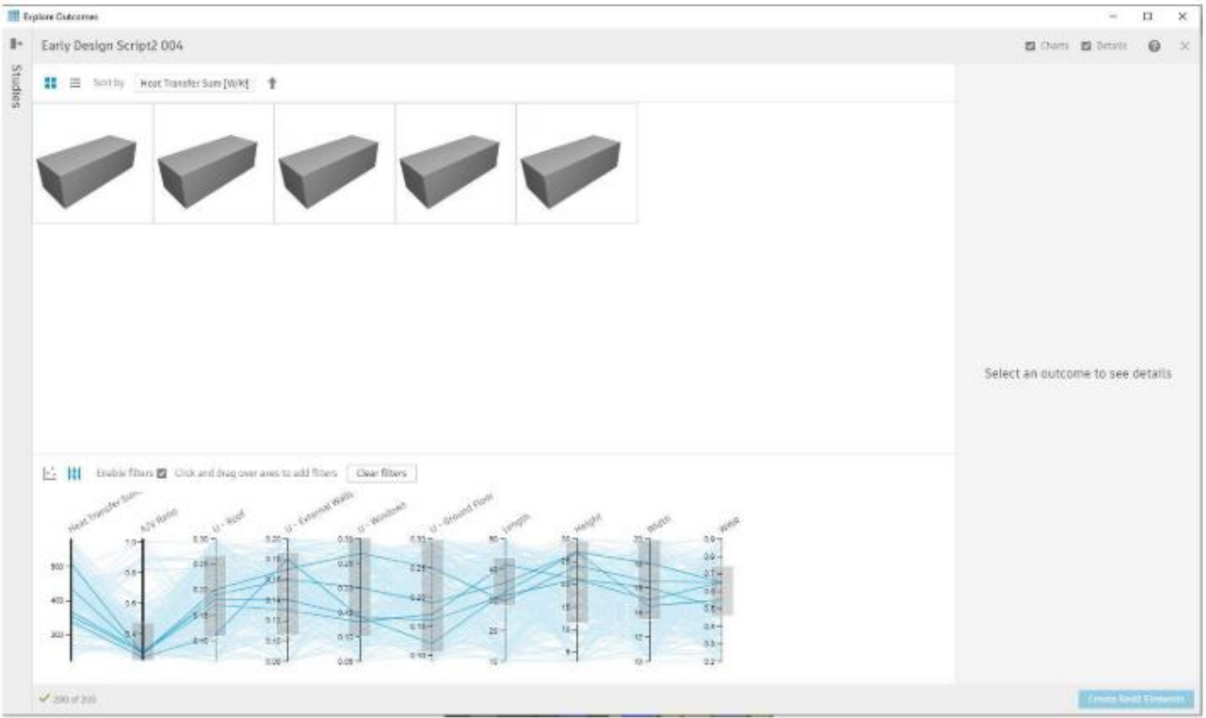

Figure 38 - Five selected variants (author´ s archive).

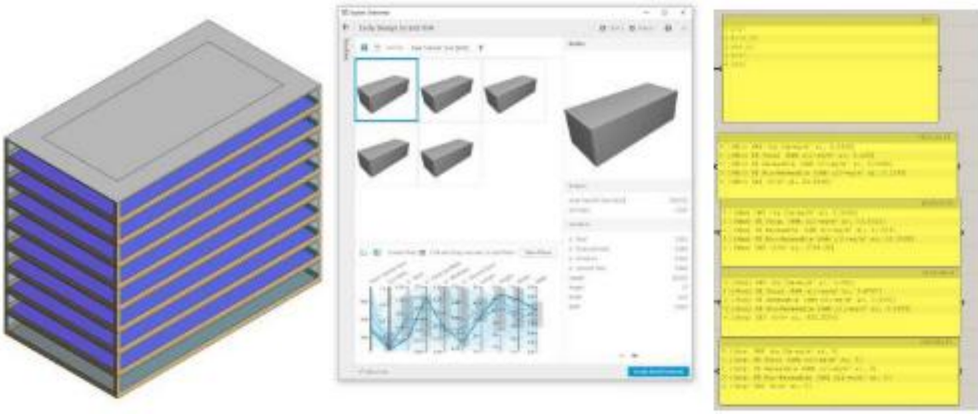

Figure 39 - Evaluation of a building mass (author´ s archive).

The study demonstrated the value of environmental analysis in the early design phase of the project. It allows the optimization of the shape of the building and thus reduces its environmental impact. However, it is necessary to arrive at an aggregated environmental database. Outcomes of the study were published in the project final report Design-integrated Life Cycle Assessment using BIM (BIM-LCA) [75].

For this study, a simple cube model has been developed; however, for practical use, it is possible to parametrically define more complex masses of a given design determined by the external conditions of a given locality.

4.2 Developed design phase

Following case studies are based on various buildings and they have been assessed within various research project as well, or for this therir itself. These projects are further described in chapter 8. Revit models and BoQ exported in Excel was used in all cases. For the environmental assessment, Ecoinvent and Envimat databases were used.

4.2.1 Experimental building B2226

Experimental office building located in Lustenau (AT). The building is designed without external insulation using two layers of cavity bricks with an air gap. The name of the project refers to the fact that the building is only able to maintain a temperature in the range of 22-26°C all year round using passive technologies and during its full occupancy. It is a five-storey building of roughly cubic shape, which adapts all its form to the above-mentioned objective. For example, the façade is openwork in many places. As a result, the building can only be heated in winter (in the foothills of the Alps) by solar and internal gains.

During the preparation of the project, an information model of the building was also created in Autodesk Revit software, roughly at LOD300 level, and included the architectural and structural part without HVAC and foundations, which served as a basis for the calculation of the environmental impacts within the participants from the different countries. The model included, all structural elements at the level of individual sub-materials. At the time of solving this environmental calculation, the author of this publication was not yet part of the team.

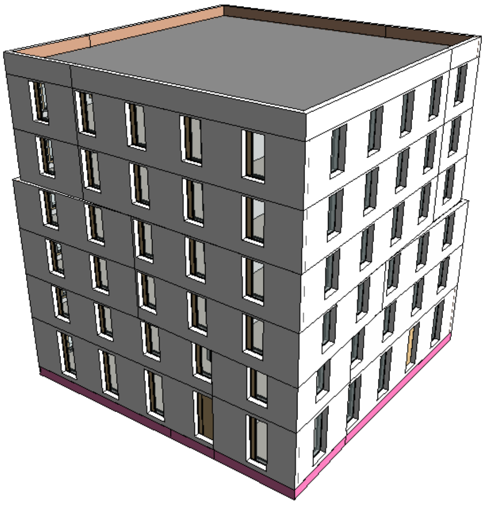

Figure 40 - Model of the be2226 (author of the model: Martin Rock; second figure author´ s archive).

The impacts of embedded and operational were addressed and the study showed significant differences in the calculations made according to different national methodologies. Given that there is no consensus between countries on the consideration of the different LCA modules, the planned lifetime and that the resulting environmental impacts are based on a quarter meter of floor area per year, the results of 10-71 kg CO2 eq/m2a is therefore highly biased. Detailed country results are shown in Figure 41 [76]. The calculation for the Czech Republic was performed by colleagues Pavla Kunova (Rykla) and Martin Volf.

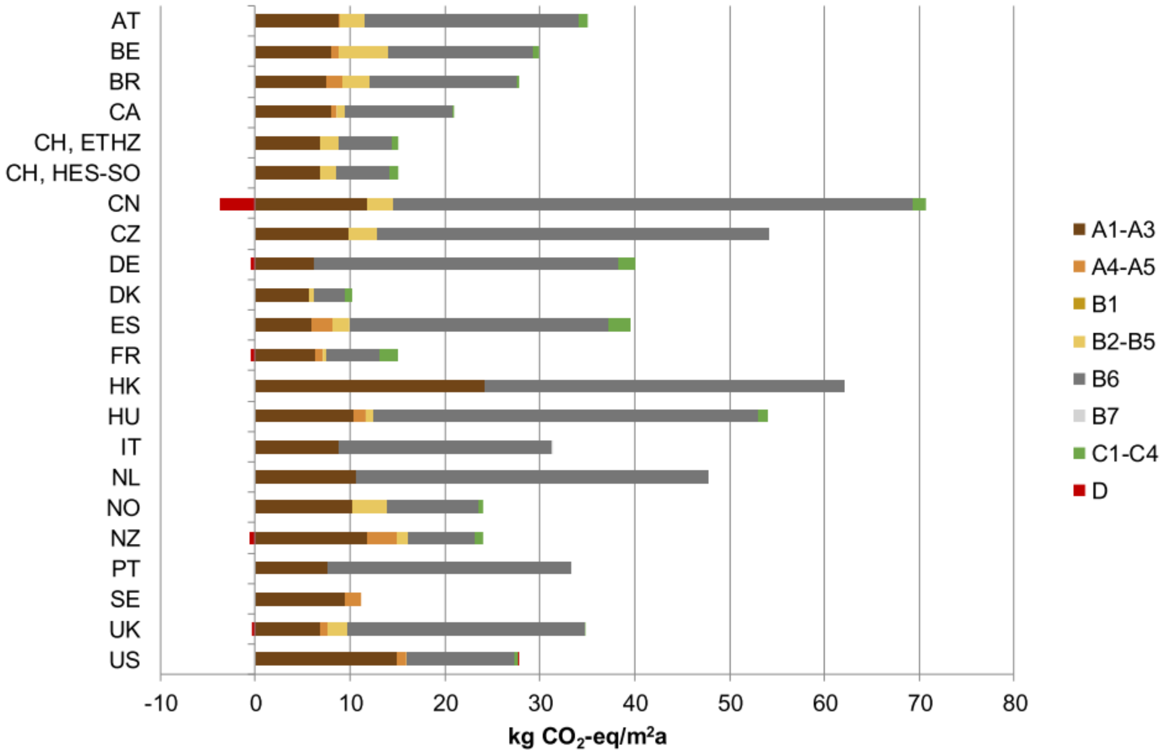

Figure 41 – Comparison of results according to the national methods [76].

4.2.2 High-rise multi-family house

An apartment building in Tianjin, China. It is a typical residential object in this area. With 11 floors above ground and one underground, the dominant material was reinforced concrete and sand-lime bricks. The information model was developed at LOD 300 level. It contained the architectural and structural part, including the foundations. No HVAC models were available.

The classification system of the model was Uniclass2 (originally from the UK). The model was originally developed in the Chinese version of Autodesk Revit software. The names of the system paremeters are automatically translated when the software is opened in another language. However, user-defined parameters are no longer automatically translated in this way. For this reason, the model had to be edited so that the names of the individual materials could be understood. To simplify the use of the environmental impact calculation according to the SBToolCZ methodology, a classification system was added to allow the subdivision of structures and materials according to this methodology. An example of the model is shown in Figure 42

Figure 42 - High-rise building in Tianjin (CN) (author of the model: team of prof. Wei Yang).

This study addressed the impacts of embedded and operational I and the study also showed significant differences in the calculations made according to different national methodologies. Again, it was confirmed that since there is no consensus between countries on the consideration of the different LCA modules, the planned lifetime and that the resulting environmental impacts are based on the quarter meter of floor area per year, the results of 14-65 kg CO2 eq/m2a [77] again show a considerable variance (although less than in the previous case). The calculation of environmental impacts for the Czech Republic was carried out in collaboration with my colleague Martin Volf. Detailed results are shown in Figure 43.

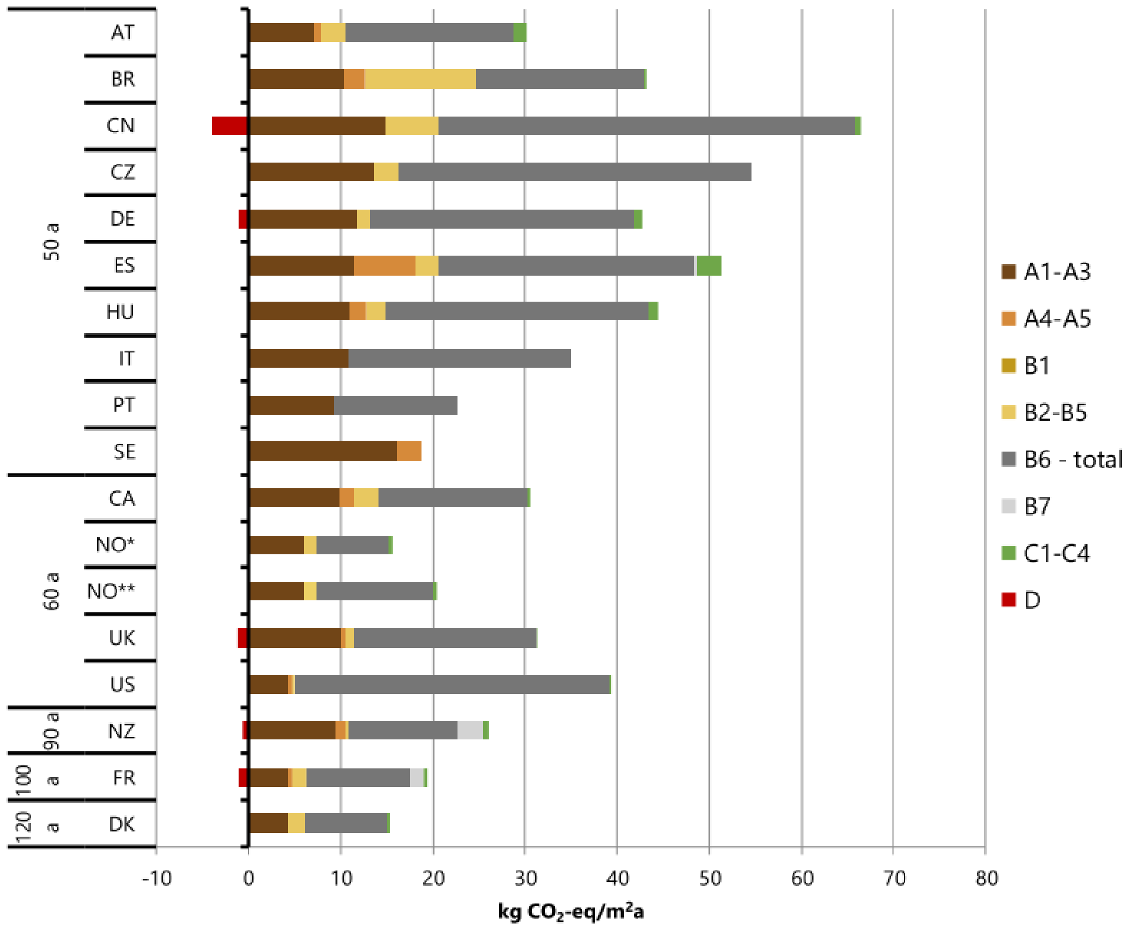

Figure 43 – Comparison of results according to the national methods [77].

4.2.3 Wooden multi-family house PAL6

A six-story apartment building located near Quebec City (CA). The structural system is a lightweight timber frame supplemented with non-combustible gypsum fibreboard elements for fire safety. A model was developed for the project at the LOD 300 level, which included the architectural and structural portion, including the foundations. A model containing the HVAC was not provided. The model had the Uniformat 2 classification system, originally from the USA. The model was available for calculation in IFC format, the bill of quantities based on which the analysis of environmental impacts according to SBToolCZ methodology was carried out based on the bill of quantities generated from the model. The model is shown in Figure 44.

Figure 44 - Multi Family house PAL6 in Quebec City (CN) (author of the model: a team of prof. Claudiane Ouellet-Plamondon).

As in the previous chapters, the resulting values of environmental impacts showed considerable dispersion. The results are 2-12 kg CO2 eq/m2a [78]. The variance, in this case, is due to the differences mentioned in the previous examples to the different approaches in accounting for biogenic carbon (all wood elements). These differences in accessions are the paper's primary focus [79]. The detailed results are shown in Figure 45. The calculation of the environmental impacts for the Czech Republic was carried out in collaboration with my colleague Martin Volf.

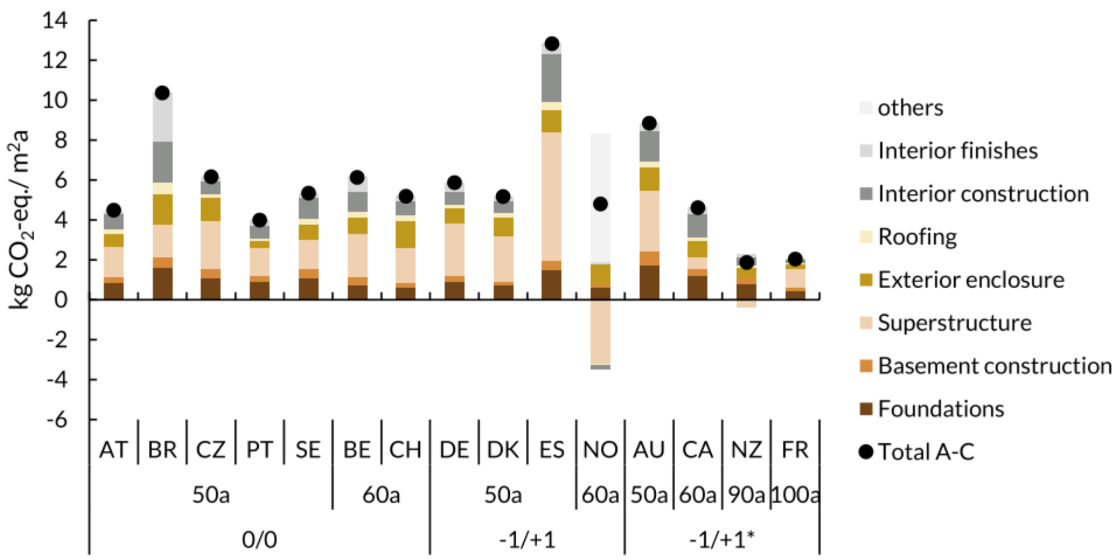

Figure 45 – Comparison of results according to the national methods [78].

4.2.4 Office building Inffeldgasse13

A seven-story office building in Graz (AT). It is a modern object of the University of Graz. The structure is a reinforced concrete frame with a lightweight suspended facade and an internal atrium. The model was created in detail in LOD 300 and contained the architectural and structural parts including the foundations. The model did not contain HVAC elements. Compared to other models, this one contained a lot of extra information, for example, a very detailed description of materials. For non-homogeneous materials, it contained precise composition values (e.g. "98.850%_MS016 concrete (floors)_2400kg/m^3_2W/mK, 01.150%_MS003 reinforcement steel_7850kg /m^3_W/mK(percentage by volume)". This allowed a very precise calculation of the representation of the different materials, from which the environmental impacts are then calculated. However, for this case study, the entire calculation of environmental impacts was not carried out, only a detailed comparison of the different procedures for exporting data from the model and identifying any errors during this process. The model and the real building are shown in Figure 46.

Figure 46 - Inffeldgasse13 building (author of the model: Daniel Plaza)

Although the information regarding the representation of each material was described in great detail, there were differences in the results sent by the different participants. The individual results divided by material are presented in Table 1 and visualized in Figure 47. The calculation of environmental impacts for the Czech Republic was carried out in collaboration with my colleague Martin Volf.

Table 1 Comparison of the results from various participants [m^3].

	MS016 concrete	MS046 aluminium	MS015 screed (2000kg/m	MS010 aluminium sheet	MS003 reinforcement	MS007 mineral wool	MS040 concrete (foundati	MS047 glas	MS017 EPS-W 25	MS008 gypsum plaster	MS022 linoleum	SUM of materials
AT	2174.68	17.76	500.57	11.84	37.12	848.16	347.81	25.31	466.61	325.97	9.46	4765.29
CA	2174.70	9.23	500.56	9.97	37.83	848.21	471.18	28.71	466.63	325.91	9.47	4882.40
CZ	2174.68	17.76	500.58	11.84	37.09	848.17	409.49	25.32	466.57	325.97	9.46	4826.92
DE	2414.39	10.07	652.18	4.55	38.32	774.26	0.00	16.63	669.86	443.75	9.57	5033.58
ES	2226.40	13.42	499.75	9.97	2.32	474.58	359.55	4.62	466.05	325.91	9.47	4392.04
NZ	2174.68	25.86	500.58	2.08	33.50	848.17	347.81	25.31	681.28	325.97	0.00	4965.25
SL	2174.71	15.63	500.56	9.97	37.13	851.71	347.81	59.90	466.63	325.91	9.47	4799.43

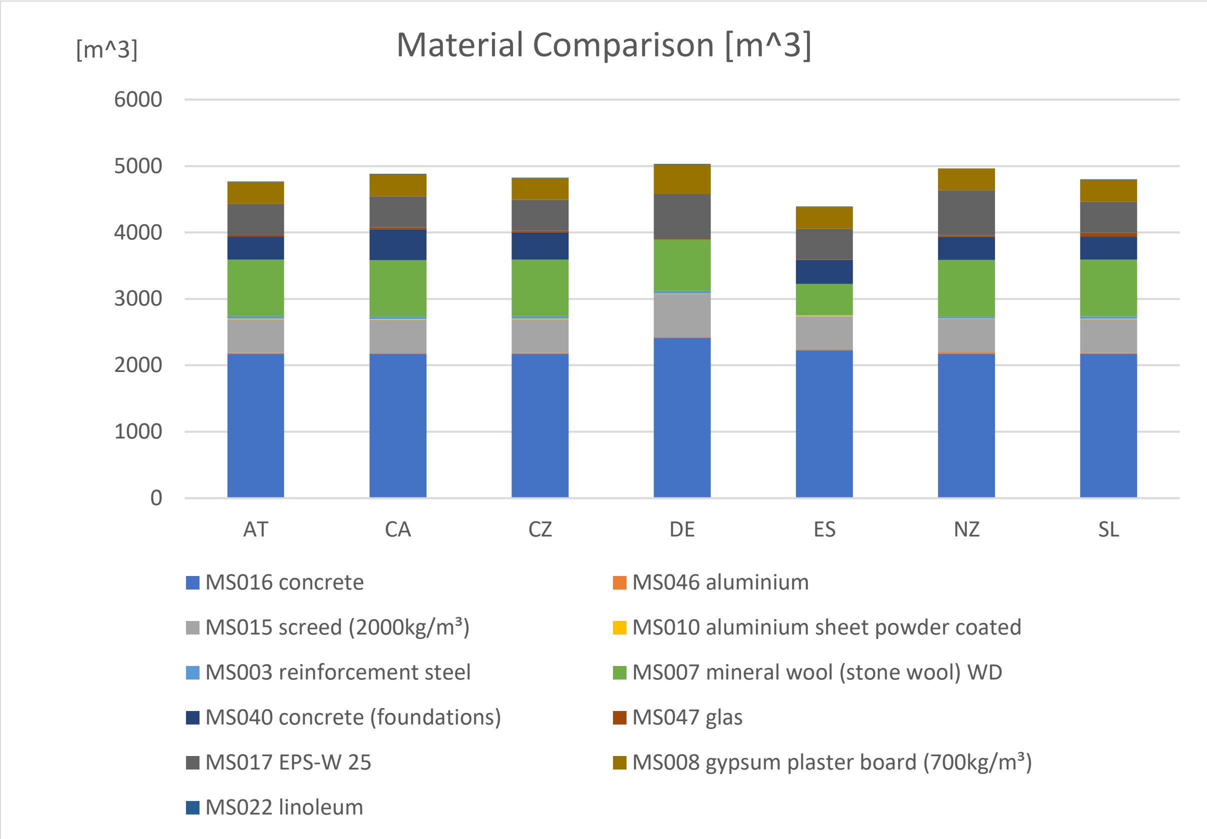

Figure 47 - Comparison of the results from various participants [m³].

This case study shows that despite a very detailed model, misinterpretation of the statement of estimates can lead to very different results in calculating environmental impacts. The quality of the information model must therefore be taken into account. Currently, the research paper describing the whole process in detail is under development.

4.2.5 Multi family house RESBy

These two case studies were developed as part of a project on building resilience. More information about the assignment is given in chapter 0. The project included mapping the building resilience area, a series of innovative elements (solar chimney, self-irrigating façade system, control system, etc.), and designing a methodology for assessing building resilience. Two information models were developed for the project. These differ only in detail at first sight, but a different structural system is used (lightweight timber frame and sand-lime bricks). The models served as a basis for the environmental analysis. This was calculated according to the SBToolCZ methodology. My colleague Pavla Kunová (Ryklová) performed the actual environmental impact calculation.

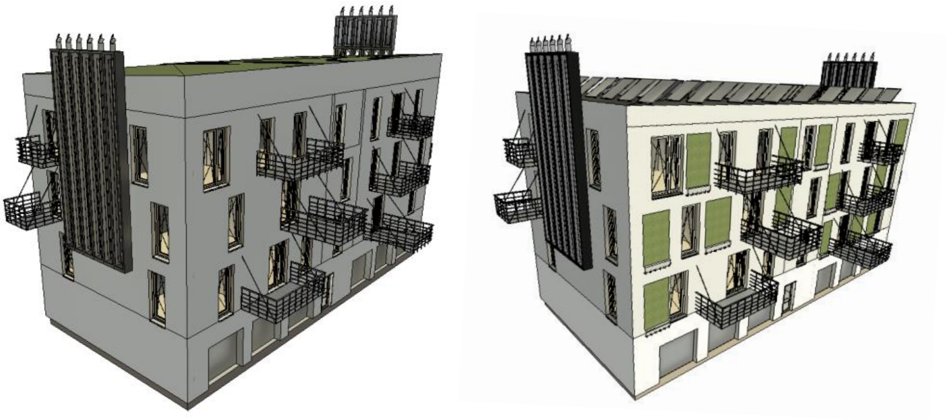

Figure 48 - Two variants of the RESBy multi-family house (author´ s archive)

4.2.6 Experimental building TiCo

The model itself was created within the TiCo (Timber-Concrete) project, thanks to which the building was also built on the experimental area in the University Centre for Energy Efficient Buildings in Bustěhrad. In the TiCo project, the minimization of environmental impacts is supported by a maximum level of prefabrication, which will greatly facilitate the dismantling of the building at the end of its life cycle. The key points in prefabrication are the assembly and joints of the individual parts. For this reason, the project has created an experimental building that represents a full-scale part of a real multi-story residential building and is the unit under evaluation in this paper. It is a two-story building with a flat roof, plan dimensions 11.85 x 10.93 m. It contains 3 residential units of varying standards. In this BIMIP research project, the original model has been enriched with several information related to the SBToolCZ assessment methodology. This model was chosen to cover another typology in addition to the detached house. The calculation of environmental impacts was carried out by the colleague Pavla Kunová (Ryklová). Example of the model and real building is shown in Figure 49. Whole assessment was presented in a paper [80].

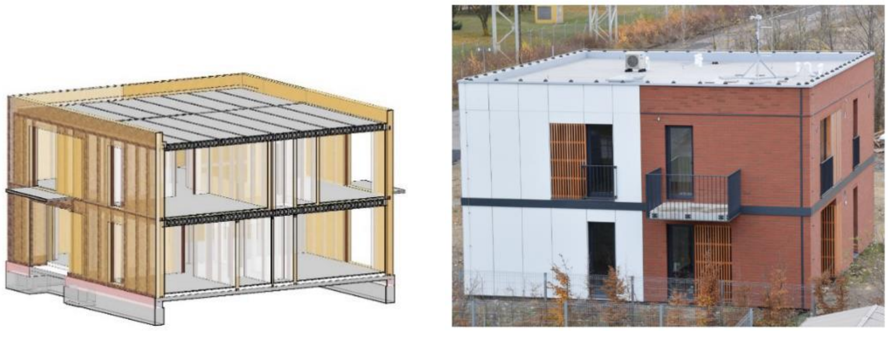

Figure 49 - The model of the TiCo project (author´ s archive).

Another aspect of this project was to extend the model into a Digital Twin, i.e., upload it to a cloud service and link it to relational sensor data. The first attempt was made as part of the master thesis of student Filip Chrást, co-supervised by the author of this thesis. This exploration of possibilities was carried out on the Autodesk Tandem platform. A sample is shown in Figure 50. Full deployment was subsequently carried out on the BIM Point platform and it is shown in Figure 61.

Thus, it is now possible to monitor the actual model in the cloud environment of this tool.

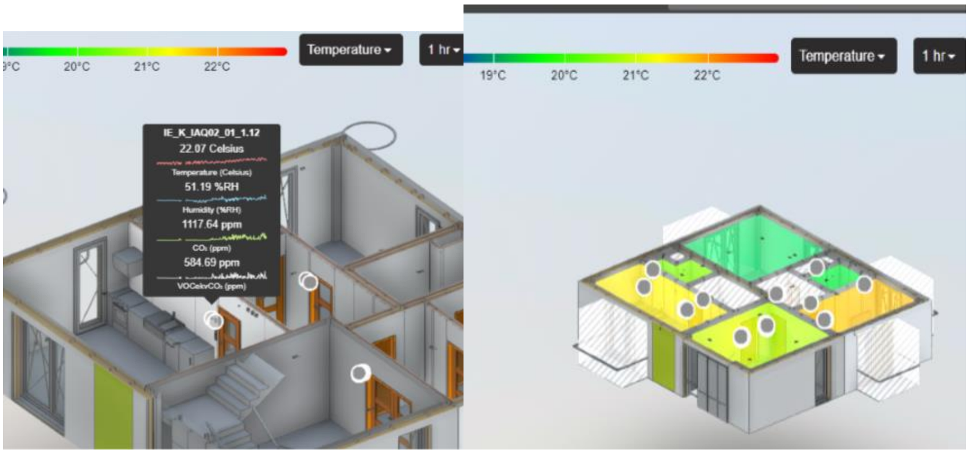

Figure 50 - Example the Digital Twin based on TiCo project (author of the model: Filip Chrást).

4.2.7 FIRSTlife house demonstration unit

The information model was created as part of a project for the Solar Decathlon Europe 21/22 competition. During the competition, members of the mostly student team design innovative solutions within different assignments. The CTU team chose an extension to an older student accommodation building located in Prague. The design included a so-called House Demonstration Unit (HDU), which represented a slice of the proposed project that was actually built as part of the competition. This HDU is shown in Figure 51.

Based on the bill of quantities from the information model, a calculation of the environmental impacts of the construction was carried out. However, this calculation was not included in the overall comparison within this thesis as it was an internal tool used within the competition and was not performed by the author of this thesis. The model is shown in Figure 51.

The BIM model was developed within the competition team of which the author was the leader. The other members were Vít Střelka, Anna Karbanová and Eliška Kopačková. The actual environmental calculation was performed in cooperation with a colleague Jan Pešta.

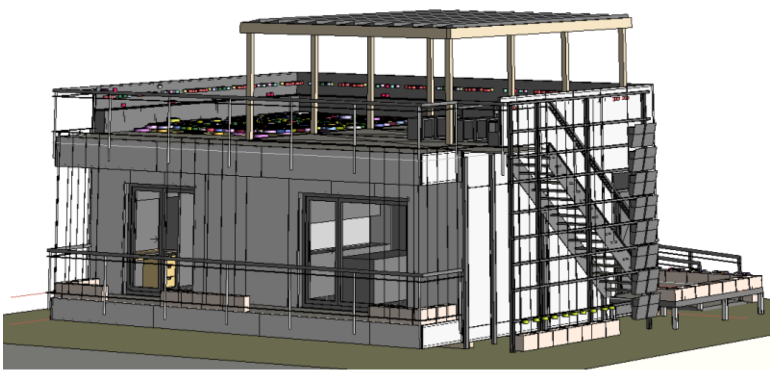

Figure 51 - Model and real building of the FIRSTlife project

4.2.8 Family house Colorado

This model was developed as part of the EnviBIM project, described in detail in the chapter 8.5. The primary purpose was to use the system compositions of DEK (the largest seller of building materials and materials in the Czech Republic), which was part of the project. According to the LCA methodology, these tracks contain environmental impacts, specifically modules A1-A3, i.e., embodied emissions. In an online platform called BIM Platform, it is possible to view a given project's embedded environmental impacts, as seen at Figure 53.

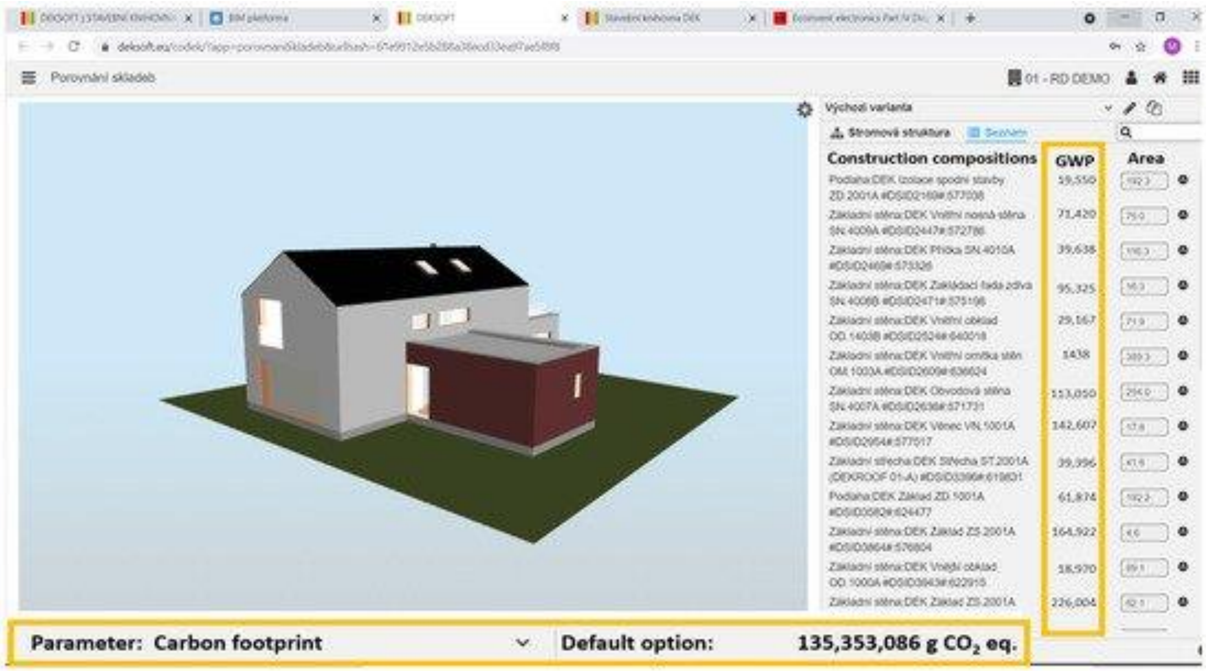

Figure 52 – Colorado project in the BIM platform [81], [82].

An essential point of this case study was comparing the environmental analysis performed based on the traditional BoQ and the BoQ generated from the BIM model. The comparison showed in Figure 53 confirms that the difference in results from the two workflows is within 10%, and thus, both methods can be considered equivalent. In the future, conducting further case studies comparing the two methods is advisable to verify that they are similar.

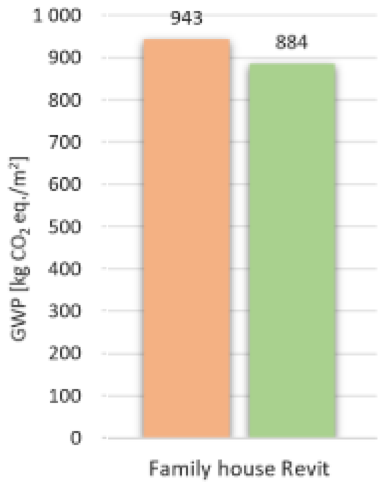

Figure 53 - Comparison of the assessmend based on classic and BIM based BoQ [81], [82].

In the future, the EnviBIM project can serve as a basis for creating an aggregated database of the environmental impact of certain structures in the Czech Republic, which is currently very lacking.

4.2.9 FlasHouse

It is an imaginary project serving as a test dataset for Autodesk clients in the Czech Republic and the model is freely available. The calculation of environmental impacts was done to test the developed methodology in commercial practice outside the academic environment. The model included the SNIM classification system, which proved very advantageous. The model was supplemented with a classification system according to the SBToolCZ methodology to classify materials according to the various durability of the sub-elements. The model itself is shown in Figure 54.

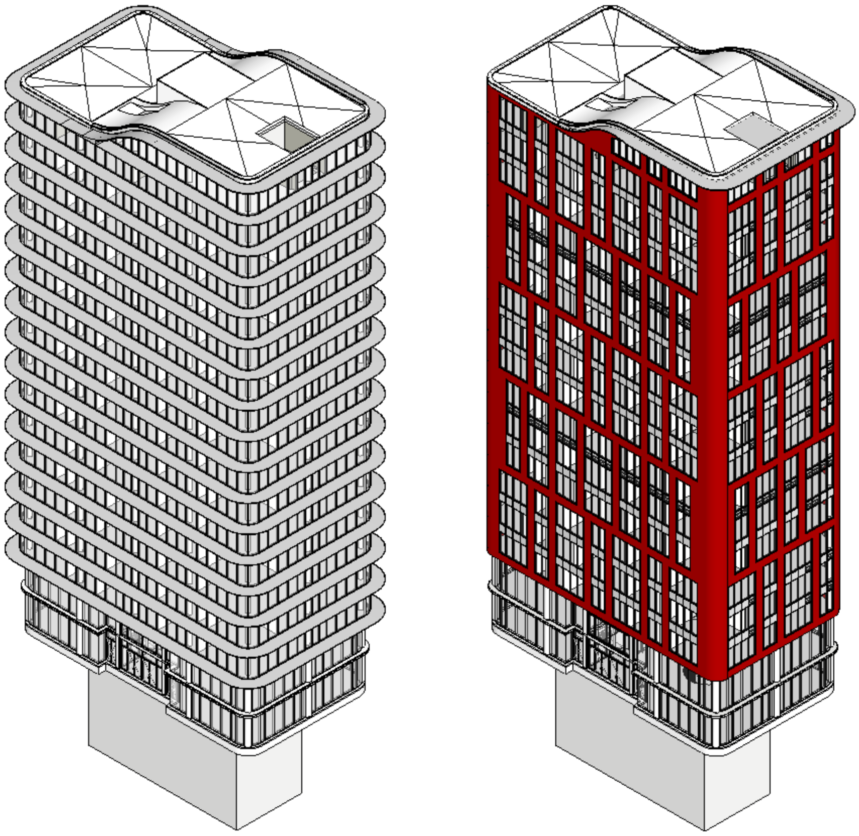

Figure 54 - FlasHouse project with 2 variants of façade (author´ s archive).

An essential aspect of this model was the environmental assessment and subsequent visualization of the results in Microsoft PowerBI software (shown in Figure 55. The classification of the elements into model components was determined based on the SBToolCZ methodology. The model also includes two facade variants. The calculation included a comparison of their environmental impacts. The project was not published in a professional journal. However, it was presented at several conferences aimed at BIM professionals in the Czech Republic, and the results served as feedback on the given workflow from the

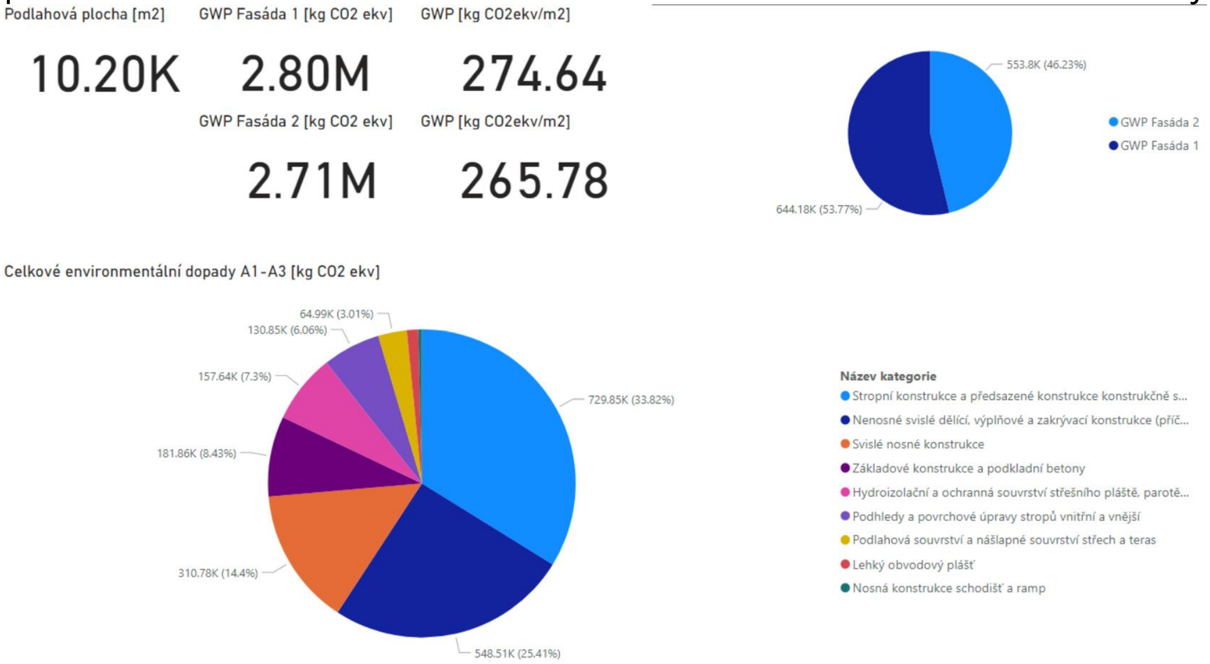

Figure 55 - Example of PowerBI Dashboard showing results from the BIM (author´s archive).

4.3 Detailed design phase

At this stage of the design, all the construction and material design details are known. A BIM model is usually developed. However, the project may continue to be set in this detail only in 2D documentation (e.g., AutoCAD). The actual BIM model is usually simpler and does not contain the necessary details. However, the model should have the most accurate information about the materials and their quantities.

4.3.1 Residential building in Paris: façade

A commercial, residential project in Paris is given as an example. Due to the very detailed floor plan and the high level of detail, it is not realistic to include all these details in the BIM model. The basis for the environmental analysis was mainly the AutoCAD drawing (shown in Figure 56). The model was only used for context change and as a database of the essential dimensions and areas used.

The study aimed to compare the environmental impacts according to the LCA methodology in modules A1-A3 and to determine the difference in the result when using standard aluminum with optimized (manufacturing workflow with optimized energy consumption) and recycled aluminum.

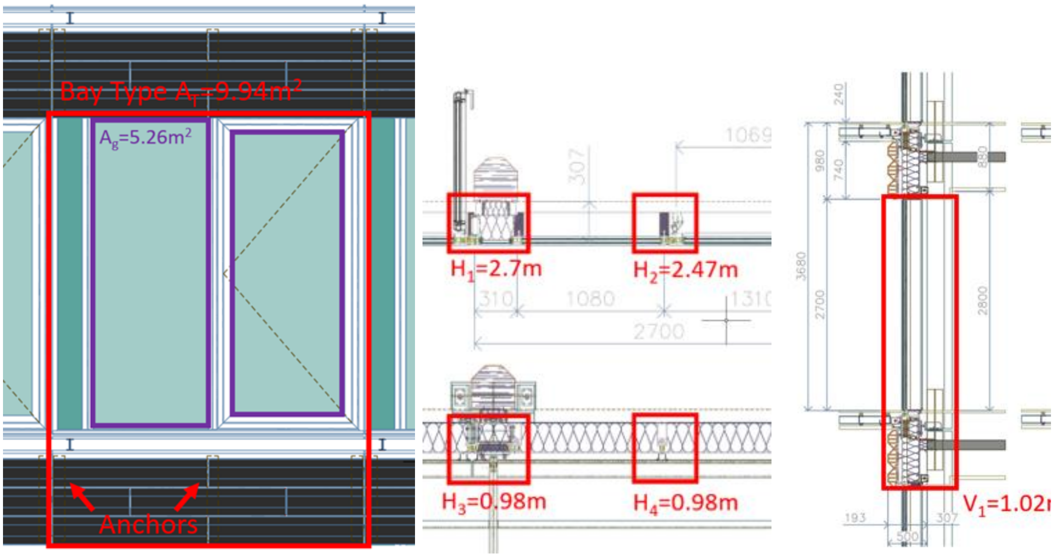

Figure 56 - Example of project documentation in detailed design project phase (author's archive).

It is clear from the results that the dominant influences on the results are mainly the materials: aluminum, glazing, and steel. When comparing several aluminum variants, its relative power in this study was progressively reduced from 53% to 30%, and the overall environmental impact was reduced by 50% (Figure 57) from about 200 to 100 (Figure 58) [kg $CO_{2\ ekv}$ / m^2]. Therefore, addressing the optimization of the different products used at this stage of the project can significantly reduce the house's environmental impact.

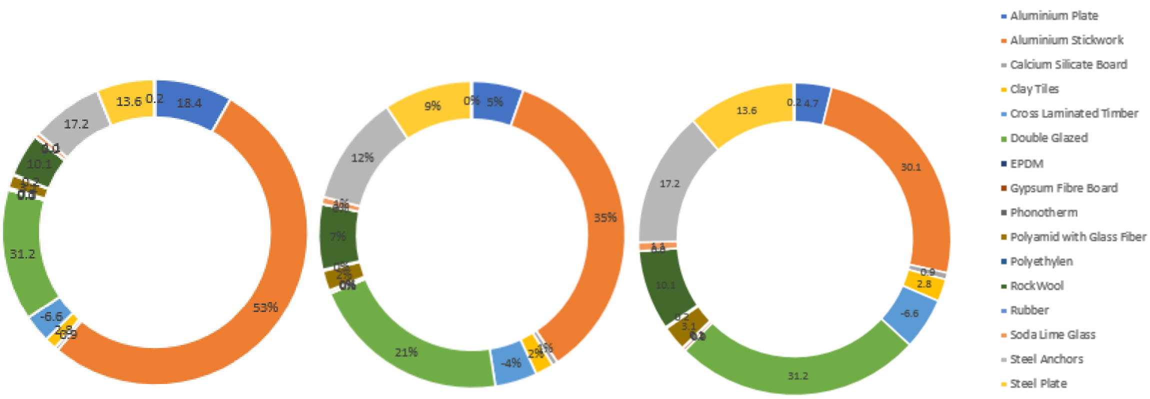

Figure 57 - The percentage comparisonof various types (standard, optimized, and recycled) of aluminium (author's archive).

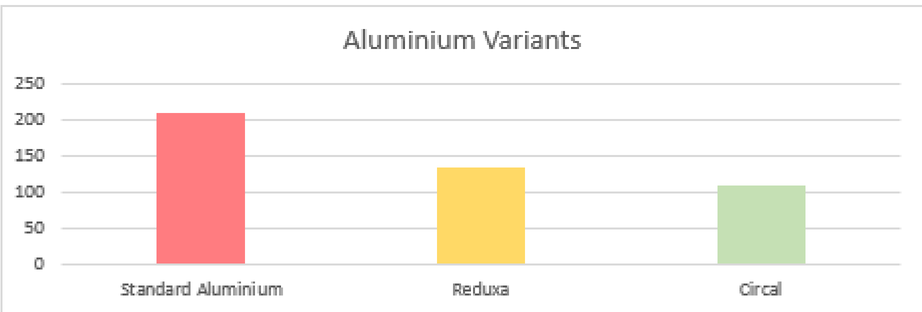

Figure 58 - Comparison of environmental impact per square meter of facade A1-A3 (author's archive).

4.4 Other phases of the building's life cycle

Operational phase

This phase of the project was already considered in projects 4.2.1 Experimental building B2226, and 4.2.2 High-rise multi-family house. Operation emissions as well as embodied emissions related to the replacement, modification, or improvement were also calculated. Results are shown in Figure 41, and Figure 43.

Demolition, Recycling, Circular Building Industry

Due to the fact that methodology for C and D modules in being developed, any study for this particular phase is provided.

5 Results

Based on case studies of imaginary and actual buildings, building information models are instrumental in calculating the environmental impacts of buildings. The results can be divided according to different criteria, for example, by construction and materials. To classify the materials and structures correctly, it is necessary to use a classification system. The BIM models can play significant role in the process of environmental assessment of the buildings. As it is shown in Figure 59, results of various case studies confirmed that results variation between traditional BoQ and BoQ taken from the models is low.

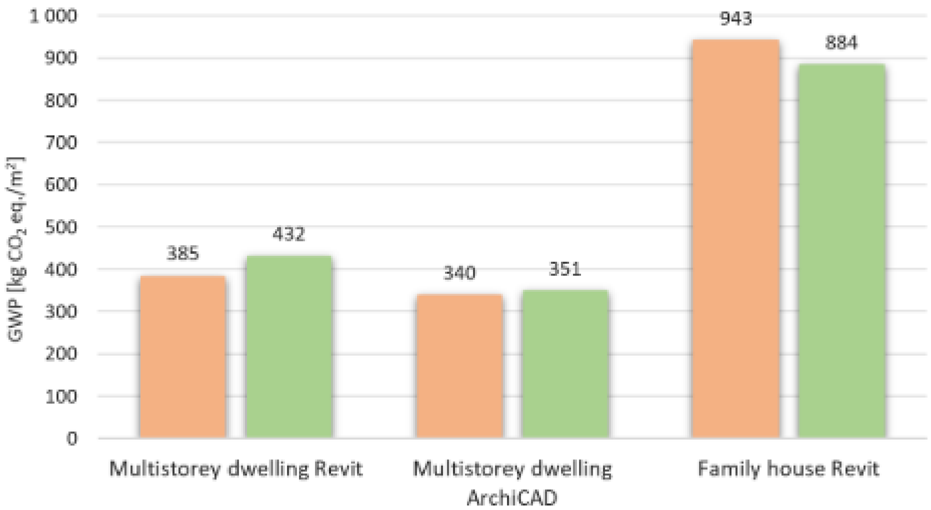

Figure 59 - Comparison of results from BIM and from traditional workflow [82].

5.1 Research questions fulfilement

The following chapter summarizes chapter 1.5, in which research questions were proposed. Based on all projects mentioned in this Thesis, BIM can play a significant role in the process of carbon footprint reduction because they contain

They contain more information than standard documentation at all project stages, so any environmental impact assessment can be carried out with less effort and greater accuracy.

Design optimization can be performed during several main phases of the project: Early; Developed; and Detailed, and each step can be used for a different form of optimization: Conceptual (Mass Optimization); Structural and Material; and Product. The most significant positive environmental benefits can be achieved if environmental issues are included in the design process from the beginning of the project and implemented in multiple iterations in all three phases.

Environmental analysis based on BIM can be done in many ways: (1) BoQ export and manual assessment; (2) model exported to IFC and use data from this format; (3) semi-automatic export from the model; (4) automated export with the addon.

The market situation is dynamic, and many changes have occurred over the last few years. BIM penetration is at a higher level and is the standard for large and medium-sized projects. These projects can now be considered ready for LCA analysis using BIM. For small projects, the traditional 2D design method still prevails. In the context of the forthcoming EPBD legislation, the calculation of environmental impacts must be simplified. It can be assumed that energy-geotechnical specialists will handle this agent, and the time consumption should be reasonable.

Larger companies, such as developers, construction companies, etc. are starting to implement the calculation of environmental impacts of buildings in their workflows. They are mainly motivated by financial reasons (green bonds with lower interest rates, fulfillment of ESG commitments, etc.).

Working hypotheses

Standardization in BIM-LCA is an essential condition for successful implementation in practice. The level varies from country to country. In the country, a Construction Data Standard will be launched during 2023, which includes three pillars: (1) Data Dictionary; (2) Classification system Construction Classification International (CCI); and (3) Level of In-formation Needed (LOIN) definition. These three parts will contain all the information necessary to calculate the environmental impacts of the construction.

Within the current practice at the University Centre for Energy Efficient Buildings and from discussions at professional conferences (i.e., Digital Construction, Prague, November 2022), it is clear that there is a significant market demand for these topics. The potential of using this work in praxis is, therefore, high.

The thesis has fulfilled its purpose by fulfilling the research questions and working hypotheses.

5.2 Goals fulfilement

This chapter summarizes the objectives of the thesis as defined in chapter 1.6.

1) To raise awareness in the professional community of the importance of environmental calculations of buildings and to demonstrate the possibilities of using building information models.
   - During the work on this study, the issue has been presented in many places within the professional community in professional articles, conference papers (list of all author's publication is shown in chapter 7.1), Czech Green Building Council seminars, BIM Breakfast organized by MFS DX company, seminars within the Saint-Gobain student competition, etc.
2) Summarise foreign methodologies, practices, and approaches.
   - There are many sources and approaches to the issue available in foreign literature, and it is clear that the topic is being addressed everywhere in the developed world. There is a consensus that BIM can play a significant role in calculating the environmental impacts of construction due to its higher design accuracy, lower error rate, and easier changes.
   - The chapter 2 summarizes the state of the art in this topic with all the references.
3) Analysis of current practice and definition of the most common problems in information models.

- The biggest problems faced by current practice are the high time consumption of environmental calculations and the need for a methodology specifying how BIM models suitable for LCA should look. There is also a need for a data standard. The following work should contribute to solving these practical problems.
- The chapter 2 summarizes the thate of the art in this topic.

4) Definition of project phases (so-called Performance Phases according to ČKAIT vs. internationally recognized LOD).
   - This issue was addressed in the framework of the international project Annex 72, the result of which was a comparison of the different phases of the project in other countries.
   - In particular, the definition of the three primary phases (Early, Developed, Detailed) related to the levels of Study documentation, Building Permit documentation, and shop-drawing documentation was necessary for this work. These project phases are thus clearly identifiable and are associated with the models' Levels of Development 200, 300, and 400.
   - See details in the chapter 2.4.5, which describes the international comparison of various project phases.
5) Propose a methodology for model development in various project phases
   - This thesis presented the methodology for creating BIM models in each phase mentioned in the previous paragraph. To perform an environmental analysis according to the LCA methodology, the models in the different stages must contain the necessary details, such as a detailed description of the materials, their object mass, etc.
   - These phases also provide scope for optimizing the design: Conceptual (Mass Optimization), Structural and Material, and Product.
   - The chapter 3 addresses the methodology.
6) Demonstrate the possibilities through case studies.
   - The model building methodology was demonstrated through 11 case studies, which were carried out in all three pproposedphases of the project.
   - The case studies were conducted within various research projects, commercial and non-commercial practices.
   - See details in the chapter 4.
7) Summarize opportunities for the automation of the process.
   - The potential for automating the entire BIM-LCA process is significant. Given the upcoming change in EPBD legislation and the resulting increased emphasis on the environmental analysis of buildings, it will be necessary. To be able to achieve it, it is essential to:
     - BIM models are to be standardized according to their internal structure.
     - Complete the definition of legislation in this area.
     - Develop specialized tools to automate the process.
   - The commercial solutions currently in use are functional but expensive or challenging.
   - See details in the chapter 2.6.3.
8) Suggest the possibility of integration into the Czech environment.
   - The chapter 3 addresses the methodology which can be fully implemented into the Czech environment.

- The results of the work will be used for implementation in the forthcoming construction industry data standard.

All the goals and research questions of the Thesis were addressed and therefore the purpose of this work is fulfilled.

5.3 Limitations

Building services models are usually not available in early stage of the project, therefore, it is complicated to calculace impact of a systems.

BIM models are always simplified and it is necessary to unferstand the process of simplification and be able to consider how to use models for BoQ suitable for the LCA.

Manual work is still related to the work and it is necessary to always consider the following list:

- Uncertainty;
- Environmental Database;
- Windows, facades and other simplifies parts of the model;
- Missing standards;
- Classification system;
- Models currently can not contain multiple choice or drop-down menu.

6 Thesis Outcomes

6.1 Summary

The most important conclusion of this thesis is the verification that BIM models can play an essential role in calculating environmental impacts according to the LCA methodology. They can facilitate the creation of the basis for this calculation. They can also play a crucial role in the design optimization process in the different phases of the project (early, developed, and detailed steps).

The essential information that models suitable for environmental analysis should contain are:

- Completed materials' details, including bulk weight and other material characteristics.
- Lifetimes of individual materials and sub-structures to enable the assessment of B2-B5 modules according to the LCA methodology.
- All requirements, including project phase details, must be contracted in the relevant documents to work effectively with the models.
- For environmental data, it is advisable to combine aggregated databases with generic databases and individual EPDs. A suitably qualified person should carry out this assessment.

6.2 Outcomes

Not only environmental data, another challenge is efficient system which allows assessment of high amount of calculations in a limited period of time. It is highly probable, that in the following years need for such a calculations will increase and most of the calculation is processed manually in Excel.

The need for creating an aggregated environmental database of building valid for the Czech Republic could be used to optimize the design of buildings in early design. Several applications for funding for such a project were submitted during the Ph.D. but were not selected by the evaluation committees. Further applications are being offered for research projects incorporating this environmental database. It is, therefore, foreseeable that such a database will appear sooner or later.

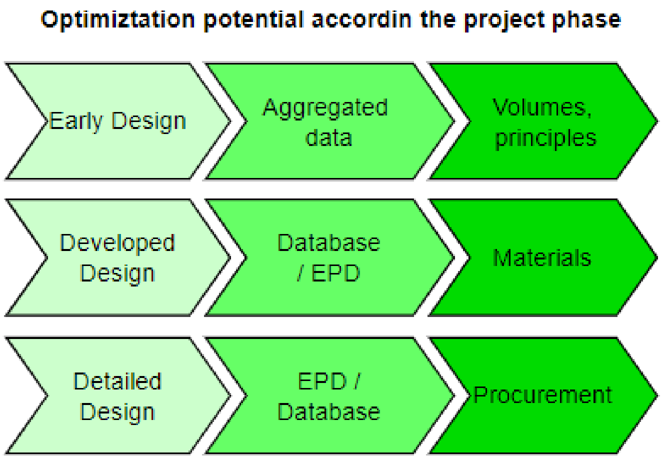

Figure 60 - Optimization potential according the project phase (author´ s archive)

6.3 Collaboration with czBIM (Building Smart) and Czech Agency for Standardization

The research results were presented to czBIM (Building Smart) representatives and the Czech Agency for Standardization. In both organizations, awareness-raising among the professional public is carried out by organizing conferences and other meetings and creating methodologies and legislative documents.

As the output of this work, cooperation with czBIM has been arranged on:

- Workshops for the professional public to promote the topic of BIM-LCA.
- Presentation of the research conclusions and this work at the BIM DAY 2023 conference for the professional public.
- Involvement in international activities and coordination within the platform buildingSMART internationally.

With Czech Agency for Standardization the current status is:

- Involvement in data standard development and integrating BIM requirements with environmental analysis.
- Collaboration with the agency will cover (1) data dictionary, (2) update of classification system CCI to cover also requirements for environmental assessment, and (3) update of Level of Information Needed document which specifies requirements for the models.

The outputs of the work will thus have an overlap in commercial practice.

6.4 Future Outlook

According the thoughts presented in the previous chapters, I try to project the future development in the BIM field in the following points.

- Digitalization is one of the key aspects of the following decade for whole construction industry.
- BIM will became an integral part of the building` s life cycle (and not only design as today) process.

- LCA will be established as an important workflow for calculating the building` s environmental impact.
- For any of the options mentioned in the previous chapter the user chooses, it is best to use a suitably modified project template within which the model is created. This should contain, in particular, the material characteristics for all materials (bulk weight) so that volumes can be easily converted to kilograms, specific parameters related to individual structures and other elements, and take statements used either directly for export or for user control if the export is done by other means.
- Digital building permit will be established in the following years as a tool for higher efficiency of the building process.
- Building models (in this case Digital Twins) will be used for the real-time facility management in combination with data from sensors and smart technologies (ventilation, heating, cooling and lighting according the building occupancy etc.).
- Models will be used for advanced simulations with combination of machine and deep learning according the data flows from buildings in operational phase.
- Buildings will be used as a material stock for the future buildings. Circularity became an important part of the design process.
- Asset managers will use data for the material circularity.
- Importance to consider building services into all calculations.
- Aggregated Environmental Database.
- Automate process with Dynamo / Python / C# addins for higher efficiency of the process.
- Create a aggregated database of environmental impact for early-design phase of the project.
- Develop a simplified method allwing fast assessment.

7 References

[1] J. Veselka, “The use of Autodesk Revit for thermal analysis of building,” Czech Technical University in Prague, 2013.

[2] J. Veselka, “BIM in Life Cycle of the Building – Case Study,” Czech Technical University in Prague, 2015.

[3] P. A. Arias, N. Bellouin, E. Coppola, and et al., “IPCC 2021: Technical Summary,” *Cambridge Univ. Press*, 2021, doi: 10.1017/9781009157896.002.

[4] S. Policymakers, “IPCC: Summary for Policy,” 2018, doi: 10.7551/mitpress/1866.003.0006.

[5] J. Hamilton *et al.*, *United Nations Environment Programme (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero‑emission, Efficient and Resilient Buildings and Construction Sector. Nairobi*. 2022.

[6] United Nations Environment Programme, *Emissions Gap Report*. 2015.

[7] V. Smil, *How the World Really Works: The Science Behind How We Got Here and Where We’re Going*. 2022.

[8] V. Smil, *Numbers Don’t Lie: 71 Stories to Help Us Understand the Modern World*. 2021.

[9] V. Smil, *Growth: From Microorganisms to Megacities*. Mit Press.

[10] V. Smil, *Energy and Civilization A History*. 2017.

[11] B. Moldan, *Conquered Planet (Podnaměná planeta)*. 2015.

[12] B. Gates, *How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need*. 2020.

[13] M. Roser, “Why did renewables become so cheap so fast?,” *Our World in Data*, 2020. https://ourworldindata.org/cheap-renewables-growth.

[14] T. Economist, “Efficiency eludes the construction industry,” 2017. https://www.economist.com/business/2017/08/19/efficiency-eludes-the-construction-industry.

[15] F. Abraham, J. Cahn, B. Fitzerald, and E. Greenberg, “Strategy in the face of disruption: A way forward for the North American building-products industry,” *McKinsey&Company*. https://www.mckinsey.com/industries/private-equity-and-principal-investors/our-insights/strategy-in-the-face-of-disruption-a-way-forward-for-the-north-american-building-products-industry.

[16] McKinsey & Company, “DIGITAL CHINA : POWERING THE ECONOMY TO GLOBAL COMPETITIVENESS,” no. December. 2017, [Online]. Available: https://www.mckinsey.com/featured-insights/china/digital-china-powering-the-economy-to-global-competitiveness.

[17] F. Barbosa *et al.*, “Reinventing Construction: A Route To Higher Productivity,” *Mckinsey Glob. Insititute*, no. February, p. 168, 2017, [Online]. Available: http://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution.

[18] McKinsey & Company, “Digital Australia: Seizing the opportunity from the Fourth Industrial Revolution,” no. May, 2016, [Online]. Available: https://www.mckinsey.com/featured-insights/asia-pacific/digital-australia-seizing-opportunity-from-the-fourth-industrial-revolution.

[19] McKinsey & Company, “DIGITAL EUROPE: PUSHING THE FRONTIER, CAPTURING THE BENEFITS,” [Online]. Available: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/digital-europe-realizing-the-continents-potential.

[20] “ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building i nformation modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles.” [Online]. Available: https://www.iso.org/standard/68078.html.

[21] “ČSN EN 15978 - Udržitelnost staveb - Posuzování environmentálních vlastností budov - Výpočtová metoda.”

[22] J. Veselka *et al.*, “Recommendations for Developing a BIM for the Purpose of LCA in Green Building Certifications,” *Sustainability*, vol. 12, no. 15, p. 6151, Jul. 2020, doi: 10.3390/su12156151.

[23] EU, “Energy performance of buildings directive (EPBD).” https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.

[24] M. Yalcinkaya and V. Singh, “Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis,” *Autom. Constr.*, vol. 59, pp. 68–80, 2015, doi: 10.1016/j.autcon.2015.07.012.

[25] J. K. W. Wong and J. Zhou, “Enhancing environmental sustainability over building life cycles through green BIM: A review,” *Automation in Construction*, vol. 57. Elsevier, pp. 156–165, Jun. 26, 2015, doi: 10.1016/j.autcon.2015.06.003.

[26] A. H. Oti, W. Tizani, F. H. Abanda, A. Jaly-Zada, and J. H. M. Tah, “Structural sustainability appraisal in BIM,” *Autom. Constr.*, vol. 69, pp. 44–58, Sep. 2016, doi: 10.1016/j.autcon.2016.05.019.

[27] R. Evins, “A review of computational optimisation methods applied to sustainable building design,” *Renew. Sustain. Energy Rev.*, vol. 22, pp. 230–245, 2013, doi: 10.1016/j.rser.2013.02.004.

[28] R. Santos, A. A. Costa, and A. Grilo, “Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015,” *Autom. Constr.*, vol. 80, pp. 118–136, 2017, doi: 10.1016/j.autcon.2017.03.005.

[29] M. Khaja, J. D. Seo, and J. J. McArthur, “Optimizing BIM Metadata Manipulation Using Parametric Tools,” *Procedia Eng.*, vol. 145, pp. 259–266, 2016, doi: 10.1016/j.proeng.2016.04.072.

[30] M. Rahmani Asl, S. Zarrinmehr, M. Bergin, and W. Yan, “BPOpt: A framework for BIM-based performance optimization,” *Energy Build.*, vol. 108, pp. 401–412, 2015, doi: 10.1016/j.enbuild.2015.09.011.

[31] R. Caspeele, L. Taerwe, and D. M. Frangopol, *Life cycle analysis and assessment in civil*

engineering : towards an integrated vision. .

[32] F. Pomponi, C. De Wolf, and A. Moncaster, *Embodied Carbon in Buildings*. Cham: Springer International Publishing, 2018.

[33] A. Hollberg, T. Lützkendorf, and G. Habert, "Top-down or bottom-up? – How environmental benchmarks can support the design process," *Build. Environ.*, vol. 153, pp. 148–157, Apr. 2019, doi: 10.1016/j.buildenv.2019.02.026.

[34] L. Wastiels and R. Decuypere, "Identification and comparison of LCA-BIM integration strategies," in *IOP Conference Series: Earth and Environmental Science*, Sep. 2019, vol. 323, p. 012101, doi: 10.1088/1755-1315/323/1/012101.

[35] T. P. Obrecht, M. Röck, E. Hoxha, and A. Passer, "BIM and LCA integration: A systematic literature review," *Sustainability (Switzerland)*, vol. 12, no. 14. 2020, doi: 10.3390/su12145534.

[36] M. Nilsen and R. A. Bohne, "Evaluation of BIM based LCA in early design phase (low LOD) of buildings," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 323, no. 1, 2019, doi: 10.1088/1755-1315/323/1/012119.

[37] C. Cavalliere, G. Habert, G. R. Dell'Osso, and A. Hollberg, "Continuous BIM-based assessment of embodied environmental impacts throughout the design process," *J. Clean. Prod.*, vol. 211, pp. 941–952, Feb. 2019, doi: 10.1016/j.jclepro.2018.11.247.

[38] J. Abualdenien *et al.*, "Consistent management and evaluation of building models in the early design stages," *J. Inf. Technol. Constr.*, vol. 25, pp. 212–232, Mar. 2020, doi: 10.36680/j.itcon.2020.013.

[39] M. Zeleny, "Management support systems: Towards integrated knowledge management," *Hum. Syst. Manag.*, vol. 7, no. 1, pp. 59–70, Apr. 1987, doi: 10.3233/HSM-1987-7108.

[40] "DIKW pyramid." https://en.wikipedia.org/wiki/DIKW_pyramid.

[41] J. Bedrick, W. Ikerd, and J. Reinhardt, "Level of Development (LOD) Specification Part I & Commentary For Building Information Models and Data," *BIMForum*, no. Dezembro, pp. 263–64, 2020, [Online]. Available: www.bimforum.org/lod.

[42] P. Matějka, "Building Information Modeling (BIM) implementation related risks," Czech Technical University in Prague, 2017.

[43] D. Olsen and J. M. Taylor, "Quantity Take-Off Using Building Information Modeling (BIM), and Its Limiting Factors," *Procedia Eng.*, vol. 196, no. June, pp. 1098–1105, 2017, doi: 10.1016/j.proeng.2017.08.067.

[44] R. K. Zimmermann, S. Bruhn, and H. Birgisdóttir, "BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs," *Sustainability*, vol. 13, no. 10, p. 5455, 2021, doi: 10.3390/su13105455.

[45] H. Liu, J. C. P. Cheng, V. J. L. Gan, and S. Zhou, "Advanced Engineering Informatics A novel Data-Driven framework based on BIM and knowledge graph for automatic model auditing and Quantity Take-off," *Adv. Eng. Informatics*, vol. 54, no. May, p. 101757, 2022, doi: 10.1016/j.aei.2022.101757.

[46] "ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema." [Online]. Available: https://www.iso.org/standard/70303.html.

[47] Š. Tomanová, M. Černý, D. Dvořák, and J. Nechyba, "Stanovisko k využití formátu IFC v návaznosti na opatření č. 7 UV č. 682," 2019, [Online]. Available: www.koncepceBIM.cz.

[48] A. Passer, T. Potrč Obrecht, and N. Alaux, *Guidelines for design decision-makers (Annex 72)*, no. November. 2022.

[49] *ČSN EN 15804+A2 Sustainability of construction works - Environmental product declaration*. 2022.

[50] *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. 2006.

[51] *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*. .

[52] J. Hodková, "Assessment of building materials in environmental context," chnical University in Prague, 2013.

[53] M. Röck *et al.*, "Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation," *Appl. Energy*, vol. 258, p. 114107, Jan. 2020, doi: 10.1016/j.apenergy.2019.114107.

[54] B. Saso, A. Hollberg, A. Galimshina, and G. Habert, "A design integrated parametric tool for real-time Life Cycle Assessment – Bombyx project," 2019, vol. 323, no. 1, doi: 10.3929/ethz-b-000370474.

[55] *ČSN EN ISO 22057 - Sustainability in buildings and civil engineering works - Data templates for the use of environmental product declaradions (EPDs) for construction products in building information modelling (BIM)*. 2022.

[56] ISO, *ISO 15686-5:2017 Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing*. 2017, p. 43.

[57] EN, *EN 16627:2015 Sustainability of construction works. Assessment of economic performance of buildings. Calculation methods*. 2015.

[58] R. Heralová, Scheinderová *et al.*, "Metodika hodnocení celoživotních nákladů staveb a popis aplikačního software řešení." [Online]. Available: https://www.cameb.cz/metodika-lccvysledky.

[59] S. Vitásek, "Nové přístupy v oceňování silničních staveb New approaches in the valuation of road infrastructure," Czech Technical University in Prague, 2019.

[60] R. Santos, A. A. Costa, J. D. Silvestre, and L. Pyl, "Integration of LCA and LCC analysis within a BIM-based environment," *Autom. Constr.*, vol. 103, pp. 127–149, Jul. 2019, doi: 10.1016/j.autcon.2019.02.011.

[61] M. C. Dejaco *et al.*, "Combining LCA and LCC in the early-design stage: a preliminary study for residential buildings technologies," in *IOP Conference Series: Earth and Environmental Science*, Nov. 2020, vol. 588, p. 042004, doi: 10.1088/1755-1315/588/4/042004.

[62] A. Galimshina *et al.*, “Probabilistic LCA and LCC to identify robust and reliable renovation strategies,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 323, no. 1, p. 012058, Sep. 2019, doi: 10.1088/1755-1315/323/1/012058.

[63] A. Galimshina *et al.*, “Statistical method to identify robust building renovation choices for environmental and economic performance,” *Build. Environ.*, vol. 183, p. 107143, 2020, doi: 10.1016/j.buildenv.2020.107143.

[64] C. Kiamili, A. Hollberg, and G. Habert, “Detailed assessment of embodied carbon of HVAC systems for a new office building based on BIM,” *Sustainability (Switzerland)*, vol. 12, no. 8. 2020, doi: 10.3390/SU12083372.

[65] K. Forth, J. Höper, J. Veselka, S. Theißen, and A. Borrmann, “Towards life cycle assessment of technical building services in early design phases using building information modelling,” *Proc. 2022 Eur. Conf. Comput. Constr.*, vol. 3, 2022, doi: 10.35490/ec3.2022.178.

[66] J. Růžička, J. Veselka, Z. Rudovský, S. Vitásek, and P. Hájek, “BIM and Automation in Complex Building Assessment,” *Sustainability*, vol. 14, no. 4, p. 2237, Feb. 2022, doi: 10.3390/su14042237.

[67] M. Motalebi, A. Rashidi, and M. M. Nasiri, “Optimization and BIM-based lifecycle assessment integration for energy efficiency retrofit of buildings,” *J. Build. Eng.*, vol. 49, no. September 2021, p. 104022, 2022, doi: 10.1016/j.jobe.2022.104022.

[68] P. Matějka, E. Hromada, N. Anisimova, J. Dobiáš, Ková\v r P., and I. Kozáková, *Základy implementace BIM na českém stavebním trhu*. 2012.

[69] M. Černý *et al.*, *BIM příručka*. czBIM, 2013.

[70] Š. Tomanová, J. Nechyba, B. Pospíšilová, P. Matějka, P. Lacina, and R. Voráč, *BIM příručka pro investory*. czBIM, 2018.

[71] Z. Dufek *et al.*, *BIM pro veřejné zadavatele*. Legios, 2018.

[72] J. Veselka, J. Hájek, M. Volf, J. Růžička, and V. Žďára, “BIM in early design phase: Workflow for preliminary assessment with SBToolCZ,” *J. Phys. Conf. Ser.*, vol. 2042, no. 1, 2021, doi: 10.1088/1742-6596/2042/1/012084.

[73] “BIMFORUM - Level of Development (LOD).” https://bimforum.org/lod/.

[74] Wicona, “Comparison of aluminium production,” 2022. https://www.wicona.com/en/int/sustainability/beyond-materials/hydro-circal-recycled-aluminium/.

[75] D. Kaushal, J. Veselka, G. Habert, and A. Hollberg, “Design-integrated Life Cycle Assessment using BIM (BIM-LCA),” no. December, 2022, doi: 10.3929/ethz-b-000584886.

[76] R. Frischknecht *et al.*, “Comparison of the environmental assessment of an identical office building with national methods,” in *IOP Conference Series: Earth and Environmental Science*, Sep. 2019, vol. 323, p. 012037, doi: 10.1088/1755-1315/323/1/012037.

[77] R. Frischknecht *et al.*, “Comparison of the greenhouse gas emissions of a high-rise

residential building assessed with different national LCA approaches – IEA EBC Annex 72,” in *IOP Conference Series: Earth and Environmental Science*, Nov. 2020, vol. 588, p. 022029, doi: 10.1088/1755-1315/588/2/022029.

[78] C. Ouellet-plamondon and L. Ramseier, “Carbon footprint assessment of a wood multi-residential building considering biogenic carbon,” doi: https://doi.org/10.21203/rs.3.rs-2273783/v1.

[79] C. M. Ouellet-Plamondon *et al.*, “Carbon footprint assessment of a wood multi-residential building considering biogenic carbon,” *J. Clean. Prod.*, p. 136834, 2023, doi: 10.1016/j.jclepro.2023.136834.

[80] P. Ryklová, J. Veselka, and Š. Mančík, “Posuzování environmentálních dopadů konstrukčního systému TiCo,” *Staverbnictví*, 2021, [Online]. Available: https://www.casopisstavebnictvi.cz/clanky-posuzovani-environmentalnich-dopadu-konstrukcniho-systemu-tico.html.

[81] M. Nehasilová, “Integration of environmental data to the cost database for construction budgets : Methodology and case studies,” Czech Technical University in Prague, 2021.

[82] M. Nehasilová *et al.*, “Rapid Environmental Assessment of Buildings: Linking Environmental and Cost Estimating Databases,” *Sustainability*, vol. 14, no. 17, p. 10928, Sep. 2022, doi: 10.3390/su141710928.

[83] J. Veselka *et al.*, “Connecting BIM and LCA: The Case Study of an Experimental Residential Building,” in *IOP Conference Series: Earth and Environmental Science*, Sep. 2019, vol. 323, p. 012106, doi: 10.1088/1755-1315/323/1/012106.

[84] B. Soust-Verdaguer *et al.*, “Implications of using systematic decomposition structures to organize building LCA information: A comparative analysis of national standards and guidelines- IEA EBC ANNEX 72,” in *IOP Conference Series: Earth and Environmental Science*, Nov. 2020, vol. 588, p. 022008, doi: 10.1088/1755-1315/588/2/022008.

[85] A. Lupíšek, J. Diviš, L. Beránek, J. Veselka, and P. Šenfeldr, “Highly automated production of prefabricated wood-based building envelopes : potential for a significant reduction of carbon footprint of residential development,” pp. 1–2.

7.1 Author's publications

As a basis for the thoughts presented in this thesis, following list of publications with authorship or co-authorship. The list is taken from an internal database of Czech Technical University in Prague V3S.

1. LUPÍŠEK, A., et al. Souhrnná výzkumná zpráva projektu Inter-Transfer: Česká účast v Annexu 72 Mezinárodní energetické agentury. [Research Report] 2022. Report no. V018.
2. POSUZOVÁNÍ DOPADŮ ŽIVOTNÍHO CYKLU BUDOV. [Workshop Hosting] 2022.
3. LUPÍŠEK, A., et al. Výzkumná zpráva o referenčních hladinách. [Research Report] 2021. Report no. E003-V008.

4. OUELLET-PLAMONDON, C., et al. Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. Journal of Cleaner Production. 2023, ISSN 1879-1786. DOI 10.1016/j.jclepro.2023.136834.
5. RŮŽIČKA, J., et al. Návrh metodiky pro analýzu reálného chování budovy a porovnání s výpočtovými modely – necertifikovaná metodika. [Other Methodology (not meeting RIV conditions)] 2022.
6. RŮŽIČKA, J., J. VESELKA, and P. ŠENFELDR. "Návrh metodiky pro implementaci BIM do výrobní přípravy stavby – necertifikovaná metodika". [Other Methodology (not meeting RIV conditions)] 2022.
7. RŮŽIČKA, J., J. VESELKA, and L. BEJČEK. Online freeware pro hodnocení komplexní kvality budov. [Software] 2022.
8. LUPÍŠEK, A., et al. HIGHLY AUTOMATED PRODUCTION OF PREFABRICATED WOOD-BASED BUILDING ENVELOPES: POTENTIAL FOR A SIGNIFICANT REDUCTION OF CARBON FOOTPRINT OF RESIDENTIAL DEVELOPMENT. In: CEES2021 Book of Abstracts. International Conference on Construction, Energy, Environment and Sustainability - CEES 2021, Coimbra, 2021-10-12/2021-10-15. Coimbra: University of Coimbra, 2022. p. 108. Available from: https://cees2021.uc.pt
9. NEHASILOVÁ, M., et al. Rapid Environmental Assessment of Buildings: Linking Environmental and Cost Estimating Databases. SUSTAINABILITY. 2022, 14(17), 1-20. ISSN 2071-1050. DOI 10.3390/su141710928.
10. KAUSHAL, D., J. VESELKA, and A. HOLLBERG. Design-integrated Life Cycle Assessment using BIM (BIM-LCA). [Technical Report] Ittigen (Bern): Swiss Federal Office of Energy, 2022.
11. FORTH, K., et al. Towards life cycle assessment of technical building services in early design phases using building information modelling. In: 2022 European Conference on Computing in Construction. European Conference on Computing in Construction, Ixia, Rhodes, 2022-07-24/2022-07-26. European Council on Computing in Construction (EC3), 2022. ISSN 2684-1150. ISBN 9788875902261. DOI 10.35490/EC3.2022.178. Available from: https://ec-3.org/publications/conference/paper/?id=EC32022_178
12. RŮŽIČKA, J., et al. BIM and Automation in Complex Building Assessment. SUSTAINABILITY. 2022, 14(4), ISSN 2071-1050. DOI 10.3390/su14042237. Available from: https://www.mdpi.com/2071-1050/14/4/2237?type=check_update&version=2
13. NEHASILOVÁ, M., et al. Metoda pro přiřazování environmentálních dopadů k položkám knihovny skladeb. Verifikace na případových studiích.. [Research Report] Praha: CTU. University Centre of Energy Efficient Buildings, 2021. Report no. TJ02000086-V2.
14. VESELKA, J., et al. BIM in Early Design Phase: Workflow for Preliminary Assessment with SBToolCZ. In: Journal of Physics: Conference Series. CISBAT 2021: Carbon Neutral Cities - Energy Efficiency & Renewables in the Digital Era, Lausanne, 2021-09-08/2021-09-10. Bristol: Journal of Physics: Conference Series (JPCS), 2021. CISBAT 2021 Carbon-neutral cities - energy efficiency and renewables in the digital era 8-10 September 2021, EPFL

Lausanne, Switzerland. vol. 2042. ISSN 1742-6596. DOI 10.1088/1742-6596/2042/1/012084. Available from: https://iopscience.iop.org/article/10.1088/1742-6596/2042/1/012084
15. VESELKA, J., et al. Katalog prvků zvyšujících resilienci. [Electronic Document with Remote Access (www)] Praha: CTU. University Centre of Energy Efficient Buildings, 2020.
16. RYKLOVÁ, P., J. VESELKA, and Š. MANČÍK. Posuzování environmentálních dopadů konstrukčního systému TiCo. Časopis Stavebnictví. 2021, XV(01-02/2021), 34-39. ISSN 1802-2030.¨
17. NEHASILOVÁ, M., et al. EnviBIM: Environmental Data Module for BIM Library of Construction Elements. In: IOP Conference Series: Earth and Environmental Science. BEYOND 2020 – World Sustainable Built Environment Online conference, Gothenburg, 2020-11-02/2020-11-04. Bristol: IOP Publishing Ltd, 2020. vol. 588. ISSN 1755-1307. DOI 10.1088/1755-1315/588/5/052019.
18. FRISCHKNECHT, R., et al. Comparison of the Greenhouse Gas Emissions of a High-rise Residential Building Assessed with Different National LCA Approaches–IEA EBC Annex 72. In: IOP Conference Series: Earth and Environmental Science. BEYOND 2020 – World Sustainable Built Environment Online conference, Gothenburg, 2020-11-02/2020-11-04. Bristol: IOP Publishing Ltd, 2020. vol. 588. ISSN 1755-1307. DOI 10.1088/1755-1315/588/2/022029.
19. SOUST-VERDAGUER, B., et al. Implications of Using Systematic Decomposition Structures to Organizebuilding LCA Information: A Comparative Analysis of National Standardsand Guidelines- IEA EBC ANNEX 72. In: IOP Conference Series: Earth and Environmental Science. BEYOND 2020 – World Sustainable Built Environment Online conference, Gothenburg, 2020-11-02/2020-11-04. Bristol: IOP Publishing Ltd, 2020. vol. 588. ISSN 1755-1307.
20. VESELKA, J., et al. Recommendations for Developing a BIM for the Purpose of LCA in Green Building Certifications. SUSTAINABILITY. 2020, 12(15), ISSN 2071-1050. DOI 10.3390/su12156151. Available from: https://www.mdpi.com/2071-1050/12/15/6151
21. VESELKA, J., et al. Connecting BIM and LCA: The Case Study of an Experimental Residential Building. In: SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019 (SBE19 Graz). Graz, 2019-09-11/2019-09-14. Graz: Graz University of Technology, 2019. IOP Conference Series: Earth and Environmental Science. vol. 323. ISSN 1755-1315. DOI 10.1088/1755-1315/323/1/012106. Available from: https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012106/pdf
22. MATĚJKA, P., et al. Rešerše a srovnání klasifikačních systémů stavebních prvků v kontextu informačního modelování staveb (BIM). [Research Report] 2018.

23. RŮŽIČKA, J., et al. Typový podklad subtilního skeletu OSEEB pro energeticky efektivní budovy. Praha: CTU. Czech Technical University Publishing House, 2016.
24. MATĚJKA, P., et al. The Implementation of Building Information Modeling into Educational Programs at CTU in Prague. In: HÁJEK, P., et al., eds. Central Europe towards Sustainable Building 2016 - Innovations for Sustainable Future. Central Europe towards Sustainable Building 2016 Innovations for Sustainable Future, Prague, 2016-06-22/2016-06-24. Praha: GRADA PUBLISHING, 2016. p. 853-860. 1st edition, Prague, June 2016, Complete edition - printed version + Flash disk with full paper version. ISBN 978-80-271-0248-8.

7.2 Thesis-related books

The following list is not directly cited in the text. These books and textbooks supported research activities within the whole study and they were helpful in steering direction of this work.

SANCHEZ, Adriana, Keith HAMPSON a Simon VAUX. Delivering value with BIM: a whole-of-life approach. New York: Routledge, 2016. ISBN 978-1-138-11899-7.

KLASCHKA, R. BIM in Small Practices: Illustrated Case Studies. London: NBS / RIBA, 2014. ISBN 978-1-85946-499-1.

LÉVY, François. BIM in small-scale sustainable design. Hoboken, N.J.: Wiley, 2012. ISBN 978-0-470-59089-8.

KRYGIEL, Eddy a Brad NIES. Green BIM: successful sustainable design with building information modeling. Indianapolis, Ind.: Wiley Pub., c2008. Serious skills. ISBN 978-.0-470-23960-5.

MORDUE, S. a R. FINCH. BIM for Construction Helath and Safety. London: RIBA, 2014. ISBN 978-1-85946-528-8.

KENSEK, K. M. Building Information Modeling. Pocket Architecture. New York: Routledge, 2014. ISBN 978-0-415-71774-8.

SMITH, D. K. a M. TARDIF. Building Information Modeling - A strategic . Implementation Guide. New Jersey: John Wiley and Sons, 2009. ISBN 978-0-470- 25003-7.

POLI, Riccardo, W. B. LANGDON a Nicholas F. MCPHEE. A field guide to genetic programming. [S.l.: Lulu Press], 2008. ISBN 978-1-4092-0073-4.

GOLDBERG, David E. Genetic Algorithms: in search, Optimization and Machine Learning. India: Repro Knowledgecast Limited, 2006. ISBN 978-81-775-8829-3.

HARDIN, Brad. Bim and construction management: proven tools, methods, and workflows, second edition. 2nd edition. Indianapolis, IN: John Wiley, 2015, pages cm. ISBN 1118942760.

KLVAŇA, Jaroslav. Modelování 20: operační výzkum 2. Vyd. 3. Praha: Vydavatelství ČVUT, 1993 [cit. 2022-05-11]. ISBN 8001032639.

KLVAŇA, Jaroslav. Modelování 10: operační výzkum 1. Vyd. 3. přeprac. Praha: České vysoké učení technické, 2000. ISBN 8001021580.

FIALA, Petr. Modely a metody rozhodování. 3., přeprac. vyd. V Praze: Oeconomica, 2013. ISBN 9788024519814.

JABLONSKÝ, Josef. Programy pro matematické modelování. Vyd. 2., přeprac. Praha: Oeconomica, 2011. ISBN 9788024518107.

JABLONSKÝ, Josef, Miroslav MAŇAS a Petr FIALA. Vícekriteriální rozhodování. 1997. Praha: Vysoká škola ekonomická v Praze, 1994. ISBN 8070797487.

8 Annex: Related Research Projects Overview

The following chapter will mention the research projects that were undertaken during PhD studies and in which the author was involved. The most of them were already cited in the main text. This chapter is ment to be a summary of them and explanation of their relation to this thesis. All the projects helped to get various experience in BIM-LCA workflow.

8.1 RESBy Project

Project Overview

The aim of the project was focused on resilience of the buildings and it looked for answer whether sophisticated or a simpler but easily replicable solution is better for resilient buildings.

BIM Implementation

BIM was not an essential part of the project, but various innovative elements were developed and tested (e.g. solar chimney, special facade elements, etc.).

A library of these elements and specific design solutions was modeled as part of this project. In addition, two design variants of the project itself were modeled, which differed in their design solutions. This was used as the basis for calculating the environmental performance of both variants.

Project Summary, lesson learned

During the involvement in the project, the tendency was to have all the environmental impact values directly included in the model. This may be appropriate in a research project, however, this solution has proved to be inappropriate for commercial practice as the modelers overwhelmingly do not have the knowledge to deal with environmental impacts competently. On the other hand, experts in the field of environmental impacts of buildings often do not know how to work with an information model. This is likely to change with time.

Therefore, it has proved more appropriate to use the information model only as a bill of quantities, which is exported from the model and further worked with in an external tool.

Using particular elements is not always necessary to increase the resilience of a building. Greater building resilience can be achieved by using commonly available parts. This may be a specific construction procedure, precautionary measure, or oversizing certain elements (see Chapter 2.2.4). The catalog contains two variants of the proposed building, developed in BIM, and seven parts developed or used to improve resilience. In addition to the graphical representation, the elements contain non-graphical information about the component. These elements can be reused in other projects.

8.2 TiCo Project

Project Overview

The project aimed to design and verify in practice the possibility of a combined construction system. This is primarily composed of reinforced concrete with a proportion of high-value cement. The other elements (walls, partitions, bathroom cores) are made of wood-based panels. This combination of timber and reinforced concrete promises a high degree of prefabrication and consequently increased speed of construction. The construction system is also suitable for apartment buildings with up to 5 stories, which are usually impossible to build using only wooden structures according to Czech standards. In the framework of this project, a demonstration building, including 3 residential units and common areas was constructed.

BIM Implementation

Detailed information models were created for the project, including all structures, individual wooden panels, etc. Also, models with building services were developed. These models were used to prepare the prefabrication of the production of the demonstration unit.

Based on the model, the environmental impacts of the building were calculated and the partial impact values for the individual materials and structures were fed back into the model. The results of the project were presented by the author at a conference in Graz [83].

Project Summary, lesson learned

The project was created at a similar time as the RESBy project mentioned in the previous chapter. The construction model thus includes a range of information, including environmental impacts. During the course of the project (as in chapter 0), this solution proved to be inappropriate. The project thus confirmed the assumption that it is more practically applicable to perform the environmental analysis externally, outside the information model itself.

As an outcome of this project was a publication Environmental impact assessment of the TiCo structural system [80] (in Czech).

8.3 Project BIMIP

Project Overview

The project is directly related to TiCo, mentioned in the previous chapter. It has several objectives:

1. Electronization of the SBToolCZ methodology while maximizing the usability of the building information model.
2. Comparison of calculated and actual values on real building operation.
3. Analyzing the possibility of using information modeling in the design process of prefabricated wooden buildings.

The SBToolCZ methodology is a robust tool for comprehensive building quality assessment, which has been developed since about 2008 and is adapted to the specifics of the Czech construction industry. To assess a project, documentation is required at approximately the level for Building Permits. However, at this stage, there is still time to make significant conceptual changes.

BIM Implementation

First, an analysis of the SBToolCZ methodology was carried out, which showed that out of about 500 parameters entering the building assessment, about 200 could be extracted directly from the model (theoretically, all of them can be extracted, however, it was assessed that this process would no longer be efficient). Subsequently, the model was modified (the TiCo model was used for this purpose) to be compatible with the requirements of the SBToolCZ evaluation. In parallel, an update of the SBToolCZ methodology was carried out, followed by the development of a web-based tool to allow the entire calculation to be performed online.

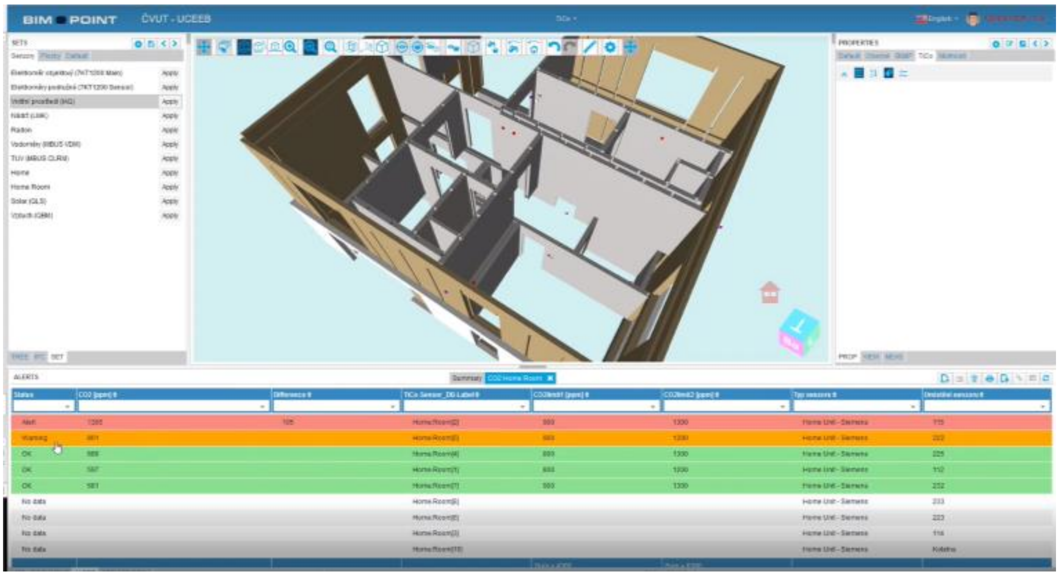

Figure 61 - The BIMIP project shown in the BIMPOINT environment (author´ s archive).

Project Summary, lesson learned

One of the outputs of this project was an article in the journal Sustainability BIM and Automation in Complex Building Assessment [66].

8.4 Preliminary SBToolCZ Project

Project Overview

This small-scale student project was a follow-up to BIMIP and aimed to identify key parameters that have an impact on the final evaluation and are already known at an earlier stage of the project. Individual indicators of the SBToolCZ methodology were analysed.

BIM Implementation

A partial objective was to use the conceptual information model, which is already available at this stage of the project, to the maximum extent possible, at approximately the LOD 200. From the model, the areas, volumes, approximate material characteristics of the substructures, the project location, etc. can be included in the preliminary calculation.

Project Summary, lesson learned

On the basis of the project, an interactive form was created, which can be filled in to make a preliminary assessment according to the SBToolCZ methodology. The form is also used to fill in information from the sub-options and the preliminary information model. The results of the project were presented by the author at the CISBAT 2021 conference BIM in early design phase: Workflow for preliminary assessment with SBToolCZ [72].

8.5 EnviBIM

Project Overview

The project was carried out in cooperation with DEK (the most prominent building materials and materials retailer in the Czech Republic). Their part DEKsoft aims to develop tools and specialized software for several professions, such as building physics, radon protection, etc. This project aimed to create an environmental impact database for a predefined range of products. This meant implementing the data structure given by budgeting practices and supplementing it with the environmental impacts of single materials or compositions.

Several thousand items were analyzed, and a system for sorting environmental impacts was created. Everything was verified in several case studies (traditional method and comparison with export from the information model). The environmental impact data was then uploaded to an online BIM platform tool managed by DEKsoft.

BIM Implementation

The implementation took place at two levels, firstly in the verification of the results on case studies (family and apartment building) and secondly in the transfer of the environmental impact database into the online tool BIM platform in which the environmental data is publicly available.

Project Summary, lesson learned

The result is a freely accessible tool where designers can find out information about the environmental impacts of individual proposed structures free of charge.

Another output of the project was an article Rapid Environmental Assessment of Buildings: Linking Environmental and Cost Estimating Databases [82].

8.6 Annex 72 Project

Project Overview

It was the most comprehensive project in the whole study, thanks to the participation of many colleagues from prestigious universities worldwide. The opportunity to meet with them regularly (although this opportunity was limited during Covid) was very inspiring. Another positive aspect was the opportunity to go on internships at ETH Zurich and TU Graz as part of this project.

Project objectives were according the project proposal (available online[27]):

- Establish a common methodology guideline to assess the life cycle based primary energy demand, greenhouse gas emissions and environmental impacts caused by buildings.
- Establish methods for the development of specific environmental benchmarks for different types of buildings.
- Derive regionally differentiated guidelines and tools for building design and planning such as BIM for architects and planners.
- Establish a number of case studies, focused to allow for answering some of the research issues and for deriving empirical benchmarks.
- Develop national or regional databases with regionally differentiated life cycle assessment data tailored to the construction sector; share experiences with the setup and update of such databases.

BIM Implementation

BIM issues have been addressed in several areas. Within the framework of possible tools, the creation of an information model, questionnaires on the specifics of the process, and research on modeling in the different phases of the project. The results were verified with case studies. All sub-outputs occur throughout this thesis.

Project Summary, lesson learned

As mentioned, the project has been beneficial in many ways. In addition to establishing international cooperation, it provided the opportunity to contribute to several peer-reviewed publications and conferences [48], [75], [77], [79], [84].

8.7 Automation 4 Timber

Project Overview

The main partner of the project is the company RD Rymarov, the largest manufacturer of wooden buildings in the Czech Republic. The project aims to streamline the process of design, preparation of project documentation and production of houses by digitizing the entire process. Colleagues from the Faculty of Mechanical Engineering of the Czech Technical University in Prague are also involved in the project. The implementation of BIM is a key element of this project.

BIM Implementation

Based on the analysis conducted, it was identified that information modelling along with advanced manufacturing automation are two key inputs that can streamline the entire construction preparation and prefabrication process at RDR. ArchiCAD and SEMA software solutions were selected. In the former, a model of the house is prepared on the basis of the prepared library of elements and the documentation for the building permit is prepared. This is followed by export to IFC format. Thanks to the chosen internal classification system, the walls are

[27] https://annex72.iea-ebc.org/about

modelled automatically after import into SEMA software, but thanks to the prepared library, including all structural elements (columns, beams, penetrations, nails, staples, etc.). The structural designer checks and adjusts the elements, if necessary, and then the data can be generated for the CNC machines. According to internal estimates, this optimized process can be accelerated by 20-30%. It turns out that a significant obstacle in project implementation is the resistance of people to change. The whole software update (and therefore the change of the work process) is very challenging and the implementation has not been fully completed yet.

Project Summary, lesson learned

This project has not yet been completed and runs until the end of 2024.

It is expected that the project will address the digitalisation of building permits in BIM. One of the outcomes is a conference paper Highly automated production of prefabricated wood-based building envelopes : potential for a significant reduction of carbon footprint of residential development [85].