The Potential of Digitalization for Sustainability: A Building Process Perspective

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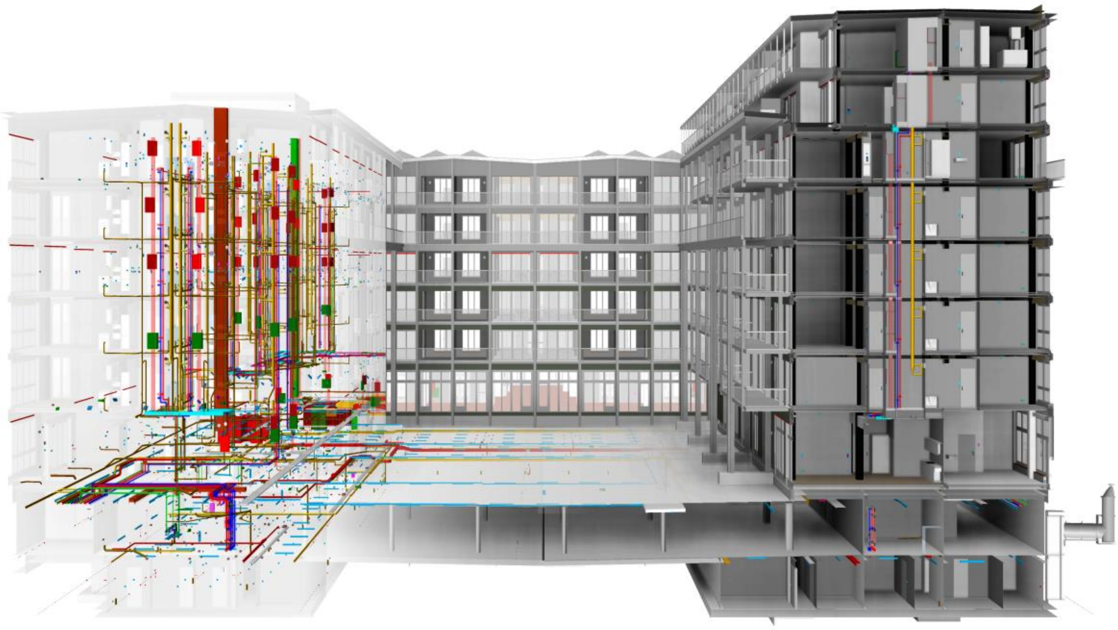

Institute of Construction and Infrastructure Management

Master Thesis | Anita Naneva

The Potential of Digitalization for Sustainability: A Building Process Perspective

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Digitalization, Sustainability, Building Process, Building Information Modelling (BIM), Life-Cycle Assessment (LCA), Level of Development (LOD)

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Abstract

There is a potential of digitalization in improving sustainability throughout the entire building process. One way to address this potential is through BIM-LCA integration. Life-Cycle Assessment (LCA) is a method for analyzing the environmental impact of buildings. Building Information Modelling (BIM) is a methodology that can help to account for LCA during the Building Process. Current industry practice and research show that there are mainly two approaches for BIM-LCA integration. Either the evaluation is done in a simplified way at the beginning of the building process, or it is accounted for at the end when the needed information is available, but it is too late for having an impact on decision-making. There is, therefore, a lack of methods and tools for implementing BIM-LCA integration over the entire building process. Based on this, the objectives of this study are to analyze the potential of integration of LCA methodology in BIM practice in the Architecture, Engineering, Construction, and Operations (AECO) industry and to define a methodology for BIM-LCA integration in the Swiss context. For the achievement of the objectives, a parametric tool for BIM-LCA evaluation is created and tested on a case study. The case study is provided by the Swiss construction company Implenia AG. Through the application of the parametric tool on the case study, it is shown that the entire building process (SIA 112, 2001) can be evaluated for its environmental impact continuously in each Building Phase (SIA 112, 2001) while applying an existing code structure (crb, 2012). In that way, the re-work that characterizes most of the current LCA practices is minimized and decision-making metrics, both at Element (SIA, 2018) and Building (MINERGIE, 2014) Levels, are provided.

Acknowledgments

I would like to express my deepest gratitude towards Prof. Dr. Daniel Hall and Dr. Marcella Bonanomi from the Chair of Innovative and Industrial Construction, my supervisors from ETH Zurich. Their valuable and constructive support during the development of this thesis, as well as their willingness to give their time whenever I had questions, or I was not sure of the direction for the development of the thesis, were of great importance to me. I highly appreciate their input.

I would like to highlight my deepest gratitude towards Prof. Dr. Guillaume Habert and Dr. Alexander Hollberg from the Chair of Sustainable Construction, my co-supervisors from ETH Zurich. They trusted me to become part of their team even before I came to Zurich and welcomed me with open hearts once I was officially part of the university. They have always supported me and guided me in our common projects, through which I have gained the knowledge to develop this master thesis.

I would also like to thank my supervisors from Implenia AG, Alar Jost and Felix Stauch from the BIM department and Yves Deluz and Nicolas Fries from the Sustainability department. I would especially like to thank Alar Jost for stimulating me and providing me with the opportunity to work on the topic of this master thesis together with such a strong industry partner as Implenia AG. My deepest gratitude towards Felix Stauch for always being there for me whenever I had questions and no matter how busy he was, and Yves Deluz and Nicolas Fries for helping my understanding of the topic on a higher level. I want to thank all of my colleagues from Implenia AG for welcoming me and making me part of their team.

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Abbreviations

AECO industry – Architecture, Engineering, Construction, and Operations industry
API - Application Programming Interface
BIM – Building Information Modeling/Models
BLM - Building Life-Cycle Management
BOQ – Bill of Quantities
CDE – Common Data Environment
EPD - Environmental Product Declaration
ERA - Energy Reference Area
GDP – Gross Domestic Product
GHG – Greenhouse Gas emissions
GWP – Global Warming Potential
IFC - Industry Foundation Classes
LCA – Life-Cycle Assessment
LCC – Life-Cycle Costing
LCI – Life-Cycle Inventory
LOD – Level of Development
LOG – Level of Geometry
LOI – Level of Information
MVD - Model View Definition
RSL - Reference Service Life
SIA - Schweizerischer Ingenieur- und Architektenverein (The Swiss National Organization of Engineers and Architects)

Disclaimer

All tables, figures and other content provided is work, developed by the author unless cited otherwise. For questions or feedback, the author can be reached by e-mail using the address provided on the cover page.

Built upon

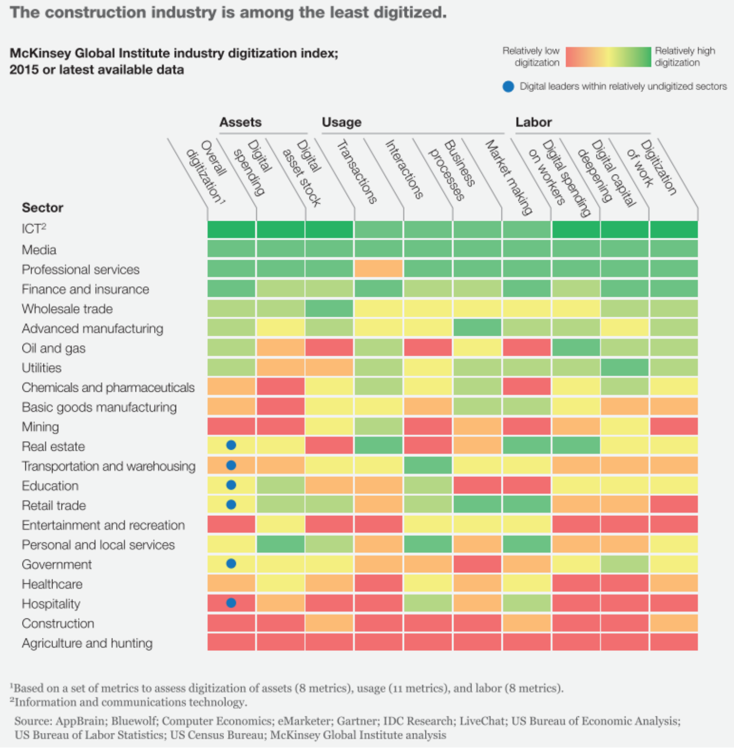
This master thesis has been built upon the work developed by the Author as a Technical Assistant in the Department of Sustainable Construction at ETH Zurich, starting from 2017. The Author has worked together with Dr. Alexander Hollberg on the topics of Life-Cycle Assessment (LCA) of Buildings, Parametric Design, Real-time Analysis Methods.

The thesis is also built upon the Journal Article by Carmine Cavalliere, Guillaume Habert, Guido Raffaele Dell'Osso and Alexander Hollberg published in November 2018 and entitled “Continuous BIM-based assessment of embodied environmental impacts throughout the design process”.

1 Motivation

The world is changing at a tremendous pace. Retief *et al.* (2016) distinguish six key megatrends associated with this transition, namely demographics, urbanization, technological innovation, power shift, resource scarcity, and climate change. All of these trends are highly related to the Architecture, Engineering, Construction, and Operations (AECO) industry. Still, the AECO industry fails to address them appropriately (McKinsey&Company, 201AD; Best, 2012; Agarwal, Chandrasekaran, and Sridhar, 2016). Given that the AECO is a key industry in many countries across the world, its transformation would have effects on the society, economy, and the environment (Group and Gerbert, 2016).

Group and Gerbert (2016) state that 30% of greenhouse gas emissions are attributed to buildings. In their work "Shaping the Future of Construction", the authors point out that the population of the world's urban areas is increasing by 200'000 people per day. The increased population is related to a higher need for affordable housing, transportation, and infrastructure. McKinsey&Company (201AD) note that globally, about $10 trillion are spent on construction-related matters, equivalent to 13% of the Gross Domestic Product (GDP). The AECO industry employees 7% of the world's working population. However, the adoption of new technologies in it is much slower compared to other industries (McKinsey&Company, 201AD). The industry has been slow to adopt process-related and technological innovations, as well as integrated supply-chain practices (Agarwal, Chandrasekaran and Sridhar, 2016). As shown in Figure 1 below, the AECO industry was in 2015, one of the least digitalized ones.


The construction industry is among the least digitized.

McKinsey Global Institute industry digitization index; 2015 or latest available data

[1] Based on a set of metrics to assess digitization of assets (8 metrics), usage (11 metrics), and labor (8 metrics).
[2] Information and communications technology.

Source: AppBrain; Bluewolf; Computer Economics; eMarketer; Gartner; IDC Research; LiveChat; US Bureau of Economic Analysis; US Bureau of Labor Statistics; US Census Bureau; McKinsey Global Institute analysis

Figure 1: Digitalization in different industries: The construction industry is amongst the least digitalized (Agarwal, Chandrasekaran and Sridhar, 2016)

1.1 Digitalization

Digitalization has the potential to bring significant opportunities for the transformation of the AECO industry (Lavikka *et al.*, 2018). Agarwal, Chandrasekaran, and Sridhar (2016) identify five trends for the industry's digital transformation:

- Higher-definition surveying and geolocation;
- Next-generation 5D building information modeling (BIM)[1];
- Digital collaboration and mobility;
- The Internet of Things and advanced analytics;
- Future-proof design and construction (Figure 2).

Source: McKinsey analysis

Figure 2: Five trends that shape construction and capital projects (Agarwal, Chandrasekaran and Sridhar, 2016)

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[1] Building Information Modeling (BIM) is the process of creating information models containing both graphical and non-graphical information in a Common Data Environment (CDE). The process has several dimensions:

- 3D BIM: three-dimensional representation of a building;
- 4D BIM: schedule analysis;
- 5D BIM: cost analysis;
- 6D BIM: sustainability assessment;
- 7D BIM: management phase of what has been achieved.

Sources: NBS - a technology platform for the construction industry (https://www.thenbs.com/); BibLus - international blog providing information for architectural, engineering and construction industry software world (http://biblus.accasoftware.com).

Group and Gerbert (2016) point out that digitalization supports data-driven decision-making based on visualizations and simulations. Collaborative value creation through new forms of interactions to improve information sharing and transparency are other positive aspects associated with digitalization (Schober, Hoff, and Sold, 2015).

As highlighted by Agarwal, Chandrasekaran, and Sridhar (2016), Building Information Modeling (BIM) is an innovative methodology associated with the digitalization of the Architecture, Engineering, Construction, and Operations (AECO) industry. The AECO industry is dealing with a significant amount of data coming from different disciplines involved in the design, construction, and maintenance processes. BIM is a 3D model-based process and technology by which a structured multi-layered organization of information obtained by different stakeholders can be gathered and a multidisciplinary collaboration amongst them could be achieved (Eadie *et al.*, 2013). Building Information Models are progressively being applied throughout the lifecycle of a building, serving various applications, expanding from the design, construction and maintenance processes (e.g., building shape selection, material selection, energy simulation, building systems analysis, scheduling and cash flows, information and actors' flows, defect detection, building renovation and refurbishment and waste-materials disposal) (Agarwal, Chandrasekaran, and Sridhar, 2016).

Eastman *et al.* (2011) indicate that BIM has received a lot of attention from both academia and industry. Bynum, Issa, and Olbina (2013) point out that BIM's usage in the design and construction industry has increased due to its ability to accelerate collaboration among diverse disciplines. According to the authors, building information models can help the structuring of information and provide the ability for the development of standards and recommendations. They point out the ability of a BIM model to generate possible solutions themselves.

Building Information Models do not consist of a two-dimensional representation of a building, but they rather represent its actual three-dimensional assembly (Krygiel, Nies, and McDowell, 2008). BIM expands further beyond documentation and materials processing. Its structure allows for a better transition from design to construction, making workflow and information available to diverse stakeholders and creating a collaborative process (Grilo and Jardim-Goncalves, 2010). Through collaboration, the usage of time and resources is reduced while improving the overall quality and efficiency (Suermann *et al.*, 2009).

In the AECO industry BIM usage can help to (1) support collaboration amongst diverse stakeholders, (2) visualize the examined structure by providing renders and animations, (3) perform energy and structural analysis, (4) facilitate team members to work on the same project simultaneously, (5) support for construction-related tasks, such as cost-analysis, quantity take-off, schedule estimation and project management (*Top Criteria for BIM Solutions: AECbytes Survey Results | AECbytes Blog*, 2007).

1.2 Sustainability

Defining sustainability

The term sustainability originates from the publication "Our Common Future" written in 1987 by the UN-established Brundtland Commission. From this publication, comes the definition of sustainability, namely: "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN-established Brundtland Commission, 1987). The United Nations maintains this definition, which is part of the 17 UN Sustainable Development Goals for the 2030 Agenda (United Nations, 2015).

Bynum *et al.* (2013) reflect on the threats caused by global warming and its relation to the built environment. The authors point out that although the AECO industry has started to address the issue, there is still a big potential for reducing carbon emissions and energy use, as well as for creating a new generation of high-performance green buildings. An investment in a more sustainable built environment is a necessity to achieve a reduction in global warming potential (GWP) (Hertwich and Peters, 2009). The application of sustainable techniques over time should bring a considerate result on reduced environmental impact on a larger ecological scale (Bynum *et al.*, 2013).

Sustainability can be described under three dimensions: environmental, economic, and social.

Environmental sustainability deals with the natural environment and its parameters, like climate and resources. It highlights the possibility of resource optimization through reuse and recycling strategies. Another aspect of environmental sustainability is lowering the environmental impact of the building throughout its whole life-cycle, for example, the production of building materials, operation of the building, and disposal/recycling of building materials. Additional focus is the impact on biodiversity and land-use by the usage of toxic substances (GXN innovation, Guldager, and Birgisdottir, 2018).

Economic sustainability focuses on the relation between cost and quality of the built environment. It balances the operational cost, quality, and life-cycle value of the building. It covers the potential of changing the use of the building as well (GXN innovation, Guldager, and Birgisdottir, 2018).

Addressing social sustainability to the built environment, it characterizes the health and safety of the inhabitants of a building and its surroundings. It focuses on human well-being and spaces encouraging social interactions. Another aspect is the promotion of sustainable transport for interaction between the inhabitants of the building and the surrounded environment (GXN innovation, Guldager, and Birgisdottir, 2018).

Green Building Assessment Organizations

Many green building standards and certification systems have been established to analyze and evaluate projects from the built environment and assess their sustainability performance. The main goal of these standards is to promote high-performance energy-efficient buildings, implementing responsive phases regarding design, construction, operation, and maintenance. Another goal is to raise awareness of building environmental issues by setting benchmarks for recommended practices (Bynum *et al.*, 2013).

Over 600 sustainability certifications exist today (Figure 3) (Reed *et al.*, 2009; GXN innovation, Guldager, and Birgisdottir, 2018). Still, there is no full overview of assessing these certificates. The first sustainable building certification was BREEAM, established in 1990. In the following 1990s years, certificates like LEED, HQE, Minergie, and Green Star were established in Europe and North America (Ebert *et al.*, 2011). In the 2000s Asia and South America found their first certificates, although making no big progress on the number of certified buildings. More commitment is needed from African countries to implement sustainable building certifications (GXN innovation, Guldager, and Birgisdottir, 2018).

Figure 3: Green Building Assessment Organizations around the world (GXN innovation, Guldager, and Birgisdottir, 2018)

Buildings, which have green building certificates, perform better than conventional buildings on social, economic, and environmental sustainability aspects (WORLD GREEN BUILDING COUNCIL, 2013). Green certificates make the benefits of certified buildings clear, insuring good quality during all the building phases while strengthening sustainable agendas (GXN innovation, Guldager, and Birgisdottir, 2018).

Certification systems bring the opportunity to measure and compare different buildings based on their sustainable performance. Still, this comparison is only possible while using the same certification system. The term sustainability is becoming broader in its meaning, thus making certification systems highly variable in their scope and application. The increase in variety in green standards makes this comparison even harder (GXN innovation, Guldager, and Birgisdottir, 2018).

To understand certification systems, we need common units and structures. GXN innovation, Guldager, and Birgisdottir (2018) review ten case studies involving different certification systems. By doing so, the authors provide a methodology for assessing building certifications on a shared definition of sustainability in the built environment. They point out that the focus on sustainable building certification is increasing, which makes the market diversifying. The authors highlight that multiple certifications can be used in combination to strengthen their sustainability characteristics. All the reviewed certificates are multiple attribute building certificates, meaning they look at the building as a whole and consider the surroundings, performance efficiency, emissions, toxicity, water, and energy use (GXN innovation, Guldager, and Birgisdottir, 2018).

As mentioned before, sustainable development can be described under three dimensions – environmental, economic, and social sustainability. GXN innovation, Guldager, and Birgisdottir (2018) use these three dimensions and define thirteen aspects for comparing green building certifications (Table 1):

Environmental sustainability dimension aspects	• Environmental impact: use of Life-Cycle Assessment (LCA) to reduce the environmental impact of the buildings life-cycle and evaluate different strategies; • Resources: minimize the use of resources (energy, materials, fuels, and water). Usage of LCA to evaluate different design strategies. Avoidance or limitation of usage of non-renewable resources; • Biodiversity: limitation of the usage of green areas for construction. Optimization of usage of developed or brownfield areas. Effective use of building sites and contribution to increase biodiversity; • Recycling: preparation of building components for recycling by design for disassembly. Provide good planning on the construction site to limit construction waste. Provide reuse when possible; • Toxicity: reduction or limitation of the usage of toxic materials. Point out if there exist problematic substances in the building.
Economic sustainability dimension aspects	• Life-cycle costing: calculation of the life-cycle costing of the building, including cost construction and operation cost, as well as facility management cost; • Area use: optimization of the layout of the usage of areas; • Stability of value: usage of robust materials that last longer and could be reused. Acknowledge possible change of function of the building.
Social sustainability dimension aspects	• Safety: insurance the safety of all people and facilities related to the built environment. Creation of procedures in case of an emergency. Design for universal accessibility; • Health: promotion of the well-being of users of the building. Thermal and visual comfort, high-quality acoustics, air, water, light and daylight user control; • Architecture: design quality in aesthetics and spatial planning. Access to outdoor areas and benefits to the existing environment; • Transport: opportunities for traveling outside and inside the building areas (e.g., bike areas and parking, stairs). Encourage healthy and sustainable transport; • Social responsibility: traceable and responsible provision of services and materials for construction (especially during the construction phase).

Table 1: Sustainability aspects (GXN innovation, Guldager, and Birgisdottir, 2018)

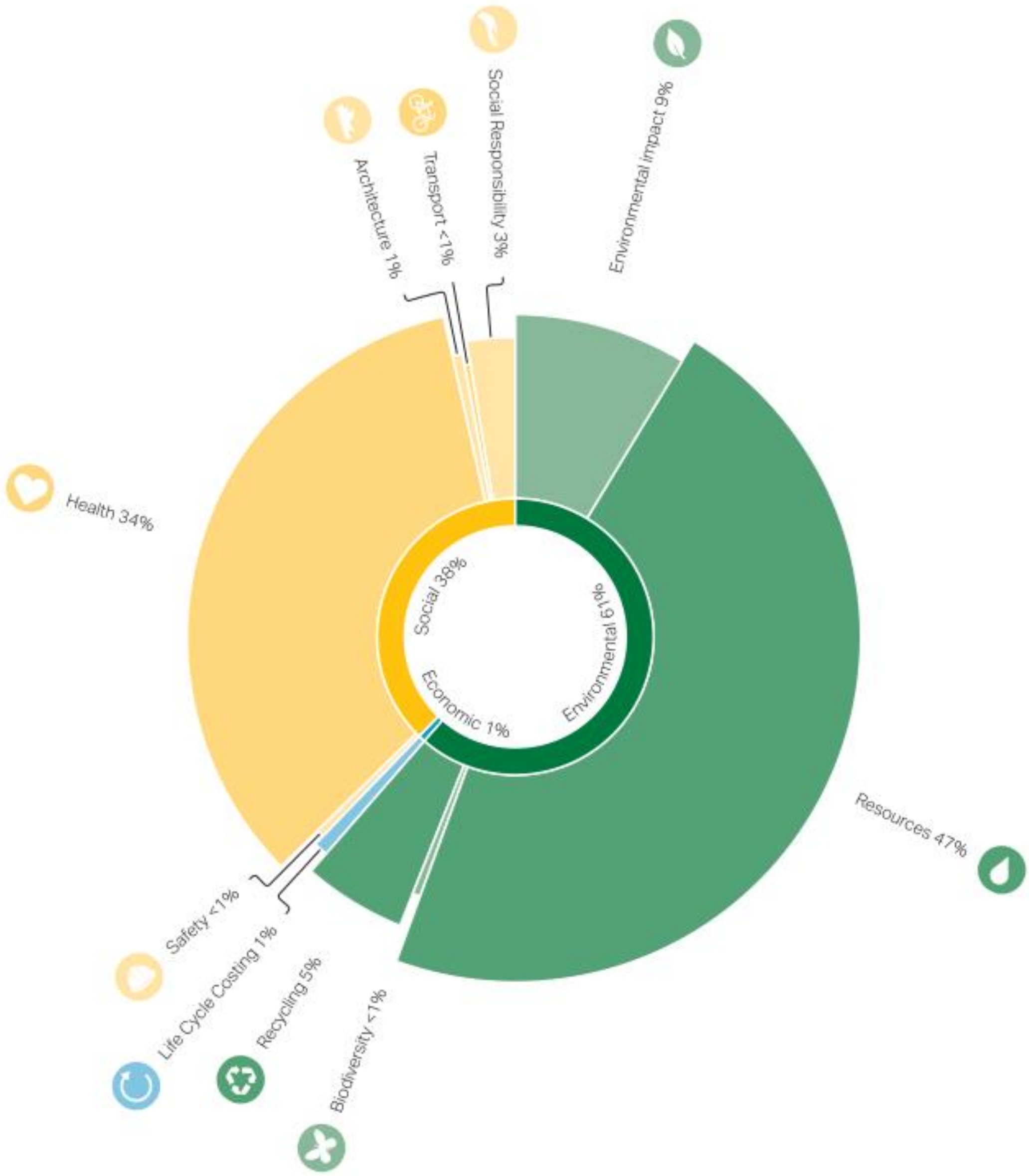

Figure 4: Environmental, Economic and Social Sustainability parameters (GXN innovation, Guldager, and Birgisdottir, 2018)

Comparing the three sustainability dimensions (Figure 4), the environmental one is the most strongly represented in the study by GXN innovation, Guldager, and Birgisdottir (2018), followed by the social one. The economic dimension exists in around 5% of the observed certificates. The authors of the analysis point out that each parameter has different aspects. The resource parameter focuses mostly on energy and water consumption and the metering of the system. The health parameter includes improvements to the indoor climate of the building. The environmental parameter focuses on the LCA of the building or the building components. However, its scope depends on the certification. The recycling parameter takes into account both the usage of recycled materials and the disposal and recycling of used materials (GXN innovation, Guldager, and Birgisdottir, 2018).

1.3 Digitalization and Sustainability

Elmualim and Gilder (2014) point out that Building Information Modeling (BIM) does not only support the building development process from a technical perspective. The authors note that BIM also supports the creation of an innovative and integrated working platform to improve productivity and sustainability throughout the project lifecycle. Through the usage of BIM, professionals can examine energy-saving alternatives early in the design phase, without the need to wait for detailed building geometry and related information (Jalaei and Jrade, 2014).

Three metrics describe sustainability: environmental, economic, and social (Khan, Dewan, and Chowdhury, 2016).

Environmental sustainability is a state in which demands are met without compromising future generations' ability to provide for themselves. It deals with the amounts of greenhouse gas emissions that enter the atmosphere (Sassi, 2016). When associated with the built environment, it accounts for energy used for building materials production (Wong and Zhou, 2015). BIM has the potential to improve LCA analysis over the building process (Cavalliere, Habert, *et al.*, 2018).

Economic sustainability is associated with creating economic value. The metric provides adequate decision-making while taking into consideration the other aspects of sustainability (CWanamaker, 2018). From an economic sustainability point of view, it is proven that BIM improves the Life-Cycle Cost (LCC) saving of a project (Lu *et al.*, 2014). BIM also enables energy-consumption analysis for optimal design selection (Guo and Wei, 2016).

Social sustainability refers to the capability of people to exist in a way that serves their needs as well as the needs of future generations (Chong, Lee and Wang, 2017). Within the built environmental perspective, social sustainability is best accomplished by taking into consideration its stakeholders' needs (Almahmoud and Doloi, 2015). BIM is related to social sustainability in two ways. It allows an overview of the design through visualization, provided by its three-dimensional component. By this visualization, owners can give feedback and review the project. BIM also enables collaboration between the different stakeholders, who are part of the project, by transforming the conventional, highly fragmented practice. Through BIM, team members can share and exchange information with other members and have a base for decision making (NBIMS, 2007).

Chong, Lee, and Wang (2017) point out that environmental, economic, and social sustainability are highly related to each other and that a discussion about sustainability should include all of them since they are hardly distinguishable. The authors conduct a research to examine the sustainable development of the built environment. Based on that research, they highlight the following seven aspects related to sustainability, BIM, and the AECO industry:

- <u>Planning Phase</u> –This phase is the most significant one. It has the greatest impact on social, economic, and environmental aspects. The phase describes the overall project's concept, as well as project delivery planning. Using BIM at this phase brings the possibility of improving the effectiveness and efficiency of project development processes mostly through reducing waste from re-works and re-planning (Gibbs et al., 2015).
- <u>Design Phase</u> – The design phase includes project development from the conceptual design to the selection of the contractor phase. BIM optimizes design and coordination amongst multidisciplinary stakeholders (Singh, Gu, and Wang, 2011).

- Construction Phase – The overall construction process from site preparation to commissioning is part of the construction phase. BIM provides early three-dimensional visualization for cost and schedule estimation (Wang et al., 2014). Construction errors can be reduced, and productivity can be improved (Chong, Lee, and Wang, 2017).
- Operation and Maintenance Phase – Part of that phase is the period from practical completion to post-occupation. BIM enables integrated operational management in a virtual environment and facilitates maintenance (Chong et al., 2014).
- Refurbishment and Demolition Phase – This phase indicates the retrofit or demolition works done at the end of the life of a project. BIM supports the appropriate method for demolition and refurbishment, as well as detailed information about the elements part of an existing project (Yun et al., 2014).
- Use of Products and Materials – This aspect has a high relation to environmental sustainability. Through 3D BIM, building materials can be evaluated (Kim et al., 2015).
- Energy consumption – Energy consumption can be simulated through energy simulation software providing information about the heating, ventilation, air-conditioning, and lighting during the project lifecycle (Ahn et al., 2014).

Bynum *et al.* (2013) indicate that BIM should work on increasing its capacity to integrate environmental analysis and improve interoperability. The authors illustrate that the technology provided by BIM should assist sustainability in establishing standards. They also highlight the importance of the AECO industry and its willingness for the implementation of these standards in practice.

The combination of BIM and sustainable design practices has the potential to provide high-performance design. BIM technologies can be used already in the early design phase to perform structural analysis, environmental control, material selection, and building systems control (Jalaei and Jrade, 2014).

1.4 Embodied and Operational energy

Iddon and Firth (2013) distinguish two types of energy use throughout the lifecycle of a building, namely embodied energy and operational energy. The embodied energy is associated with the construction of the building, while the operational energy with the post-construction stage.

NHBC (2011) describes embodied energy as embodied CO_2 emissions, resulting from excavation and manufacture of construction materials, as well as their transportation to site, assembly to finish the dwelling, refurbishment, and demolition. The authors see the operational energy as operational CO_2 emissions, which are emissions resulting from space and water heating, ventilation, lighting, and appliances in a building. The two types of energies are distinguished in Figure 5.

Figure 5: Total CO2 emissions arising from the life-cycle of a dwelling (blue: embodied energy, purple: operational energy) (NHBC, 2011)

The authors of several studies mention that the significance of the embodied energy may account for up to 60% of the building's total energy (Thormark, 2002; Lützkendorf *et al.*, 2015; Sartori and Hestnes, 2007). A considerable fraction of this embodied energy is associated with off-site production of building materials and their transportation to the construction site (Chau, Leung and Ng, 2015).

Capper, Matthews, and Lockley (2012) highlight the need for more information about the embodied energy of building materials to be incorporated as early as possible so that a better outcome could be achieved (Table 2). Shadram *et al.* (2016) state that the building materials supply chain contributes significantly to both the embodied energy and the total energy use.

		Progression through design process			
		Conceptual Design	**Schematic Design**	**Detailed Design**	**Construction**
Increasing Level of Detail	**Building**	✓			
	e.g. school				
	System		✓		
	e.g. external walling				
	Element			✓	
	e.g. cavity wall				
	Material				✓
	e.g. brick				

Table 2: Level of detail by stage of design (Capper, Matthews and Lockley, 2012)

For the evaluation of operational energy, information regarding aspects related to building systems, like structural integrity, ventilation, temperature control, circulation, lighting, energy distribution, and consumption, need to be taken into account. Such aspects can be integrated into the BIM model for their easier assessment (Azhar, Brown, and Sattineni, 2017). Building regulations and certifications are part of the measures applied to reduce operational energy (Iddon and Firth, 2013). As a result, the designed buildings are more energy-efficient, in particular, minimizing the space heat demands by reducing the fabric and infiltration heat losses (NBS Services, 2010).

With the reduction of operational energy, the embodied one gets a greater proportion of the building's life-cycle carbon emissions (Iddon and Firth, 2013). A study conducted by NHBC (2011) examines the proportion of embodied carbon over 60 and 120 lifespans for a typical detached and terraced house. The study shows that embodied energy tends to increase when attempts to reduce operational energy are made. According to Liljenström *et al.* (2015 b), embodied energy is comparable to operational energy at a given lifespan of 50 years.

Howard and Björk (2008) point out that knowledge about building requirements should be structured so that as much data as possible is accumulated during all phases of the design process.

2 Theoretical background (Literature review)

2.1 Life-Cycle Assessment (LCA)

Life-Cycle Assessment (LCA) is a methodology through which environmental loads and energy required by activities and processes (extraction, transport, construction, operation, renovation, and demolition of building materials), could be assessed. It covers the whole life-cycle of a building, from raw materials extraction and processing to the end-of-life stage (Figure 6) (Cavalliere, Dell'Osso, *et al.*, 2018).

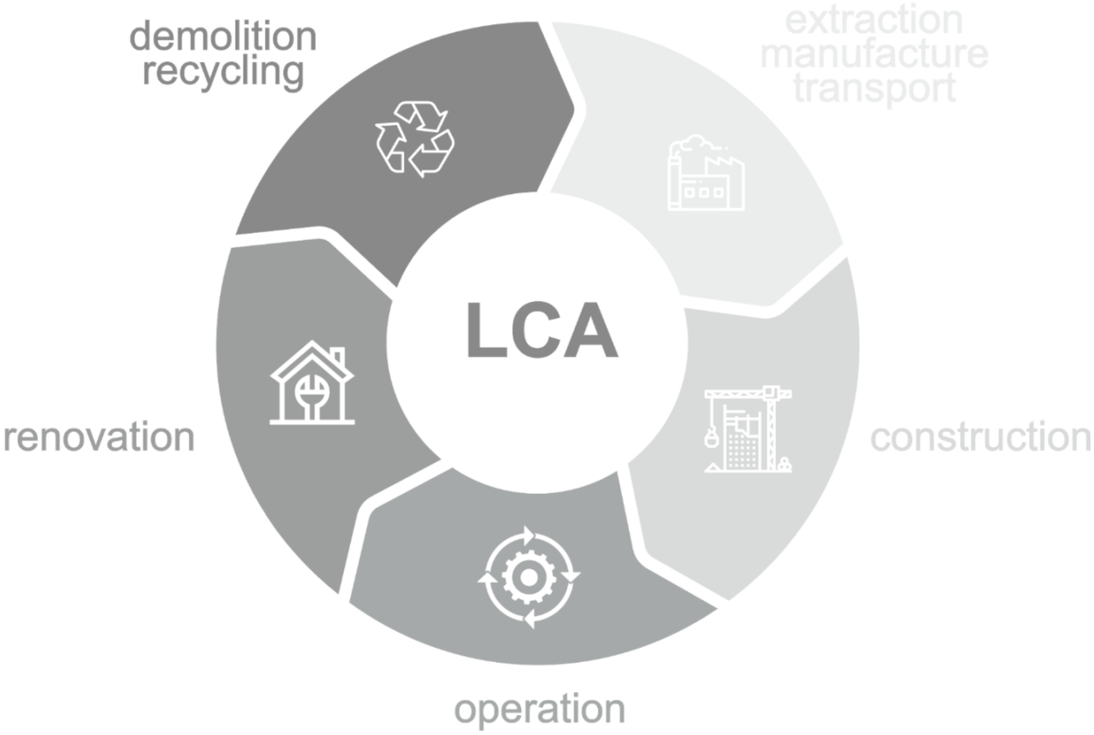

Figure 6: Life-Cycle Assessment (LCA)

Life-Cycle Assessment (LCA) is widely used for environmental evaluation in industrial practices, involving controlled processes (Braet, 2011). When applied in the AECO industry, however, LCA becomes more challenging, because of the involvement of more complex processes: the long lifespan of the entire building (50-100 years), lower predictability of uncertainties, different lifespan of different building materials, variability of building materials and processes, uniqueness of each different building, varying transport distances to different resource providers, maintenance, retrofitting (Ortiz, Castells and Sonnemann, 2009; Ramesh, Prakash and Shukla, 2010; Zabalza Bribián, Aranda Usón and Scarpellini, 2009; Sharma *et al.*, 2011). Because of the less standardized processes, more assumptions should be taken into account (Buyle, Braet, and Audenaert, 2013).

For the assessment of the complex product system of an entire building, different methodologies and standards are used, resulting in challenges to understand and compare outcomes (Röck *et al.*, 2019). There are recent developments in standardization aiming to overcome these issues (e.g., ISO 15804/15789, CEN TC 442, PEF Guidance).

According to Russell-Smith and Lepech (2012), LCA can predict the environmental impact of buildings during their life-cycle and support sustainable decisions. LCA of buildings must consider the specific features of the AECO industry (Cavalliere, Dell'Osso, *et al.*, 2018). Each building is a unique structure composed of different elements, each of which has its life-cycle (Means and Guggemos, 2015).

For the LCA application on buildings, a variety of information is needed: general information about the building itself, building components, and materials used in the building, information about the building operation. Recent studies observe the potential of using digital building models to handle the big amount of information required (Röck *et al.*, 2019).

2.2 Life-Cycle Assessment (LCA) and Building Information Modeling (BIM)

To apply LCA of buildings, the potential benefits of BIM-LCA integration has gained a lot of attention amongst researchers (Figure 7) (Röck *et al.*, 2019).

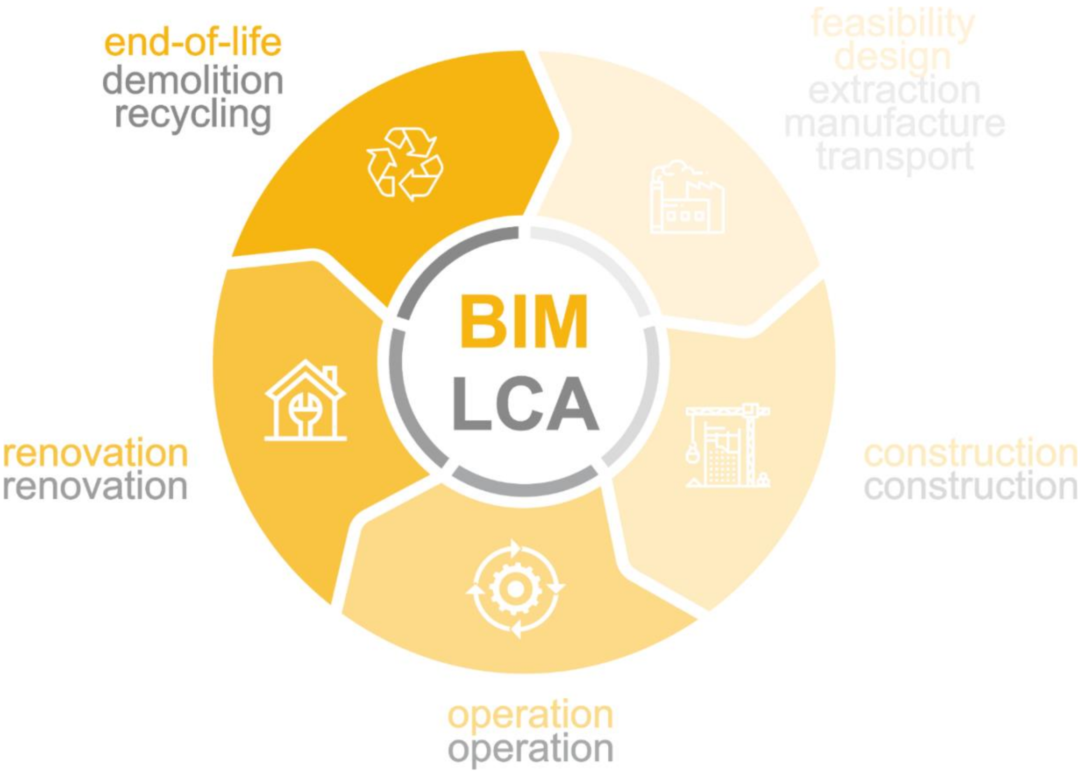

Figure 7: Life-Cycle Assessment (LCA) and Building Information Modeling (BIM)

For the adoption of LCA as a decision-making tool, uncertainties, related to the building process, should be reduced. BIM is a method through which these issues could be overcome (Cavalliere, Dell'Osso, *et al.*, 2018). BIM is a process involving human activities, that require paradigmatic process changes in all phases related to the AECO industry (Eastman *et al.*, 2011). BIM offers the possibility to implement different types of information while allowing their take-off, e.g., for quantities, cost estimations, and material properties (Cheung *et al.*, 2012). A successful BIM model is strongly related to interoperability. This interoperability could be achieved by the usage of Industry Foundation Classes (IFC) (Grilo and Jardim-Goncalves, 2010).

The integration of BIM and LCA has many advantages for the building process and decision making. It can reduce the time for the assessment and improve the application of the environmental criteria of a building from the early design stages. The usage of data from the BIM model allows achieving a more accurate LCA. Having defined data sources from the BIM model eliminates the necessity for manual data re-entry. A BIM model with a certain maturity level and Level of Development (LOD) might include environmental indicators that are not considered in a conventional LCA methodology (Bueno and Fabricio, 2016b).

For the creation of LCA, the collection of data about materials and information regarding their production and transportation is required. The process of re-entering this data is time-consuming and not done by the specialists involved in the creation of the BIM model (Fischer *et al.*, 2004). A computational framework is required for an efficient, dynamic life-cycle approach, that links design software with environmental assessment tools. The integration of BIM and LCA has the potential to automate this approach by using material specifications and material quantity take-off that is included in the BIM model. The integration of BIM and LCA accelerates the overall environmental assessment process (Russell-Smith, Lepech, and Student, 2011). BIM models can be used to represent the entire life-cycle of a project (Eastman *et al.*, 2011). BIM is expected to accelerate LCA application throughout the entire building process (Röck *et al.*, 2019).

2.3 Life-Cycle Assessment (LCA) implementation

Through the application of Life-Cycle Assessment (LCA), the overall impact of a building life-cycle can be evaluated. This application can be conducted in two ways: a bottom-up approach, which focuses on the selection of building materials, and a top-down approach, which takes into account the whole building as a starting point for further improvements (Bueno and Fabricio, 2016b).

2.3.1 LCA Databases structure

Floor area-based LCA Databases: SIA2040/SIA-Effizienzpfad Energie

Floor area-based LCA Databases use building components surface area (m^2) and floor area (m^2) to calculate the environmental impact. They allow the first estimation of LCA parameters at the beginning of the building process. An example of such a database, mainly used in the Swiss context, is the SIA2040, or SIA-Effizienzpfad Energie (SIA-Energy-efficiency path) (SIA2040, 2011). The SIA2040 provides estimation and prediction of LCA Parameters during the Building Phases 1 and 2 (Strategic Briefing and Preliminary Studies)[2] in the areas of design, operation, and mobility. Through a calculation based on SIA2040, a preliminary analysis can be done, and the potential LCA evaluated.

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[2] Described in part 2.4.2 BIM-LCA Integration: Building phases, of this report.

Component-based LCA Databases: Bauteilkatalog

Component-based LCA Databases provide information regarding LCA parameters for different building components (m^2). An example from Switzerland is the Bauteilkatalog which combines building component data from BFE (Bundesamt für Energie)[3] / Hollinger Consult GmbH[4] and LCA data from KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) [5] / eco-bau[6] / IPB (Interessengemeinschaft privater professioneller Bauherren)[7] (Bauteilkatalog, 2016). In this way, the building components are evaluated according to LCA parameters per m^2 for their easier implementation and decision-making basis provision.

Material-based LCA Databases: KBOB/eco-bau/IPB (KBOB, 2018)

Material-based LCA Databases make a step further in providing details about LCA parameters. The databases provide information regarding the environmental impact of different building materials. A Swiss example is the KBOB[5] / eco-bau[6] / IPB[7] database. The information regarding LCA provided by the database is based on surface area (m^2) or mass (kg) of building materials.

2.3.2 LCA Application time

Different approaches try to simplify LCA so that its applicability is enhanced. Some studies propose LCA related to a specific building phase, using a simplified method at the beginning and performing a full LCA at the end (Röck *et al.*, 2019).

For the provision of simplified data for early design phases, the levels of detail of building elements and sub-elements are investigated by many authors (Kellenberger and Althaus, 2009; Marsh, 2016; Passer *et al.*, 2015). Trigaux *et al.* (2017) suggest a hierarchical and modular approach to organize LCA databases on different levels, from building level macro-perspective to construction materials micro-perspective.

Existing studies present methods for BIM-based LCA with application in a specific phase (Cavalliere, Dell'Osso, *et al.*, 2018). The focus is usually on an early conceptual phase, thus taking many assumptions into account, or on a late detailed phase when the needed information is accessible but it is too late for influencing the decision-making process. In both these cases, the BIM-based LCA cannot provide decision-making support, because the entire process is not included and nor is the evolution of information considered. BIM-based LCA also does not declare Level of Development (LOD) (Soust-Verdaguer, Llatas, and García-Martínez, 2017).

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[3] BFE (Bundesamt für Energie) – Swiss Federal Office of Energy. The Federal Office of Energy is a federal agency of the Swiss Confederation. It is responsible for national energy supply and use. The Office is part of the Federal Department of the Environment, Transport, Energy and Communications (DETEC). Source: https://www.bfe.admin.ch/

[4] Hollinger Consult GmbH – a consulting company working in the area of sustainability. Source: https://www.holligerconsult.ch/

[5] KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) - Coordination conference of the building and real estate organs of public builders. The KBOB was founded in 1968 as a coordinating body of the federal building authorities, namely for questions of submission, the inflation compensation on construction works and the architect and engineer fees. Source: https://www.kbob.admin.ch/

[6] eco-bau - The eco-bau association was founded in 2005 to promote sustainable building environment. Members of the association are public builders of the federal government, cantons and cities as well as organizations such as KBOB, crb and educational institutions. Source: https://www.eco-bau.ch/

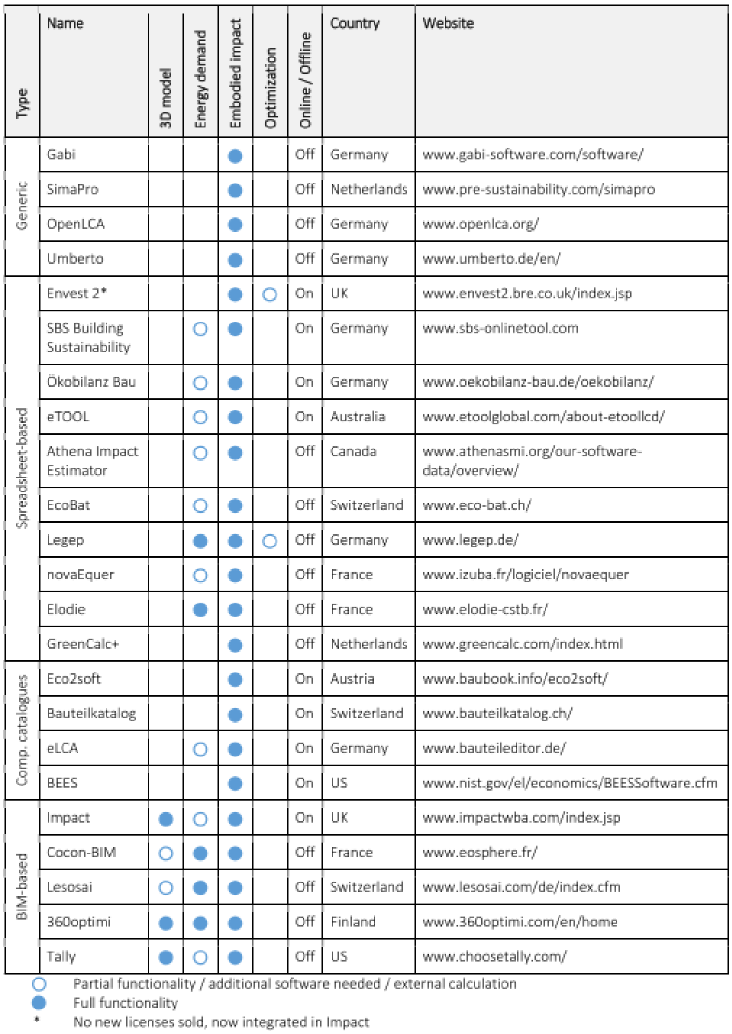
[7] IPB (Interessengemeinschaft privater professioneller Bauherren) - Interest group of private professional builders. The association represents the interests of private professional builders, service providers, trade associations, authorities and other organizations. Source: http://www.ipb-online.ch/

2.3.3 LCA Tools

Hollberg (2017) clusters existing tools for LCA in four groups: generic LCA tools, spreadsheet-based calculation, online component catalogs, and BIM-based tools (Table 3):

- Generic LCA tools: Generic LCA tools provide detailed functions for element-based models. The input in these tools is manual. The tools are commonly used for Environmental Product Declaration (EPD). They require extensive background knowledge and are not suitable for non-LCA experts;
- Spreadsheet-based calculation: Most LCA tools use spreadsheets in which bills of quantities (BOQ) are input manually. The LCA calculations are done through formulas integrated into the spreadsheets;
- Online component catalogs: There are different online component-based catalogs that enable the LCA for building elements. For the usage of these catalogs, manual input of quantities is required, from which BOQ is generated and multiplied with LCA values so that the environmental impact is calculated;
- BIM-based tools: BIM-based tools are plug-ins for BIM software that generate BOQ automatically and combine it with environmental data. Even though the process is automated, the material matching is a quite challenging process.

Source: Hollberg (2017), (Table 3)



Type	Name	3D model	Energy demand	Embodied impact	Optimization	Online / Offline	Country	Website
Generic	Gabi			●		Off	Germany	www.gabi-software.com/software/
	SimaPro			●		Off	Netherlands	www.pre-sustainability.com/simapro
	OpenLCA			●		Off	Germany	www.openlca.org/
	Umberto			●		Off	Germany	www.umberto.de/en/
Spreadsheet-based	Envest 2*			●	○	On	UK	www.envest2.bre.co.uk/index.jsp
	SBS Building Sustainability		○	●		On	Germany	www.sbs-onlinetool.com
	Ökobilanz Bau		○	●		On	Germany	www.oekobilanz-bau.de/oekobilanz/
	eTOOL		○	●		On	Australia	www.etoolglobal.com/about-etoollcd/
	Athena Impact Estimator		○	●		Off	Canada	www.athenasmi.org/our-software-data/overview/
	EcoBat		○	●		Off	Switzerland	www.eco-bat.ch/
	Legep		●	●	○	Off	Germany	www.legep.de/
	novaEquer		○	●		Off	France	www.izuba.fr/logiciel/novaequer
	Elodie		●	●		Off	France	www.elodie-cstb.fr/
	GreenCalc+			●		Off	Netherlands	www.greencalc.com/index.html
Comp. catalogues	Eco2soft			●		On	Austria	www.baubook.info/eco2soft/
	Bauteilkatalog			●		On	Switzerland	www.bauteilkatalog.ch/
	eLCA		○	●		On	Germany	www.bauteileditor.de/
	BEES			●		On	US	www.nist.gov/el/economics/BEESSoftware.cfm
BIM-based	Impact	●	○	●		On	UK	www.impactwba.com/index.jsp
	Cocon-BIM	○	●	●		Off	France	www.eosphere.fr/
	Lesosai	○	●	●		Off	Switzerland	www.lesosai.com/de/index.cfm
	360optimi	●	●	●		Off	Finland	www.360optimi.com/en/home
	Tally	●	○	●		Off	US	www.choosetally.com/

○ Partial functionality / additional software needed / external calculation
● Full functionality
* No new licenses sold, now integrated in Impact

Table 3: Current computer-aided LCA tools (Hollberg, 2017)

2.3.4 LCA Methodologies

The LCA tools described above can be clustered further into two main groups by considering the methodology through which they are applied: Static methods for LCA and Dynamic methods for LCA.

Static methods for LCA

Figure 8 below proposes a generalization of how the static methods for LCA typically operate. The Static methods for LCA represent the current practice adopted by most construction companies. The unstructured and informal interviews[8] held with different industry participants help highlight the issues related to the current practice. The generic LCA tools, the Spreadsheet-based calculation, and the Online component catalogs[9] use this method for LCA implementation.

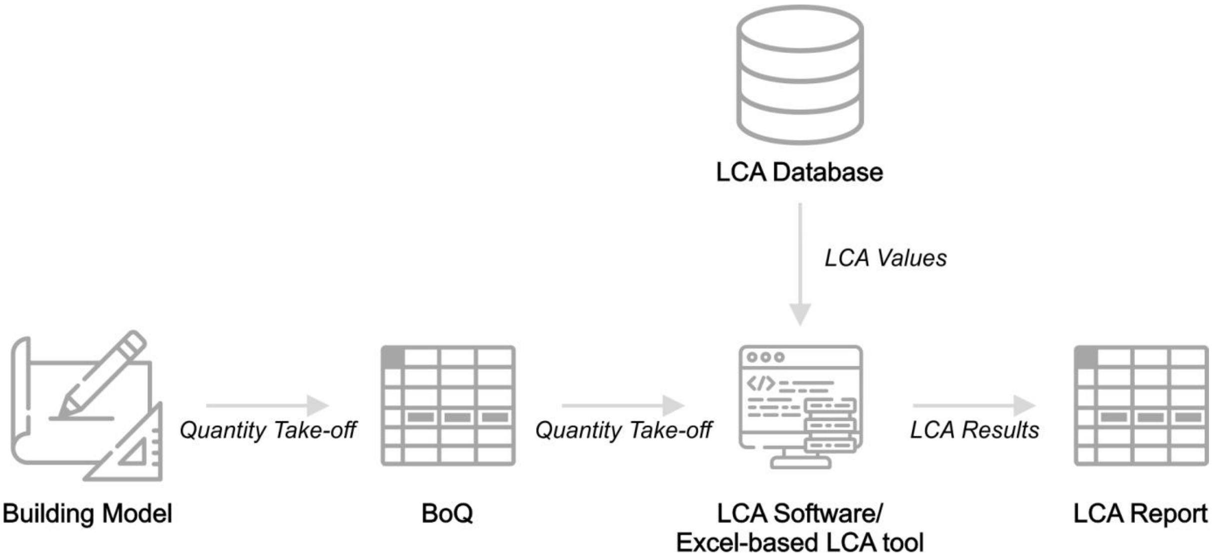


Figure 8: Static method for LCA

The process starts with a Building model that can be a 2D, 3D, or a BIM model. Depending on the model, the BOQ can be extracted manually or automatically. After its extraction, the quantities are input manually in a selected tool. The tool itself requires either a manual LCA parameters input or is connected to an LCA Database. For the connection to the database, additional work is required, since there is no common code structure used for associating the quantities to the LCA parameters. After connecting the quantities with the LCA parameters, an LCA Report can be created. However, the data from the report are not connected with the Building Model, so the information flow is linear, and the decision-making is difficult. The method is highly dependent on the Building Phase during which it is applied since the information in the model might not be sufficient for LCA or at the same Level of Information (LOI) as the LCA Database.

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[8] Described in part 4.2 Unstructured and informal interviews with experts, of this report.

[9] Described in part 2.3.3 Life-Cycle Assessment (LCA) implementation: LCA Tools, of this report.

The static method can be described with the following issues:

- **Quantity Take-off** that is challenging;
- **Data input and output** that are manual and are associated with a potential for errors;
- **Information flow** that is linear and provides no direct feedback;
- **Data complexity** that requires specified LCA skills;
- **Decision-making** that is difficult;
- **High dependency** on the **LCA Database Code Structure** and the **Building Phase** during which the method is applied.

Dynamic methods for LCA

The Dynamic methods for LCA (Figure 9) can be associated with BIM-based tools[10]:

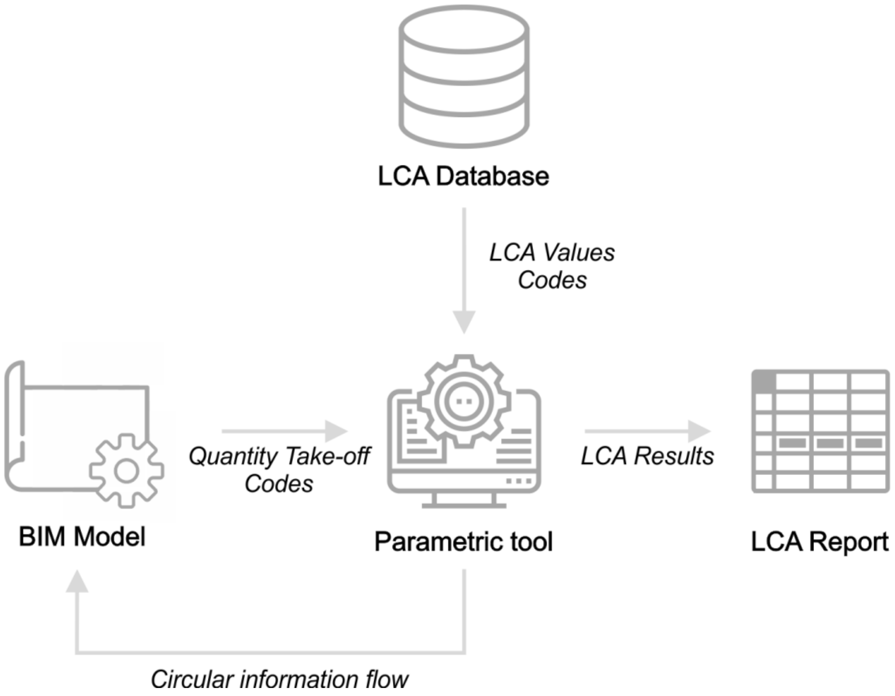

Figure 9: Dynamic method for LCA

For the implementation of the dynamic method, a BIM Model is needed as a starting point. With the help of the BIM Model, the BOQ can be extracted automatically. Then the quantities are linked to an LCA Database with the help of a parametric tool. Still, if the quantities are not associated with a code structure existing in the BIM Model, there should be a manual adjustment in the model for their proper mapping to the related LCA parameters. Once the quantities are mapped, the LCA results can be extracted as an LCA Report. The method is again highly dependent on the Building Phase in which it is applied. The information flow in this method can be circular since the Parametric tool, together with the BIM Model, provides this opportunity. The decision-making is yet challenging since it is hard to make conclusions based on LCA values.

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[10] Described in part 2.3.3 Life-Cycle Assessment (LCA) implementation: LCA Tools, of this report.

The dynamic method for LCA provides potential through its BIM-LCA integration, since:

- The **Quantity Take-off** is effortless;
- The **Data input and output** are automated;
- The **Information flow** is circular;
- The **Data complexity** can be parameterized.

However:

- The **Decision-making** is still difficult;
- The **High dependency** on the **LCA Database Code Structure** and on the **Building Phase** in which the method is applied is still not prevented.

2.4 BIM-LCA Integration

Howard and Björk (2008) point out that knowledge about building requirements should be structured so that as much data as possible is accumulated during all the phases of the design process.

Mcarthur (2015) highlights four key challenges to develop BIM models suitable for sustainable operations:

- Identification of critical information;
- Management and transfer of information in real-time;
- A significant amount of effort to create new or modify existing BIM models;
- Handling of uncertainty based on incomplete building documentation.

BIM-LCA integration provides many benefits, mainly through the automation of the Life-Cycle Inventory (LCI) that is related to LCA Values. However, the integration strongly depends on the Level of Development (LOD) of the BIM model and the structure of the LCA database. The BIM model structure, BIM maturity level, and LOD need to be clarified before assessment workflow and tools can be used (Röck *et al.*, 2019).

According to Röck *et al.* (2019), the potential for BIM-LCA integration can be supported by:

- Organization of inventory according to international standards for results interpretation;
- Structure, composed of building elements and sub-elements with different levels of detail;
- Link between BIM elements and quantities and LCA databases for integrated establishment of LCI;
- Parametric approach for establishing LCA based on BIM and LCA.

2.4.1 BIM Maturity and Level of Development (LOD)

By integrating BIM and LCA, an environmental impact can be achieved. For the integration to take place, BIM models should have a certain level of maturity for the LCA calculation to happen accurately in the backend (Hollberg, 2017).

BIM has begun to broaden the opportunities it provides for project stakeholders by allowing them to combine new digital technologies. In each level of BIM Maturity[11], the provided benefits expand (Figure 10). The most advanced level of BIM is Level 3, in which the data is fully transferable across project stakeholders. The combination of BIM data and LCA creates Building Life-Cycle Management (BLM). BLM increases predictability, profitability, and long-term value for project owners (DASSAULT SYSTEMS, 2015).

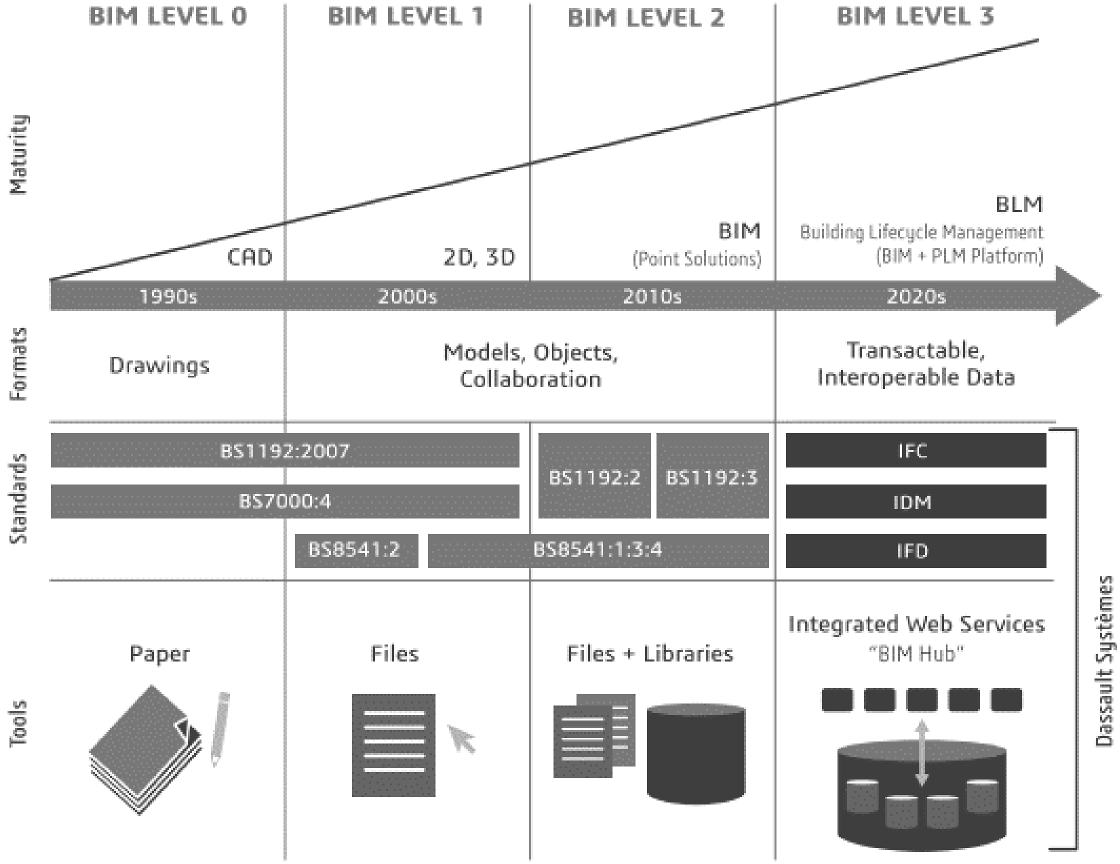

Figure 10: BIM Maturity (DASSAULT SYSTEMS, 2015)

Every BIM Software creates a different data structure (Bueno and Fabricio, 2016a). Röck *et al.* (2019) point out that the quality of a BIM model depends on its Level of Development (LOD). The authors highlight that the LOD depends on two other factors, namely Level of Geometry (LOG) and Level of Information (LOI). For the environmental impact to be better understood, both the geometrical and the data structure of the BIM model should be examined (Bueno and Fabricio, 2016a).

In general, the LOD concept proposes for the design process to start with generic, yet representative elements, that are being constantly refined throughout the design decision-making process (Meex *et al.*, 2018).

Curschellas *et al.* (2018) from Bauen Digital Schweiz and buildingSMART Switzerland (part of BuildingSMART International) develop definitions about LOD, LOI, and LOG in the context of Switzerland (Figure 11).

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[11] BIM Maturity is described by BIM Levels from 0 to 3. BIM Level 0 describes the period when mainly paper tools and CAD files were used. BIM Level 1 is for the period when 2D and 3D files appeared. In BIM Level 2 these 3D files were associated with certain information. BIM Level 3 - Building Lifecycle Management (BLM) is about the combination of BIM and LCA data (Figure 10) *(DASSAULT SYSTEMS, 2015).*

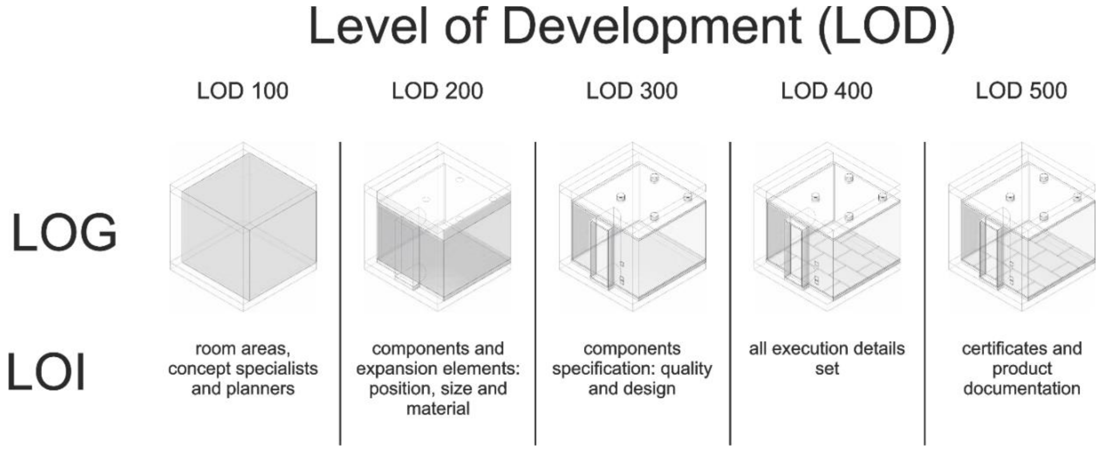

Figure 11: Level of Development (LOD) and its respective Level of Information (LOI) and Level of Geometry (LOG)[12] *(Curschellas et al., 2018)*

The Swiss BIM LOIN Definition (LOD) is a guideline that helps project participants define and articulate the content of models in different phases of the planning and construction process with high clarity (Curschellas *et al.*, 2018). It is related to the components, the requirements, and the performance values. LOD describes how detailed a model element must be to achieve the required degree of completion (depth of information, visualization). The degree of completion is the degree to which the element's geometry (LOG) and associated information (LOI) are developed. It represents the degree to which the project teams can rely on when using the model. Level of detail can thus be described as a required input into the element, while Level of Development (LOD) is the reliable output (state of knowledge, state of planning).

According to the authors (Curschellas *et al.*, 2018), the LOD:

- forms the basis for communication in the project to make the respective levels within a project readable;
- follows the usage plan and the applications described therein, where the respective need for information can be read;
- is the basis for the definition of the degree of completion and to what extent the model elements are to be developed for the requirements of planning, construction, and operation;
- includes the geometric representation with LOG (Level of Geometry) and the alphanumeric information with LOI (Level of Information);
- is described in terms of its degree of completion from 100 to 500;
- provides clarity and assurance about what is expected from all stakeholders involved in building and maintaining a model;
- forms the basis for organizing cooperation, responsibilities, and results to be delivered by stakeholders;
- forms a central element of the project management and the BIM development plan.

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[12] In LOD100, the room areas are defined and the concept determined by different specialists and planners. In LOD200, information regarding components and expansion of elements, as well as their position, size and material from which they are composed, is provided. LOD300 gives input about components specifications, quality and design. In LOD400, all execution details are set and in LOD500 the certificates and product documentation are composed.

2.4.2 Building phases

The Swiss National Organization of Engineers and Architects (SIA - Schweizerischer Ingenieur- und Architektenverein), distinguishes six Building phases: Building Phase 1, Strategic Briefing; Building Phase 2, Preliminary Studies; Building Phase 3, Project; Building Phase 4, Invitation to Tender; Building Phase 5, Construction; Building Phase 6, Facility Management (SIA 112, 2001)[13]. In addition to this, Menz, Bastianello, and Eglin (2014) point out the different goals and services associated with each of the phases (Figure 12) (Appendix A.1).

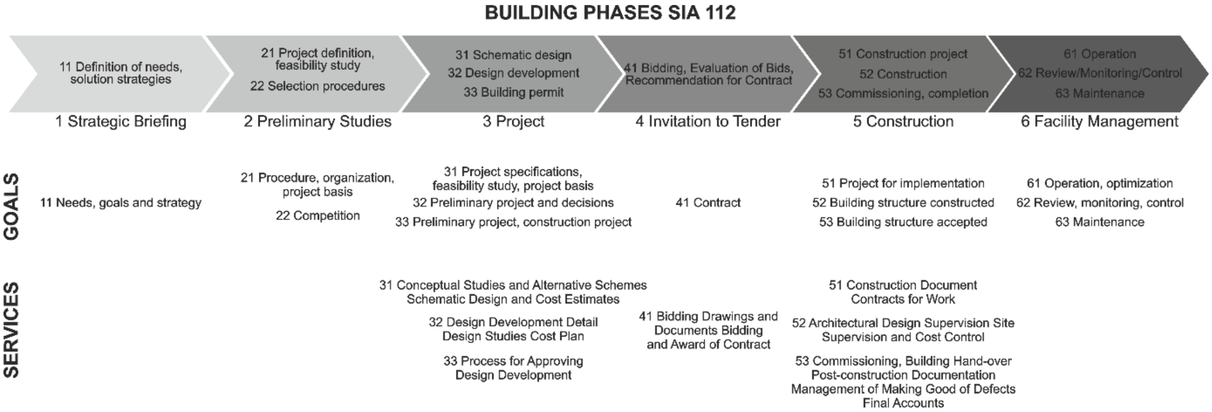

Figure 12: Building phases (SIA) and related services and goals (SIA 112, 2001; Menz, Bastianello and Eglin, 2014)

In their book, entitled “Drei Bücher über den Bauprozess”, Menz, Bastianello, and Eglin (2014) also distinguish different stakeholders involved in the building process (Figure 13) (Appendix A.1).

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[13] Building Phase 1, Strategic Briefing, is related to Building Sub-Phase 11, namely Definition of needs and solution strategies. In this phase, needs, goals and general conditions are defined and the strategy for solution determined.

Building Phase 2, Preliminary Studies, contains the Sub-Phase 21, Project definition and feasibility study, and the Sub-Phase 22, Selection procedures. During Sub-Phase 21, the procedures and organization are defined, as well as the project basis, and the feasibility is demonstrated. During Sub-Phase 22, the project, which best meets the requirements defined, as well as its provider, are selected.

Building Phase 3, Project, is composed of Sub-Phase 31, Schematic design, Sub-Phase 32, Design development, and Sub-Phase 33, Building permit. During Sub-Phase 31, the concept and the profitability are optimized. In Sub-Phase 32, the project and the cost are optimized and defined and in Sub-Phase 33 the project is approved, the cost and the schedule verified and the construction credit granted.

Building Phase 4, Invitation to Tender, includes Sub-Phase 41, namely Bidding, evaluation of bids and recommendation for contract. During this phase, the contract is prepared for awarding.

Building Phase 5, Construction, includes Sub-Phase 51, Construction project, Sub-Phase 52, Construction and Sub-Phase 53, Commissioning and completion. During Sub-Phase 51, the project is prepared for implementation, while in Sub-Phase 52 the building structure is constructed according to the specifications and the contract. In Sub-Phase 53, the building structure is accepted and commissioned, the final cost settled and accepted and the defects corrected.

Building Phase 6 includes Sub-Phase 61, Operation, Sub-Phase 62, Review, monitoring and control and Sub-Phase 63, Maintenance. During Sub-Phase 61, the operation is ensured and optimized. In Sub-Phase 62, the real estate`s status is determined and the maintenance ensured and in Sub-Phase 63 the fitness for use and value of the building structure maintained for defined period of time.

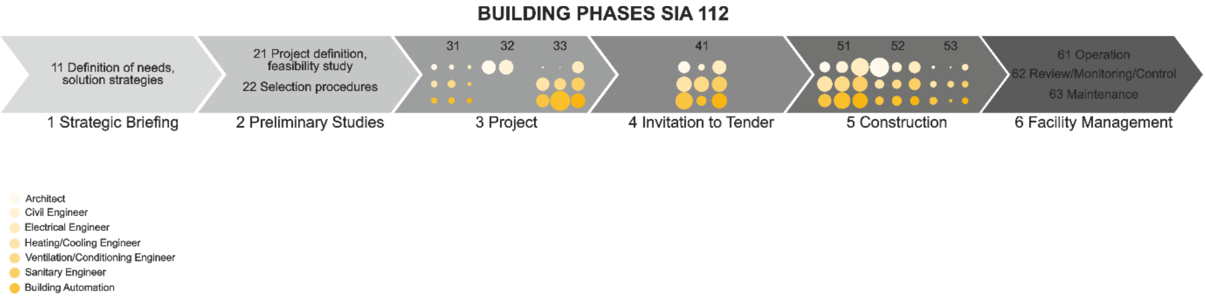
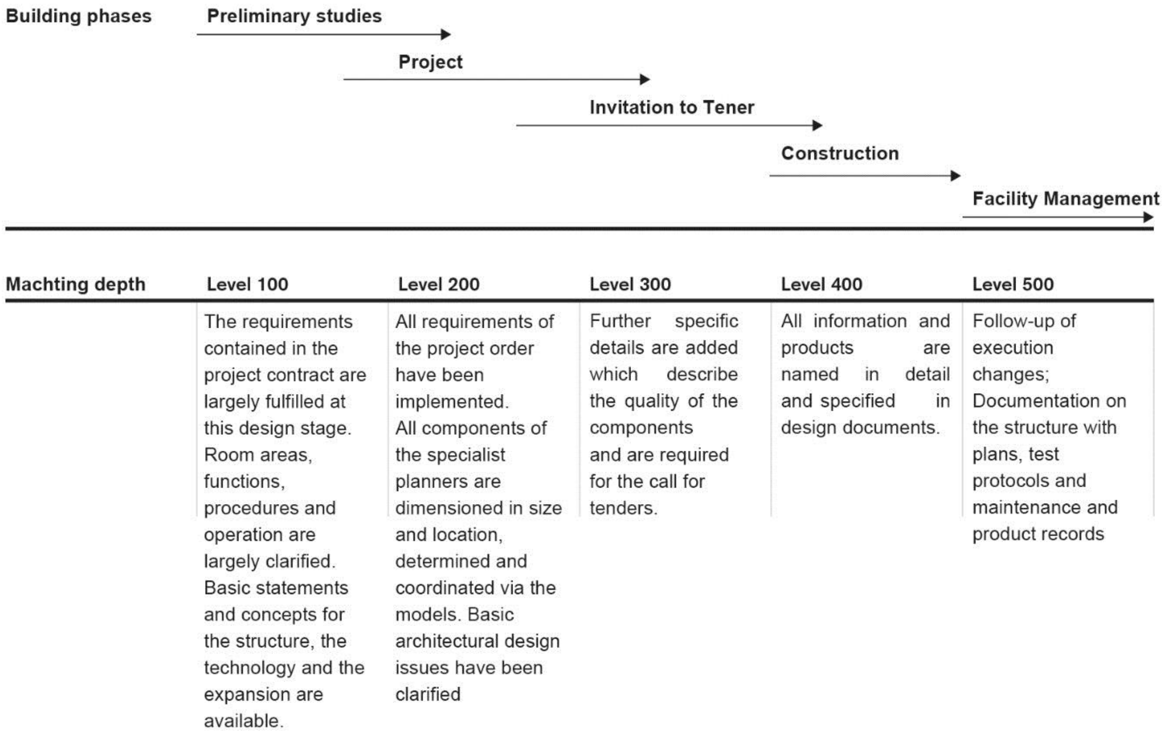


Figure 13: Building phases (SIA) and different stakeholders associated with them (SIA 112, 2001; Menz, Bastianello and Eglin, 2014)

2.4.3 Level of Development (LOD) and Building phases

Maier *et al.* (2018) develop a BIM Workbook (for Bauen Digital Schweiz and buildingSMART Switzerland), in which the authors associate different LODs with the Building Phases as defined by SIA (SIA 112, 2001) (Figure 14).



Machting depth	Level 100	Level 200	Level 300	Level 400	Level 500
	The requirements contained in the project contract are largely fulfilled at this design stage. Room areas, functions, procedures and operation are largely clarified. Basic statements and concepts for the structure, the technology and the expansion are available.	All requirements of the project order have been implemented. All components of the specialist planners are dimensioned in size and location, determined and coordinated via the models. Basic architectural design issues have been clarified	Further specific details are added which describe the quality of the components and are required for the call for tenders.	All information and products are named in detail and specified in design documents.	Follow-up of execution changes; Documentation on the structure with plans, test protocols and maintenance and product records

Figure 14: LODs and their relation to Building Phases (SIA) (Maier et al., 2018)

The authors exclude Building Phase 1, Strategic Briefing, from their analysis and start with Building Phase 2, Preliminary Studies. More or less each different LOD is related to an existing Building Phase, starting from the Building Phase 2.

Cavalliere, Habert, *et al.* (2018) associate LODs to process phases as follows (Figure 15):

- LOD100 – Project Planning (PP);
- LOD300 – Project Phase (P);
- LOD400 – Building Permit Application (BPA), Tendering (T) and Construction (C).

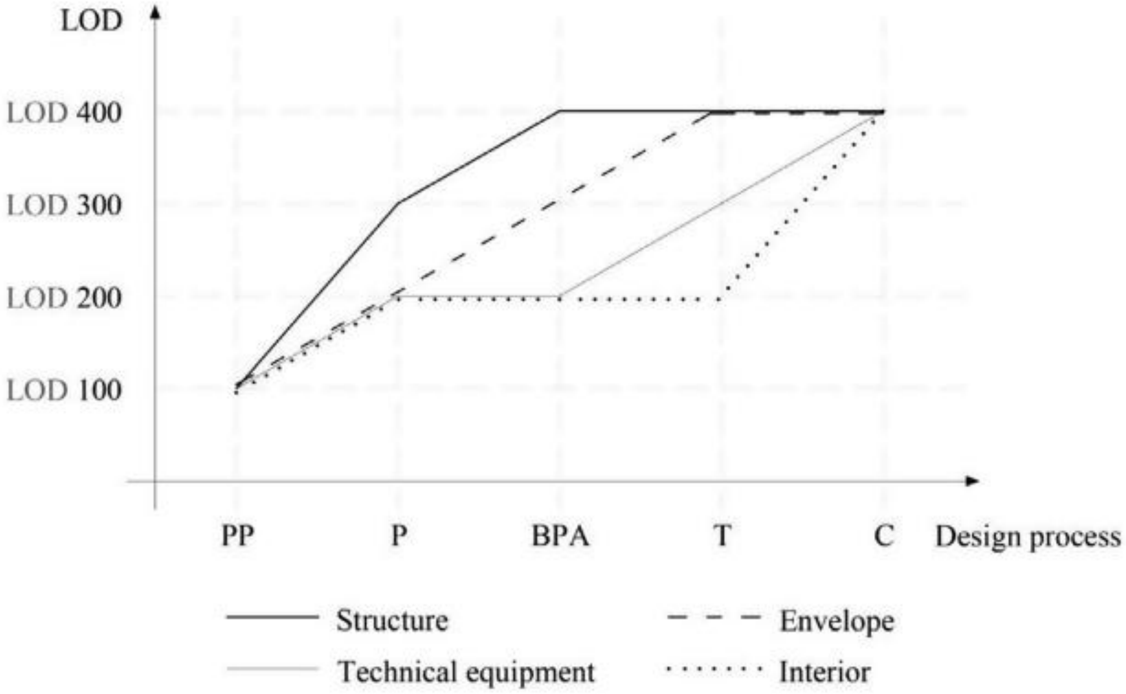


Figure 15: Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction (Cavalliere, Habert, et al., 2018)

Implenia AG associates different Building Phases (SIA) with different LODs through their daily work (Appendix A.1). That is yet another example of how BIM modeling is connected to LOD. The company maps Building Phases (SIA) and LODs accordingly:

- Building Phase 2, Preliminary Studies – LOD100;
- Building Phase 3, Project – LOD200;
- Building Phase 4, Invitation to Tender – LOD300;
- Building Phase 5, Construction – LOD400;
- Building Phase 6, Facility Management – LOD500.

This research will study the abovementioned processes and BIM in relation to supporting sustainability. Possibilities of managing relevant information throughout the lifecycle of a building with regard to embodied energy will be evaluated. The overall building process is to be examined while pointing out the potential of increasing the impact of sustainability.

3 Research questions

Based on the theoretical background, four main points can be highlighted to describe the current state of the art in both research and practice:

1) The entire building process is currently not evaluated in terms of environmental LCA. The current practice rather focuses on an early conceptual phase, relying on conceptual methods for applying LCA, or on a very late detailed phase by implementing detailed inputs.
2) The current practice mainly employs static methods for implementing LCA. These methods manually deal with data input and outputs, are time-consuming, and do not provide any decision-making support.
3) The existing LCA databases are not associated with the different Building Phases and do not declare LODs.
4) BIM models and LCA Databases are currently not aligned to a common code structure for the LCA to be parameterized in a simple and reliable way.

Given these considerations, the main research question standing behind the development of this master thesis is:

How could BIM support LCA over the entire building process?

The three sub-questions that follow from it are:

- ***What digital tools and related workflows can support a BIM-based method for LCA? How can they provide decision-making support?***
- ***What LCA-related data can be embedded into a BIM model? Which databases can be linked to a BIM model?***
- ***How can the re-entering of LCA data into the BIM model be prevented? Is there a common code data structure existing in BIM that can be used?***

4 Methodology and research steps

4.1 Literature review

As a first part of the methodology and the research steps, undertaken during the development of this thesis, a literature review is performed. Through the literature review, the author aims at identifying the current state of the art about the topic of this study. The literature review is described in part 2 Theoretical background (Literature review) of this master thesis.

The body of the literature analyzed can be categorized as follows:

- 18 book sections;
- 53 journal articles;
- 10 consultancy reports;
- 20 working papers;
- 7 LCA Databases.

It should be noted that only the most important analyzed literature developments are included in this master thesis report.

Previous work by different authors is reviewed to provide a clearer understanding of the current state of the art about the potential of digitalization for sustainability in the building sector. Relevant articles are selected with the use of online scientific research platforms (e.g., Google Scholar). Different consultancy reports and working papers are examined as well. The purpose behind that is an attempt to bring the topic closer to the current practice applied in the building industry.

Through the literature review, topics, related to the potential of digitalization in sustainability with a perspective of the building process are reviewed. Such topics include Life-Cycle Assessment (LCA) and Building Information Modeling (BIM) and the integration between the two. For the acknowledgment of the potential for integration, structures, and methodologies associated with LCA and BIM, and their relation to the building process, are researched. Different LCA implementation techniques are reviewed: LCA Databases structure, LCA Application time, LCA Tools, LCA Methodologies. Techniques related to BIM implementation are evaluated as well: BIM Maturity, BIM Level of Development (LOD), BIM LOD, and its association with existing Building Phases in Switzerland.

The literature review is performed by using the following twenty-five keyword phrases: Sustainability, Digitalization, Building process, Life-Cycle Assessment (LCA), Building Information Modelling (BIM), BIM-LCA integration, construction digital future, SIA, Minergie, green building standards, dynamic Life-Cycle Assessment, Life-Cycle Assessment data structure, environmental benchmarks, design process, building process, grey energy, embodied energy, operational energy, building sustainability parameters, embodied environmental impact, Level of Development (LOD), energy efficiency, building performance simulation, building life-cycle, sustainable buildings.

4.2 Unstructured and informal interviews with experts

Qualitative studies can obtain a more extensive and in-depth understanding of the field through interviews, gaining insights into opinions, attitudes, experiences, processes, or predictions (Rowley, 2012). Therefore, 35 unstructured and informal interviews with 10 industry experts are performed. The interviews have a length between 30 to 60 minutes and are carried out face to face or over the telephone.

Through the unstructured and informal interviews, knowledge about existing LCA Databases in Switzerland is derived and examined. This information is accounted for in part 2.3.1 Life-Cycle Assessment (LCA) implementation: LCA Databases structure. Through the interviews, the current practice adopted for LCA application is outlined, and issues related to it identified. These issues are elaborated in part 2.3.4 Life-Cycle Assessment (LCA) implementation: LCA Methodologies. The interviews with experts help the identification of existing Building Phases in Implenia AG and their association with LODs. That relation is elaborated further on in part 2.4.3 BIM-LCA Integration: Level of Development (LOD) and Building phases. Furthermore, the interviews with experts help to derive the results, described in part 5 Results, of this report.

The interviewed industry experts can be categorized as follows:

- 4 BIM experts from Implenia AG;
- 2 Sustainability experts from Implenia AG;
- 2 Sustainability-Consultancy experts from Intep GmbH[14];
- 2 Database experts from eco-bau and Lignum AG[15].

The interviews are held to determine other possible challenges and solutions, which may not be identified by the literature review. Another reason is to develop an understanding of the existing challenges and solutions identified in the literature from an industry perspective.

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[14] Intep GmbH - an interdisciplinary consulting and research company for environment, economy and society with around 70 employees at 8 locations in Switzerland, Germany, USA and China. Source: https://intep.com/.

[15] Lignum, timber industry Switzerland is the umbrella organization of the Swiss forestry and timber industry. It brings together all the major associations and organizations in the wood chain with a total of around 80000 jobs ranging from forestry, sawmill, trade and wood-based material production to carpentry, carpentry and furniture production. In addition there are institutions from research and teaching, public corporations and companies as well as a large number of architects and engineers. Source: https://www.lignum.ch/.

4.3 Case study analysis

In addition to the literature review and the interviews, data is also collected through a case study analysis. Research shows that case studies can provide the opportunity to gather in-depth information about a real-life situation, as well as the possibility to test the results in a specific context (Yin, 2011).

The Swiss construction company Implenia AG is the provider of the case study. Implenia is a leading multinational firm, providing construction services with a mission to develop projects sustainably for both buildings' environment and infrastructure. The company's employees account for more than 10'000 people in Europe. Additionally, Implenia is listed on the SIX Swiss Exchange (IMPN, CH0023868554). The values resembled by Implenia are related to Excellence, Collaboration, Agility, Integrity, and Sustainability.

The case study itself is a mixed-use new building called Krokodil (Figure 16). The building is located in the Lokstadt district, in Winterthur, Switzerland.

Figure 16: Case study – mixed-use new building Krokodil, Lokstadt, Winterthur, Switzerland (Source: Implenia AG)

The project has started in 2016 and is expected to be completed in 2020. The gross floor area of the building is 31 559 m^2. The cost of the project is CHF 98.5 Million. The building is composed of eight floors above ground level and two floors below.

The general planner and the total entrepreneur of the project is Implenia Schweiz AG. The constructor is Implenia Immobilien AG, the architects - ARGE Baumberger & Stegmeier Architekten und KilgaPopp Architekten and the engineers - Dr. Grob & Partner AG. One of the main strategic goals of the project design is the achievement of the sustainability targets set by the 2000-Watt Society[16].

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[16] 2000-Watt Society is a program created by The City of Zurich that defines target values for 2050 year of 3500 Watts and 2 tonnes of CO_2-eq per person. The program sets goals related to consumption, settlement, buildings, energy supply and mobility for reaching these target values (City of Zurich, 2011).

To collect data about the case study, the following methods are employed:

- 15 files document analysis (10 .ifc files from building phases 22, 31, 32, 41 and 51; 5 .doc files with general information about the case study);
- 15 unstructured and informal interviews with project participants.

The case study analysis helps for the derivation of part of the results, described in part 5 Results of this report. For that purpose, two floors of the building are extracted for their prompt evaluation. In that sense, the results provided by the evaluation do not resemble the environmental impact of the whole building.

The Dynamic tool for LCA and the related workflow, part of this master thesis, are tested on the case study. The concept behind them is shown in Figure 17 below. The proposed workflow for BIM-based LCA evaluation allows a BIM model and an LCA Database to be connected through a parametric tool. The parametric tool is developed by the author of this study using a software program called Dynamo. Specifically, this parametric tool is composed of eight different scripts. These scripts automatically create LCA Parameters in the BIM model, relate them to the LCA Database and calculate the LCA Values at different LOD levels. In the end, the tool provides an LCA Report in the form of an Excel sheet (Figure 17).

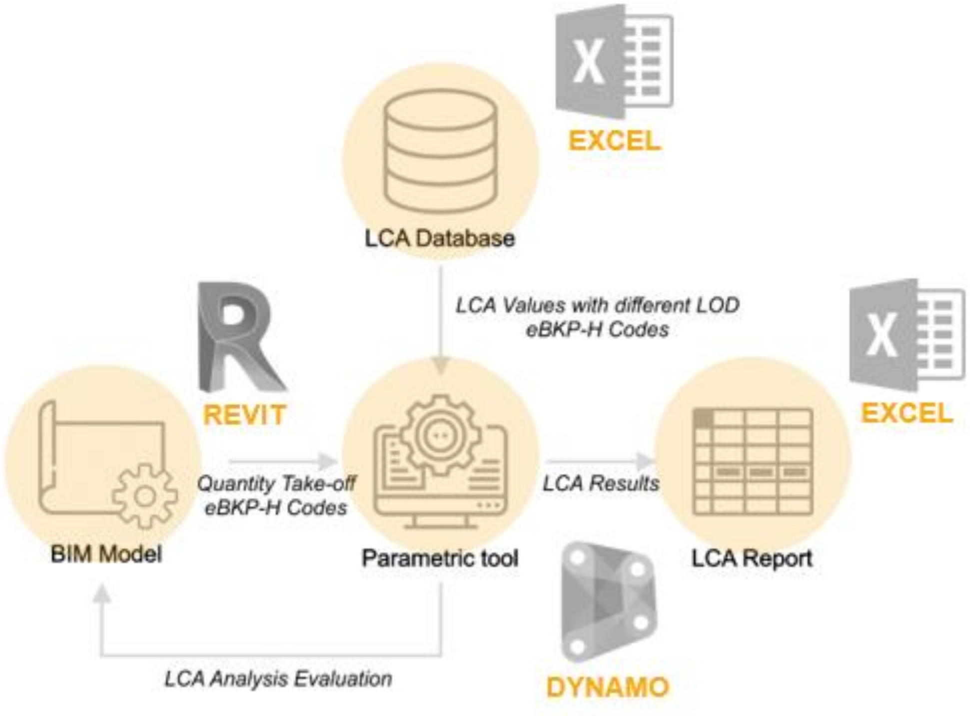


Figure 17: Dynamic tool for LCA and related workflow - concept

5 Results

5.1 Dynamic tool for LCA and related workflow

5.1.1 Concept

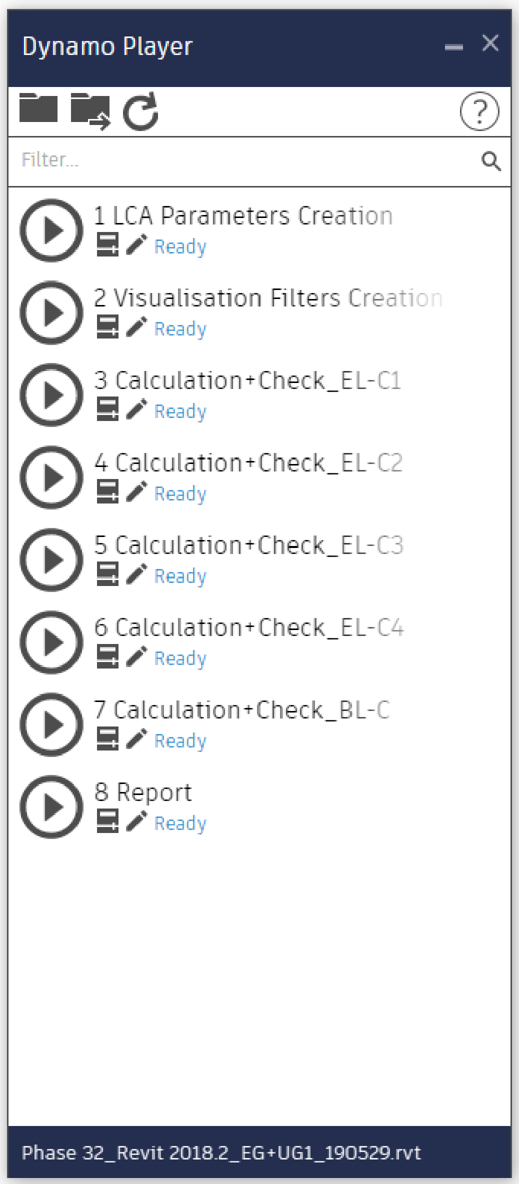
The Dynamic tool for LCA and the related workflow developed by the author of this study aim at providing an automated method for a BIM-based LCA calculation. The development's objective is also to propose a methodology for LCA evaluation that could be implemented in the specific context of Swiss companies. Through the implementation of this automated method, the manual input of data would be limited and hence, the potential of errors, caused by the human factor, minimized. Another associated benefit is the capacity to provide decision-making support while implementing LCA Values (Bauteilkatalog, 2016) and LCA Benchmarks (SIA2032, 2018), related to the different Building Phases (SIA112, 2001) and their associated LODs (Curschellas *et al.*, 2018).

The Dynamic tool for LCA is composed of eight different scripts developed in the parametric program Dynamo. These scripts create LCA Parameters in the BIM model, provide filters and calculations for their visualization and evaluation, and export the results in the form of an LCA Report.

5.1.2 Dynamo scripts

User interface: Dynamo player

As mentioned earlier, the Dynamic tool includes eight scripts, created in a parametric tool for the BIM software program Revit, called Dynamo. For their easier execution, a plug-in for Revit, called Dynamo player[17], has been used (Figure 18). Through its usage, the dynamic tool for LCA developed in Dynamo can be implemented by users who do not possess specific LCA or BIM knowledge, nor coding skills. In that sense, it provides a method for LCA that can be easily applied by different specialists working on the building project, for a prompt, yet reliable estimation for LCA to be achieved.



1 LCA Parameters Creation
Ready
2 Visualisation Filters Creation
Ready
3 Calculation+Check_EL-C1
Ready
4 Calculation+Check_EL-C2
Ready
5 Calculation+Check_EL-C3
Ready
6 Calculation+Check_EL-C4
Ready
7 Calculation+Check_BL-C
Ready
8 Report
Ready

Phase 32_Revit 2018.2_EG+UG1_190529.rvt

Figure 18: User interface: Dynamo player

---

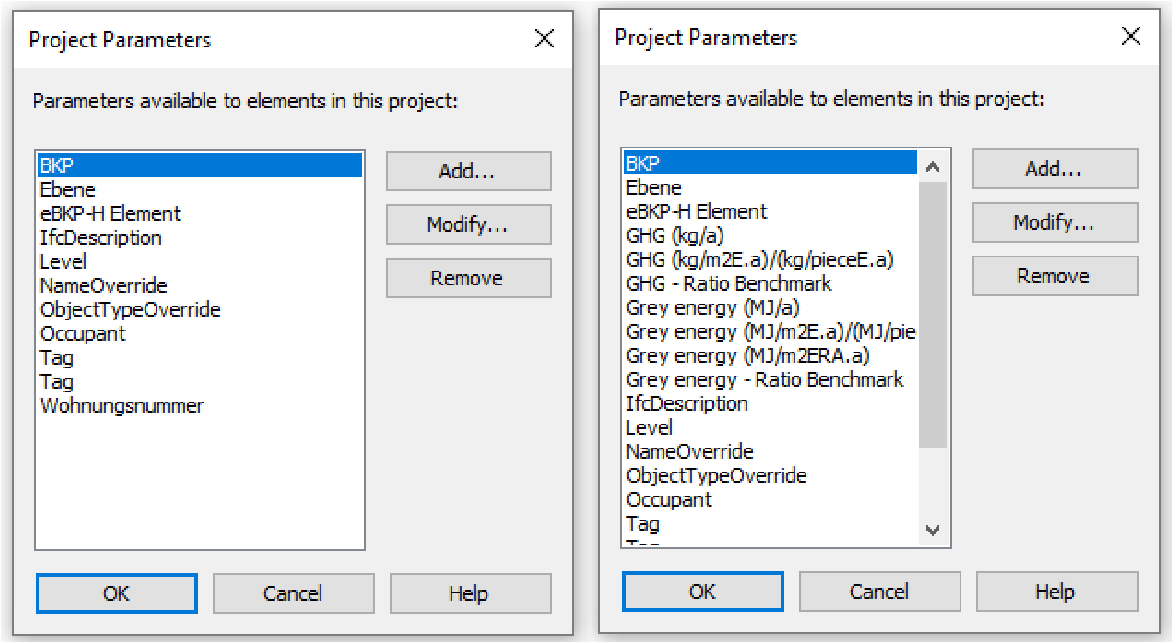
[17] Dynamo player is an easy to navigate dialog that displays Dynamo scripts from a specified directory. It provides a status for each script, possibility for scripts filtering, input in different scripts and their editing Source: https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-AddIns/files/GUID-BFCE20D2-86D4-4591-8CF3-5405D26DB825-htm.html.

LCA Parameters creation

The first Dynamo script creates LCA Parameters in Revit (Appendix A.2). After running the script, the following parameters are created:

- Grey energy (MJ/m2E.a)/(MJ/pieceE.a)[18];
- GHG (kg/m2E.a)/(kg/pieceE.a)[19];
- UBP (Pt/m2E.a)/(Pt/pieceE.a)[20];
- Grey energy (MJ/a);
- GHG (kg/a);
- UBP (Pt/a);
- Grey energy - Ratio Benchmark;
- GHG - Ratio Benchmark;
- Grey energy (MJ/m2ERA.a).

The script allows an automated creation of project parameters in Revit (Figure 19), eliminating the need for manual parameters input. Once the parameters are created, they are assigned to different Revit element categories (e.g., walls, floors, roofs, etc.). The parameters can be accessed when choosing an element from a Revit category or through the creation of Element Schedule/Multi-Category Material Takeoff table in Revit.


Project Parameters

Parameters available to elements in this project:

BKP
Ebene
eBKP-H Element
IfcDescription
Level
NameOverride
ObjectTypeOverride
Occupant
Tag
Tag
Wohnungsnummer

Project Parameters

Parameters available to elements in this project:

BKP
Ebene
eBKP-H Element
GHG (kg/a)
GHG (kg/m2E.a)/(kg/pieceE.a)
GHG - Ratio Benchmark
Grey energy (MJ/a)
Grey energy (MJ/m2E.a)/(MJ/pie
Grey energy (MJ/m2ERA.a)
Grey energy - Ratio Benchmark
IfcDescription
Level
NameOverride
ObjectTypeOverride
Occupant
Tag

Figure 19: Dynamo script 1: LCA Parameters Creation – before and after running the script

---

[18] Grey energy - Grey energy is the hidden energy associated with a product, meaning the total energy consumed throughout the product's life cycle from its production to its disposal.

[19] GHG (greenhouse gas) - Greenhouse gases are the gases in the Earth's atmosphere that produce the greenhouse effect, respectively contribute to Climate Change.

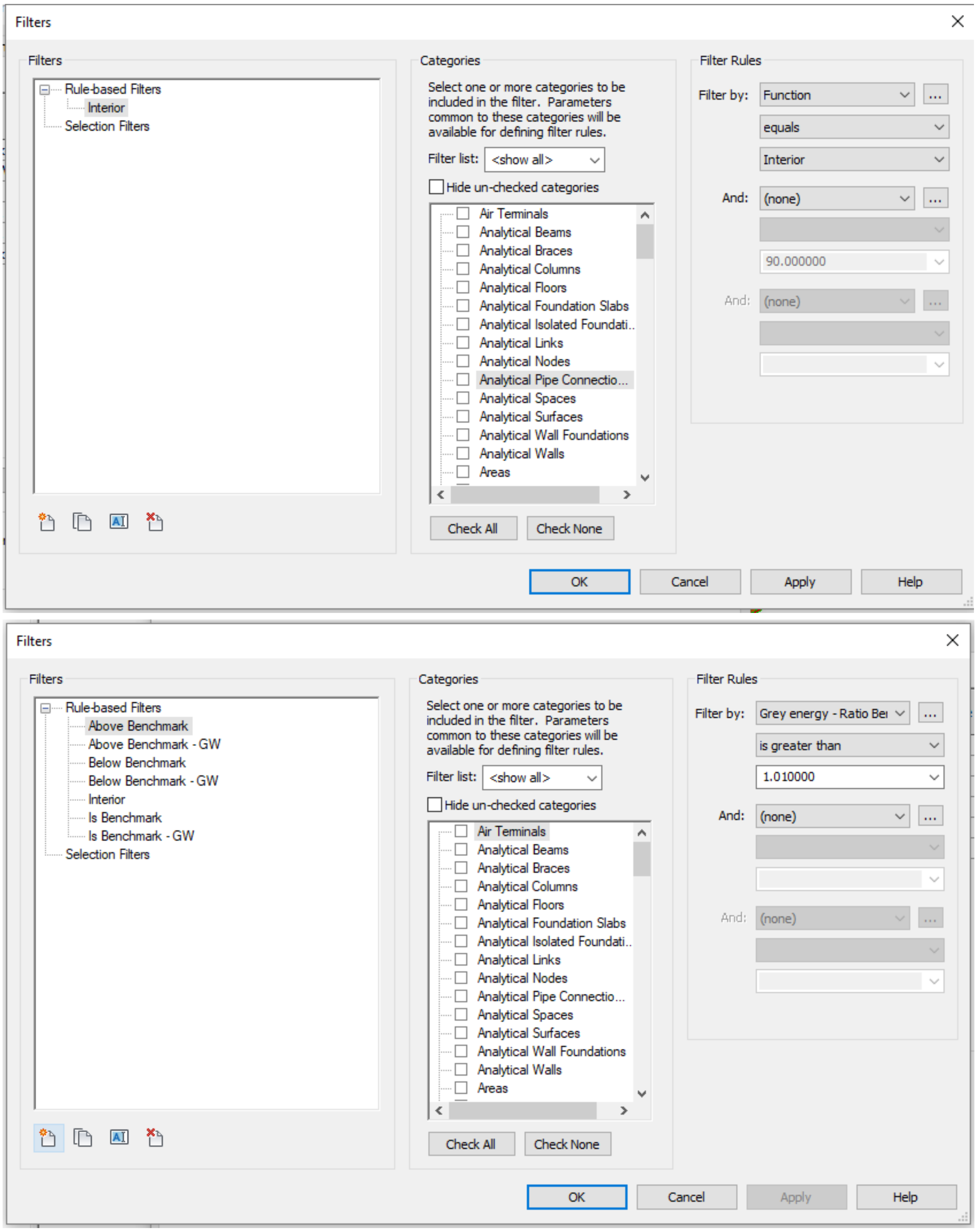
[20] UBP – a point system that quantifies the environmental impact through the use of energy resources.

Source: MINERGIE (2014).

Visualization filters creation

The second Dynamo script creates visualization filters in Revit (Appendix A.2).

The script incorporates the LCA Benchmarks from the newly created LCA Database at the Element Level, set by SIA2032 (SIA2032, 2018) and ETH Zurich, Chair of Sustainable Construction (Hollberg, Lützkendorf and Habert, 2019). At the Building Level, a benchmark for Energy Reference Area (ERA) is used (MINERGIE, 2014) (Figure 20).



Filters

Rule-based Filters
Interior
Selection Filters

Select one or more categories to be included in the filter. Parameters common to these categories will be available for defining filter rules.

Filter list: <show all>

☐ Hide un-checked categories

Filter by: Function
equals
Interior
And: (none)
90.000000
And: (none)

Filters

Rule-based Filters
Above Benchmark
Above Benchmark - GW
Below Benchmark
Below Benchmark - GW
Interior
Is Benchmark
Is Benchmark - GW
Selection Filters

Select one or more categories to be included in the filter. Parameters common to these categories will be available for defining filter rules.

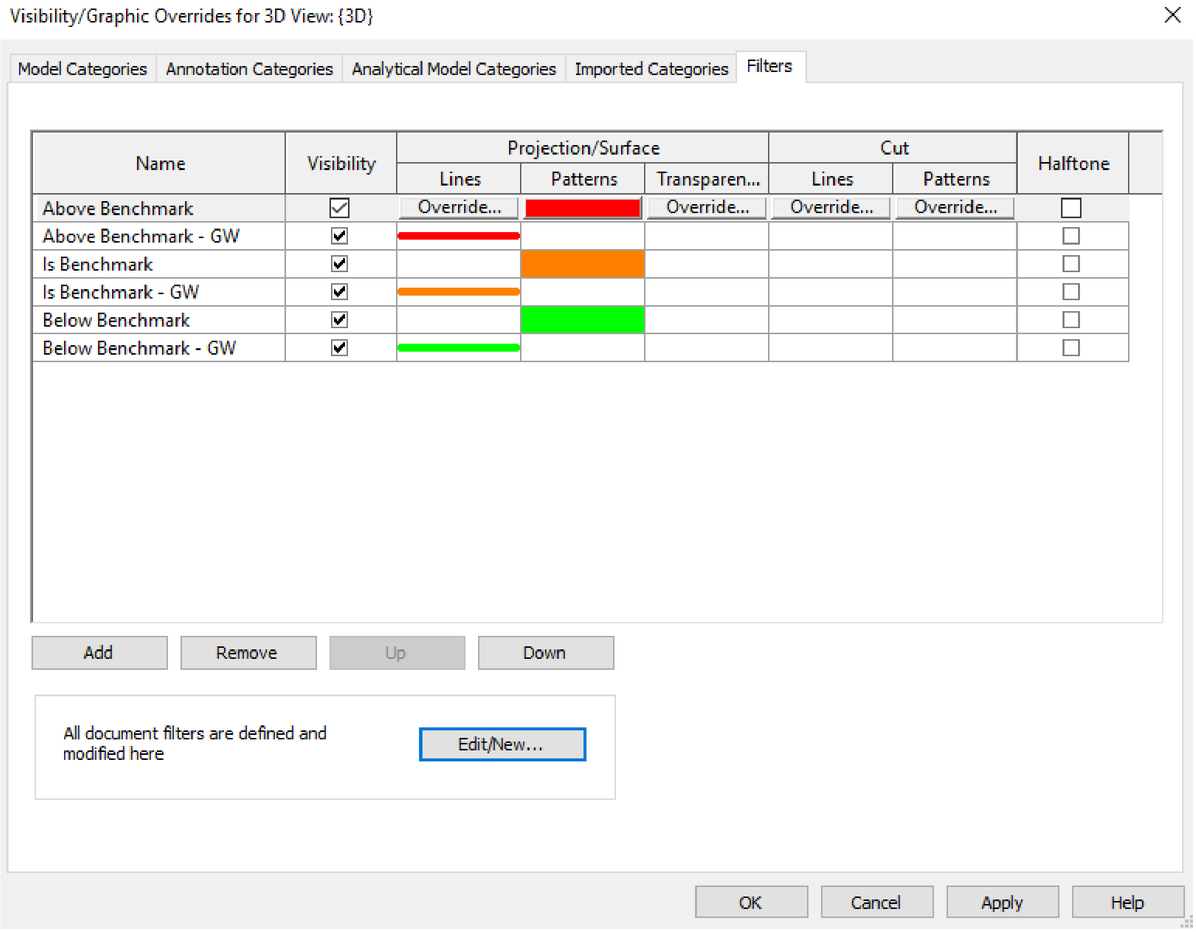
Filter list: <show all>

☐ Hide un-checked categories

Filter by: Grey energy - Ratio Ber
is greater than
1.010000
And: (none)
And: (none)

Figure 20: Dynamo script 2: Visualization Filters Creation – before and after running the script

The filters color the Revit categories surfaces (for an indication on Element Level) and lines (for an indication on Building Level) in three colors: red, orange, and green[21] (Figure 21).



Visibility/Graphic Overrides for 3D View: {3D}

Name	Visibility	Projection/Surface			Cut		Halftone
		Lines	Patterns	Transparen...	Lines	Patterns	
Above Benchmark	☑	Override...	🟥	Override...	Override...	Override...	☐
Above Benchmark - GW	☑	🟥					☐
Is Benchmark	☑		🟧				☐
Is Benchmark - GW	☑	🟧					☐
Below Benchmark	☑		🟩				☐
Below Benchmark - GW	☑	🟩					☐

All document filters are defined and modified here

Figure 21: Dynamo script 2: Visualization Filters Creation – Filters color designation

---

[21] The red color shows an LCA Value above the LCA Benchmark, the orange color indicates an LCA Value at the LCA Benchmark, and the green color designates an LCA Value below the LCA Benchmark.

Calculation and check

Dynamo scripts 3 to 7 allow the calculation of LCA Values (Bauteilkatalog, 2016) and check of LCA Benchmarks (SIA2032, 2018) at both the Element (SIA2032, 2018) and Building Levels (MINERGIE, 2014). Scripts 3 to 6 operate at the Element Level while script 7 at the Building Level (Appendix A.2).

After running the scripts at the Element Level, the LCA Values from the newly created LCA Database[22] are multiplied with the respective Element quantities from the BIM Model. These values are then filled in the LCA Parameters created with the Dynamo script 1. The LOD for the LCA Values extracted from the LCA Database can be defined either with the help of Dynamo player or in the Dynamo script itself. After these calculations are finished, they are compared with the LCA Benchmarks. Then the Revit Category Elements' surfaces are colored respectively. Subsequently running the scripts at the Element Level, Dynamo script 7 operating at the Building Level can be run. The script gathers the LCA Parameters for Grey Energy for all the Revit Category Elements and divides it with the ERA. The ERA itself is also calculated with script 7. Then the lines of each Revit Category Element is colored according to the received value (Figure 22).

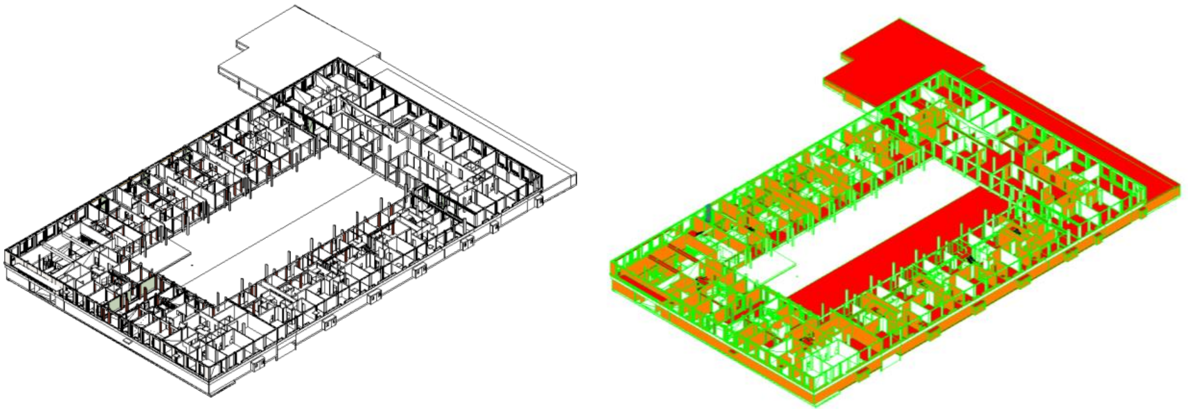


Figure 22: Dynamo scripts 3-7: Calculation and Check – before and after running the scripts

Both the calculations at the Element (SIA2032, 2018) and Building (MINERGIE, 2014) Levels provide decision-making metrics by visualizing the results simultaneously.

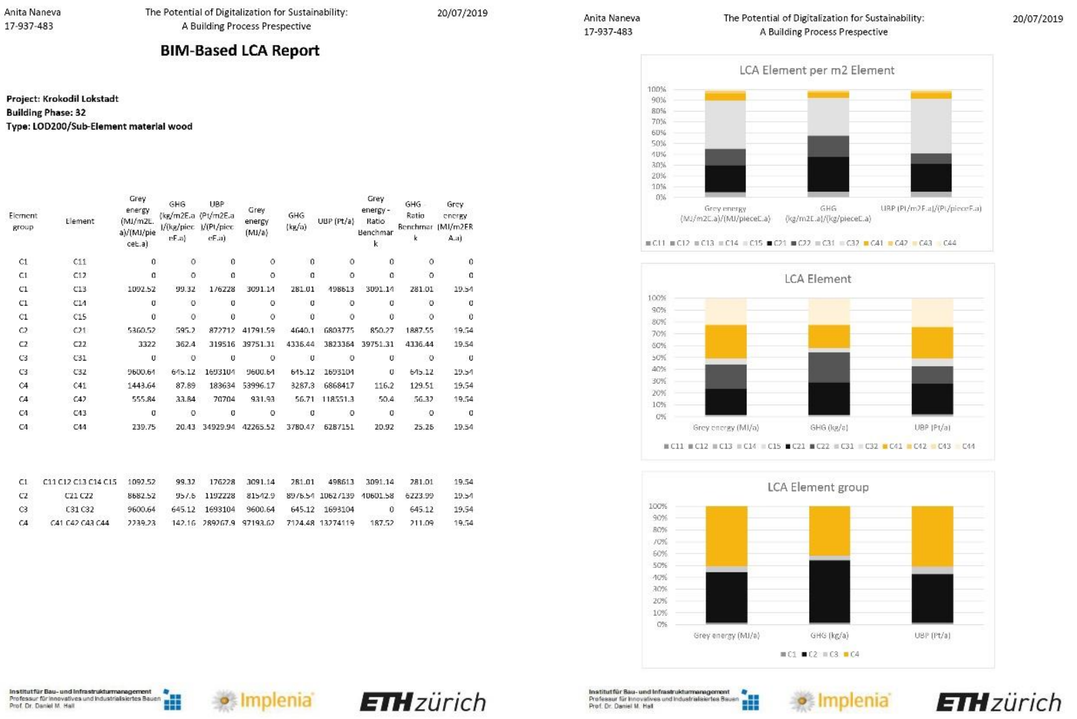
---

[22] Described in part 5.1 LCA Database, of this report.

Report

The last Dynamo script 8 creates a Report in the form of an Excel file (Appendix A.2 and A.4).

The script collects all the values for the LCA Parameters created in Dynamo script 1 for all the Revit Category Elements and sums them up according to the Main Group (C), Element Group (C1, C2, C3, C4) or Element (C11, C12, C13, C14, C15, C21, C22, C31, C32, C41, C42, C43, C44). Finally, the information is extracted and input in an Excel sheet, while creating a table and graphs with the respective values on respective LOD (Figure 23).



Anita Naneva
17-937-483

The Potential of Digitalization for Sustainability:
A Building Process Prespective

20/07/2019

BIM-Based LCA Report

Project: Krokodil Lokstadt
Building Phase: 32
Type: LOD200/Sub-Element material wood

Element group	Element	Grey energy (MJ/m2E.a)/(MJ/pieceE.a)	GHG (kg/m2E.a)/(kg/pieceE.a)	UBP (Pt/m2E.a)/(Pt/pieceE.a)	Grey energy (MJ/a)	GHG (kg/a)	UBP (Pt/a)	Grey energy - Ratio Benchmark	GHG Ratio Benchmark	Grey energy (MJ/m2ERA.a)
C1	C11	0	0	0	0	0	0	0	0	0
C1	C12	0	0	0	0	0	0	0	0	0
C1	C13	1092.52	99.32	176228	3091.14	281.01	498613	3091.14	281.01	19.54
C1	C14	0	0	0	0	0	0	0	0	0
C1	C15	0	0	0	0	0	0	0	0	0
C2	C21	5360.52	595.2	872712	41791.59	4640.1	6803775	850.27	1887.55	19.54
C2	C22	3322	362.4	319516	39751.31	4336.44	3823364	39751.31	4336.44	19.54
C3	C31	0	0	0	0	0	0	0	0	0
C3	C32	9600.64	645.12	1693104	9600.64	645.12	1693104	0	645.12	19.54
C4	C41	1443.64	87.89	183634	53996.17	3287.3	6868417	116.2	129.51	19.54
C4	C42	555.84	33.84	70704	931.93	56.71	118551.3	50.4	56.32	19.54
C4	C43	0	0	0	0	0	0	0	0	0
C4	C44	239.75	20.43	34929.94	42265.52	3780.47	6287151	20.92	25.26	19.54
C1	C11 C12 C13 C14 C15	1092.52	99.32	176228	3091.14	281.01	498613	3091.14	281.01	19.54
C2	C21 C22	8682.52	957.6	1192228	81542.9	8976.54	10627139	40601.58	6223.99	19.54
C3	C31 C32	9600.64	645.12	1693104	9600.64	645.12	1693104	0	645.12	19.54
C4	C41 C42 C43 C44	2239.23	142.16	289267.9	97193.62	7124.48	13274119	187.52	211.09	19.54

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The Potential of Digitalization for Sustainability:
A Building Process Prespective

20/07/2019

Institut für Bau- und Infrastrukturmanagement
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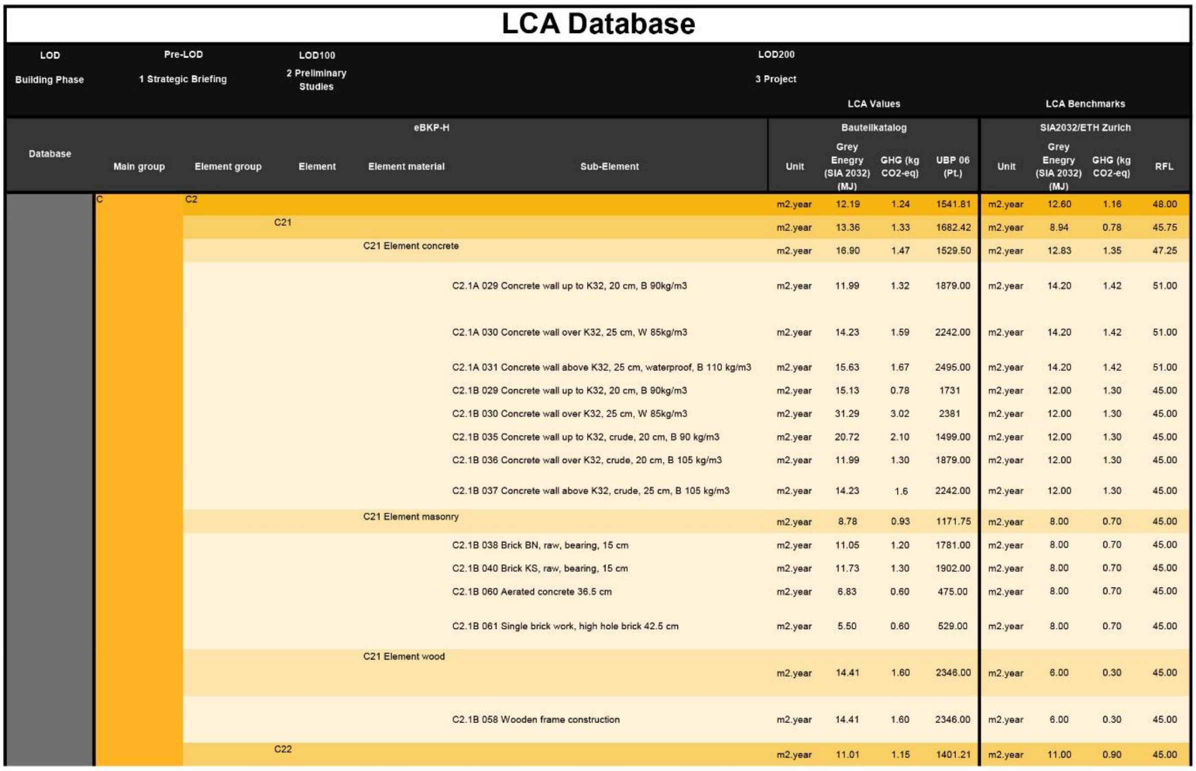
Figure 23: Dynamo script 8: Report – Results

5.2 LCA Database

Through the development of the dynamic parametric tool for LCA and the related automated workflow, a new LCA Database is composed by the author of this study (Table 4) (Appendix A.3).



LCA Database

LOD	Pre-LOD		LOD100			LOD200							
Building Phase	1 Strategic Briefing		2 Preliminary Studies			3 Project							
						LCA Values				LCA Benchmarks			
	eBKP-H					Bauteilkatalog				SIA2032/ETH Zurich			
Database	Main group	Element group	Element	Element material	Sub-Element	Unit	Grey Enegry (SIA 2032) (MJ)	GHG (kg CO2-eq)	UBP 06 (Pt.)	Unit	Grey Enegry (SIA 2032) (MJ)	GHG (kg CO2-eq)	RFL
	C	C2				m2.year	12.19	1.24	1541.81	m2.year	12.60	1.16	48.00
			C21			m2.year	13.36	1.33	1682.42	m2.year	8.94	0.78	45.75
				C21 Element concrete		m2.year	16.90	1.47	1529.50	m2.year	12.83	1.35	47.25
					C2.1A 029 Concrete wall up to K32, 20 cm, B 90kg/m3	m2.year	11.99	1.32	1879.00	m2.year	14.20	1.42	51.00
					C2.1A 030 Concrete wall over K32, 25 cm, W 85kg/m3	m2.year	14.23	1.59	2242.00	m2.year	14.20	1.42	51.00
					C2.1A 031 Concrete wall above K32, 25 cm, waterproof, B 110 kg/m3	m2.year	15.63	1.67	2495.00	m2.year	14.20	1.42	51.00
					C2.1B 029 Concrete wall up to K32, 20 cm, B 90kg/m3	m2.year	15.13	0.78	1731	m2.year	12.00	1.30	45.00
					C2.1B 030 Concrete wall over K32, 25 cm, W 85kg/m3	m2.year	31.29	3.02	2381	m2.year	12.00	1.30	45.00
					C2.1B 035 Concrete wall up to K32, crude, 20 cm, B 90 kg/m3	m2.year	20.72	2.10	1499.00	m2.year	12.00	1.30	45.00
					C2.1B 036 Concrete wall over K32, crude, 20 cm, B 105 kg/m3	m2.year	11.99	1.30	1879.00	m2.year	12.00	1.30	45.00
					C2.1B 037 Concrete wall above K32, crude, 25 cm, B 105 kg/m3	m2.year	14.23	1.6	2242.00	m2.year	12.00	1.30	45.00
				C21 Element masonry		m2.year	8.78	0.93	1171.75	m2.year	8.00	0.70	45.00
					C2.1B 038 Brick BN, raw, bearing, 15 cm	m2.year	11.05	1.20	1781.00	m2.year	8.00	0.70	45.00
					C2.1B 040 Brick KS, raw, bearing, 15 cm	m2.year	11.73	1.30	1902.00	m2.year	8.00	0.70	45.00
					C2.1B 060 Aerated concrete 36.5 cm	m2.year	6.83	0.60	475.00	m2.year	8.00	0.70	45.00
					C2.1B 061 Single brick work, high hole brick 42.5 cm	m2.year	5.50	0.60	529.00	m2.year	8.00	0.70	45.00
				C21 Element wood		m2.year	14.41	1.60	2346.00	m2.year	6.00	0.30	45.00
					C2.1B 058 Wooden frame construction	m2.year	14.41	1.60	2346.00	m2.year	6.00	0.30	45.00
			C22			m2.year	11.01	1.15	1401.21	m2.year	11.00	0.90	45.00

Table 4: Newly composed LOD-based LCA Database

The Database is structured according to different Building Phases (Building Phase 1-3, Strategic Briefing, Preliminary Studies, Project) (SIA 112, 2001) and their related LODs (Curschellas *et al.*, 2018). It is also structured according to an existing code-based structure for cost planning, called eBKP-H (crb, 2012). It combines data from existing LCA Databases and provides information about LCA Values (Bauteilkatalog, 2016) and LCA Benchmarks (SIA2032, 2018).

5.2.1 Decision-making support

LCA Benchmarks

The Database provides decision-making support at both the Element (SIA2032, 2018) and Building (MINERGIE, 2014) Levels.

For the LCA Benchmarks at the Element Level, two options are considered. The first one focuses on LCA Target Values provided by Hollberg, Lützkendorf, and Habert (2019) in their paper “Top-down or bottom-up? – How environmental benchmarks can support the design process” (Table 5).

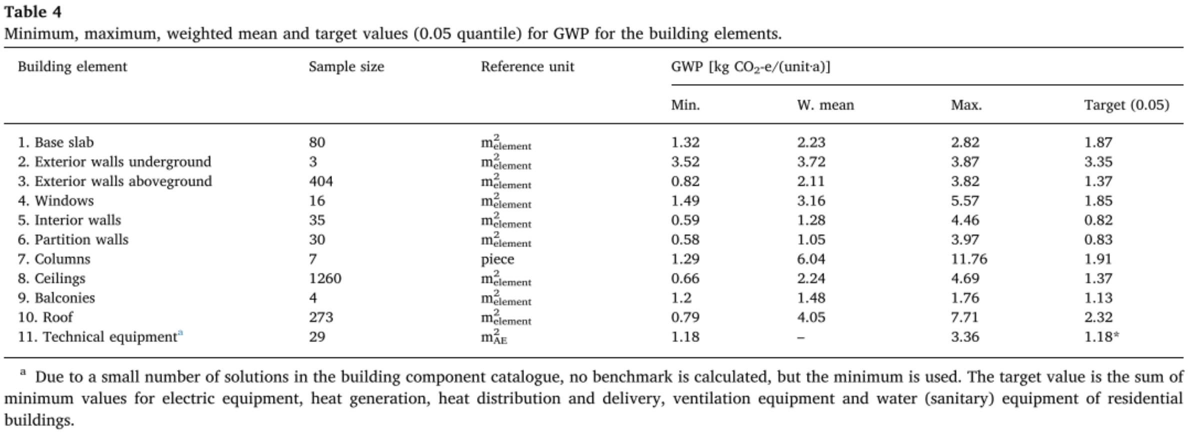


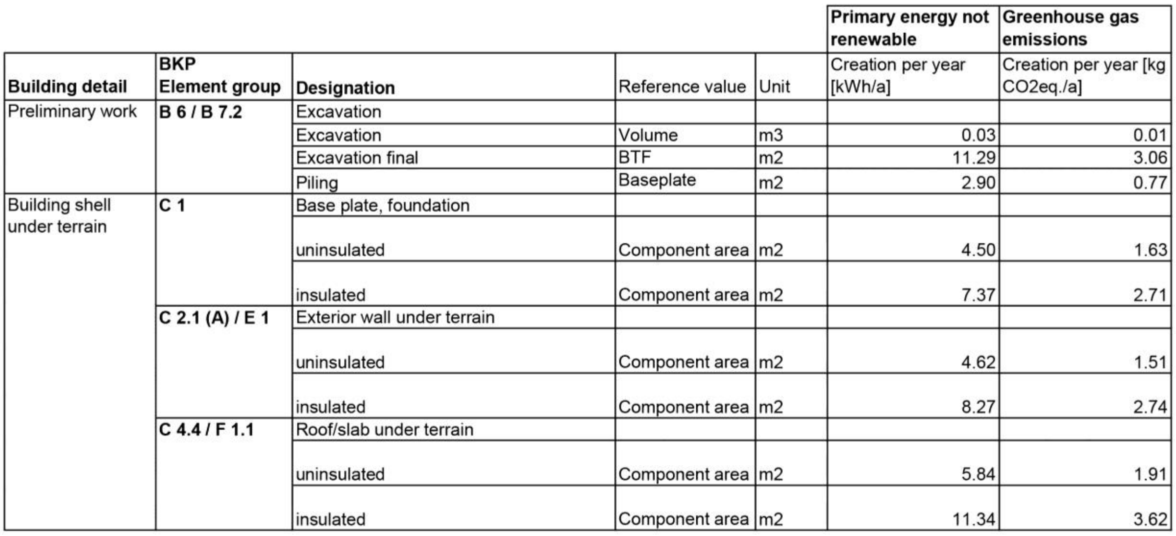
Table 4
Minimum, maximum, weighted mean and target values (0.05 quantile) for GWP for the building elements.

Building element	Sample size	Reference unit	GWP [kg CO_2-e/(unit·a)]			
			Min.	W. mean	Max.	Target (0.05)
1. Base slab	80	$m^2_{element}$	1.32	2.23	2.82	1.87
2. Exterior walls underground	3	$m^2_{element}$	3.52	3.72	3.87	3.35
3. Exterior walls aboveground	404	$m^2_{element}$	0.82	2.11	3.82	1.37
4. Windows	16	$m^2_{element}$	1.49	3.16	5.57	1.85
5. Interior walls	35	$m^2_{element}$	0.59	1.28	4.46	0.82
6. Partition walls	30	$m^2_{element}$	0.58	1.05	3.97	0.83
7. Columns	7	piece	1.29	6.04	11.76	1.91
8. Ceilings	1260	$m^2_{element}$	0.66	2.24	4.69	1.37
9. Balconies	4	$m^2_{element}$	1.2	1.48	1.76	1.13
10. Roof	273	$m^2_{element}$	0.79	4.05	7.71	2.32
11. Technical equipment[a]	29	m^2_{AE}	1.18	–	3.36	1.18*

[a] Due to a small number of solutions in the building component catalogue, no benchmark is calculated, but the minimum is used. The target value is the sum of minimum values for electric equipment, heat generation, heat distribution and delivery, ventilation equipment and water (sanitary) equipment of residential buildings.

Table 5: Minimum, maximum, weighted mean and target values (0.05 quantile) for GWP for the building elements (Hollberg, Lützkendorf and Habert, 2019)

The second option is related to the benchmarks provided by the SIA2032 (Table 6) (SIA2032, 2018).



					Primary energy not renewable	**Greenhouse gas emissions**
Building detail	**BKP Element group**	**Designation**	Reference value	Unit	Creation per year [kWh/a]	Creation per year [kg CO2eq./a]
Preliminary work	**B 6 / B 7.2**	Excavation				
		Excavation	Volume	m3	0.03	0.01
		Excavation final	BTF	m2	11.29	3.06
		Piling	Baseplate	m2	2.90	0.77
Building shell under terrain	**C 1**	Base plate, foundation				
		uninsulated	Component area	m2	4.50	1.63
		insulated	Component area	m2	7.37	2.71
	C 2.1 (A) / E 1	Exterior wall under terrain				
		uninsulated	Component area	m2	4.62	1.51
		insulated	Component area	m2	8.27	2.74
	C 4.4 / F 1.1	Roof/slab under terrain				
		uninsulated	Component area	m2	5.84	1.91
		insulated	Component area	m2	11.34	3.62

Table 6: Benchmarks for building elements during preliminary studies, according to SIA2032 (SIA2032, 2018)

Considering that SIA2032 provides more detailed benchmarks, its recommendations are taken into account for the creation of the new LCA Database. However, SIA2032 does not provide benchmarks for the Element Group C3 – Columns. For this reason, the benchmarks for that Element Group are taken from Hollberg, Lützkendorf, and Habert (2019) (Table 5) (ETH Zurich, Chair of Sustainable Construction).

At the Building Level, benchmarks suggested by the Swiss Green Building Standard Minergie-ECO are considered (Table 7) (MINERGIE, 2014). The benchmarks are provided and categorized according to three building types: administrative, educational, and living. As shown in Table 7 below, they provide recommended values for building elements per square meter Energy Reference Area (ERA) (the area which is heated, cooled, or conditioned in a certain way) (MINERGIE, 2014).

Function	**Limit value1 [MJ/m^2a]**	**Limit value2 [MJ/m^2a]**	**Limit value1 [MJ/m^2a]**	**Limit value2 [MJ/m^2a]**
	heated area		unheated area	
Office	110	150	30	50
School	90	130		
Living	90	130		

Table 7: Benchmarks for different building types related to the building Energy Reference Area (MINERGIE, 2014)

LCA Values

Regarding the LCA Values, the following LCA databases are examined:

- An element-based database developed by eco-bau and Intep AG;
- An element-based database developed by crd (EAK - Energiekennwerte Elementarten Katalog) (crb, 2011);
- An element-based database developed by the architect of the project case study;
- An element-based database developed by the construction firm of the project case-study;
- Beuteilkatalog - Element-based database developed by eco-bau and BFE/Hollinger Consult[23] (Bauteilkatalog, 2016).

The element-based database developed by eco-bau and Intep AG provides information regarding different building elements. The database is structured according to the cost-planning structure provided by crd[24] (crb, 2012). In that sense, it provides not only information related to LCA parameters, but also a reliable structure that can help its implementation. However, the database is not officially released yet, so the information it provides is not publicly accessible, and it could not be implemented in the development of this master thesis.

The element-based database developed by crd (EAK - Energiekennwerte Elementarten Katalog) provides both a reliable structure (eBKP-H) and LCA values (crb, 2012; crb, 2011). However, the catalog has been updated for the last time in 2011, meaning the LCA values it provides are not updated. Moreover, it does not cover all the building elements listed in the eBKP-H catalog. For these reasons, this database is not considered for further implementation in this master thesis.

Element-based databases developed by the project's architect are also examined for their potential implementation in the newly formed LCA Database. However, it is concluded that such databases follow a structure proposed by the architect. In that sense, these databases are project-specific and cannot be used in an industrialized environment unless a whole new structure is developed. The same conclusion is reached for the element-based databases developed by the construction company that is responsible for the construction of the building.

Beuteilkatalog - an element-based database developed by eco-bau and BFE/Hollinger Consult[25] (Bauteilkatalog, 2016) provides information about LCA values for different building components. The database is composed according to the eBKP-H structure (Figure 24) (crb, 2012). For that reason, the LCA values it provides are adopted for the development of the newly formed LCA database.

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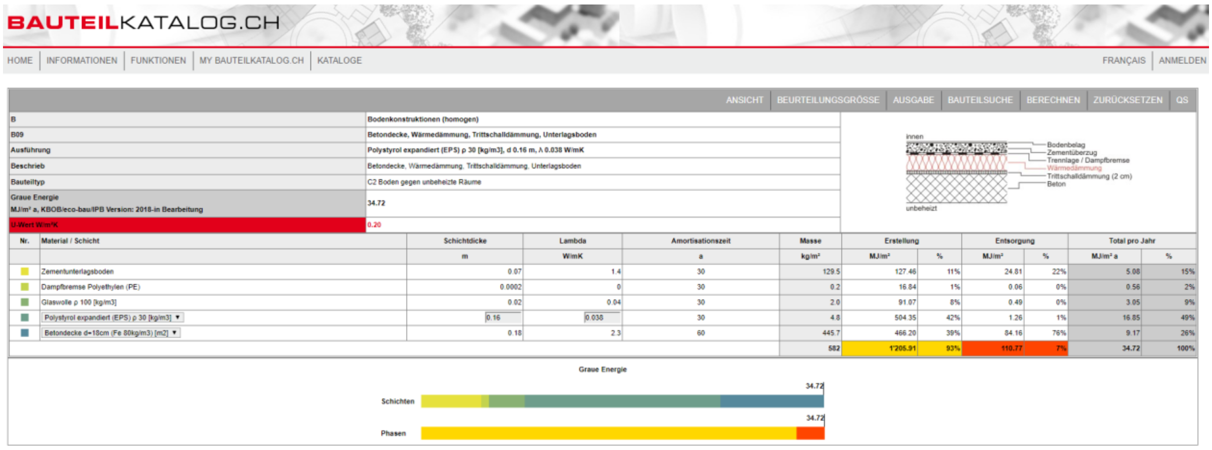
[23] Described in part 2.3.1 Life-Cycle Assessment (LCA) implementation: LCA Databases structure, of this report.

[24] Described in part 5.2.2 LCA Database: Code structure, of this report.

[25] Described in part 2.3.1 Life-Cycle Assessment (LCA) implementation: LCA Databases structure, of this report.



B	Bodenkonstruktionen (homogen)
B09	Betondecke, Wärmedämmung, Trittschalldämmung, Unterlagsboden
Ausführung	Polystyrol expandiert (EPS) ρ 30 [kg/m3], d 0.16 m, λ 0.038 W/mK
Beschrieb	Betondecke, Wärmedämmung, Trittschalldämmung, Unterlagsboden
Bauteiltyp	C2 Boden gegen unbeheizte Räume
Graue Energie MJ/m² a, KBOB/eco-bau/IPB Version: 2018-in Bearbeitung	34.72
U-Wert W/m²K	0.20

Nr.	Material / Schicht	Schichtdicke	Lambda	Amortisationszeit	Masse	Erstellung		Entsorgung		Total pro Jahr	
		m	W/mK	a	kg/m²	MJ/m²	%	MJ/m²	%	MJ/m² a	%
🟨	Zementunterlagsboden	0.07	1.4	30	129.5	127.46	11%	24.81	22%	5.08	15%
🟨	Dampfbremse Polyethylen (PE)	0.0002	0	30	0.2	16.84	1%	0.06	0%	0.56	2%
🟩	Glaswolle ρ 100 [kg/m3]	0.02	0.04	30	2.0	91.07	8%	0.49	0%	3.05	9%
🟩	Polystyrol expandiert (EPS) ρ 30 [kg/m3] ▼	0.16	0.038	30	4.8	504.35	42%	1.26	1%	16.85	49%
🟦	Betondecke d=18cm (Fe 80kg/m3) [m2] ▼	0.18	2.3	60	445.7	466.20	39%	84.16	76%	9.17	26%
					582	1'205.91	93%	110.77	7%	34.72	100%

Figure 24: Beuteilkatalog - Element-based database developed by eco-bau and BFE/Hollinger Consult (Bauteilkatalog, 2016)

5.2.2 Code structure

The LCA Database proposed in this study is composed according to an existing cost-planning structure for buildings (eBKP-H – Baukostenplan Hochbau (Cost-plan Buildings)) developed by crb[26] (crb, 2012). eBKP-H – Baukostenplan Hochbau (Cost-plan Buildings) is a structure used by most Swiss construction companies for cost-planning. The structure is used for BIM models elements identification as well (Figures 25-28 – removed from the report due to confidentiality issues). In that way, it provides a code-base that is commonly used for BIM modeling in Switzerland, meaning there is no need for data re-entry and restructuring.

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[26] crb - competence center for standards in the construction and real estate industry in Switzerland. Together with professional and partner organizations, work equipment is developed and provided in the form of catalogs, web applications and data for software programs. Source: (http://crb.ch).

The eBKP-H structure is used for the evaluation of different Green Building Standards as well (Figure 29) (SIA2032, 2018; MINERGIE, 2014).

SIA2032		**MINERGIE-ECO**	
B 6.2	Excavation, not contaminated foundation	**B 6.2**	Excavation, not contaminated
C 1	Foundation	**C1**	Foundation
C 2.1(A)	Exterior wall construction (under terrain)	**C 2.1(A)**	(A) Exterior wall constructions (under terrain)
C 2.1 (B)	Exterior wall construction (over terrain)	**C 2.1 (B)**	(B) Exterior wall constructions (over terrain)
C 2.2	Interior wall construction incl. G 1.3 and G 1.4	**C 4.3**	Balcony
C 3	Support structure	**C 4.4**	Roof construction
C 4.1	Ceiling	**E 1**	Outside wallcoverings under the terrain
C 4.3	Balcony	**E 2**	Outside wallcoverings over terrain
C 4.4	Roof construction	**E 3**	Built-in to an exterior wall (windows, doors)
D 1	Electrical system	**F 1**	Roof
D 5	Heating system	**F 2**	Internals to the roof (without fall protection roof)
D 7	Air conditioning system	**C 2.2**	Inner wall construction
D 8	Water system	**C 3**	Support structure
E 1	Outside wallcovering under terrain	**C 4.1**	Ceiling (including stairs/ramp)
E 2	Outside wallcovering over terrain	**G 1**	Partition
E 3	Fittings to outside wall (windows, doors, gates)	**G 2**	Flooring
F 2	Installations to roof	**G 3**	Wallcovering
G 1	Partition wall	**G 4**	Ceiling clothing, roofing clothing inside
G 2	Flooring	**D 1**	Electrical systems
G 3	Wallcovering, prop clothing	**D 5**	Heat systems
G 4	Ceiling clothing, roofing clothing inside	**D 7**	Air conditioning systems
		D 8	Water systems

Figure 29: Building elements evaluated during SIA2032 and Minergie-ECO (SIA2032, 2018; MINERGIE, 2014)

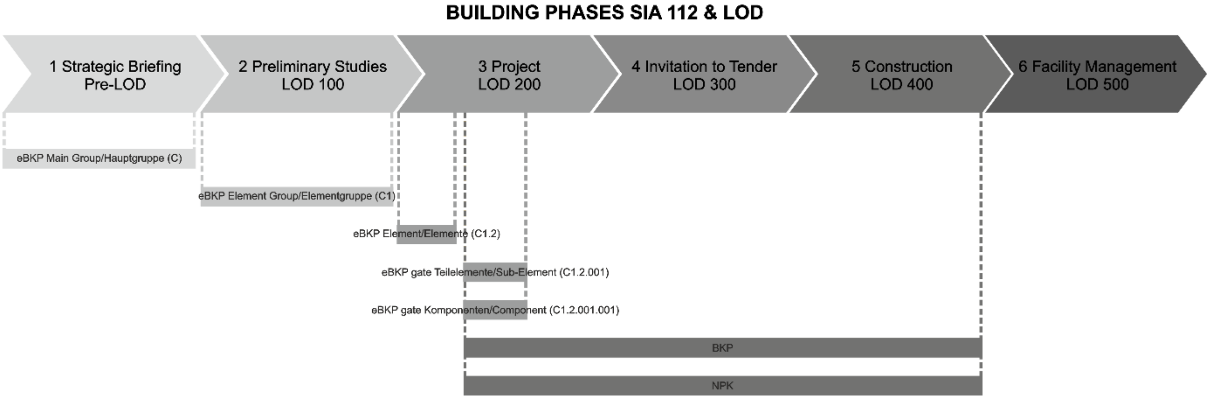

Figure 30: Cost-planning system over the Building Process (eBKP-H, BKP, and NPK) developed by crb (crb, 2017)

The developer crb proposes a system that covers the building process up to Building Phase 5, Construction (Figure 30) *(crb, 2017)*. The system is composed of three structures or catalogs, which are developed by crb as well – BKP Baukostenplan (Cost-plan), eBKP-H Baukostenplan Hochbau (Cost-plan Buildings) and NPK Normpositionen-Katalog (Standard positions catalog). These three structures are composed of different main groups, groups, sub-groups, etc. (Figure 31) *(crb, 2012*; *crb, 2018; crb, 2017)*.

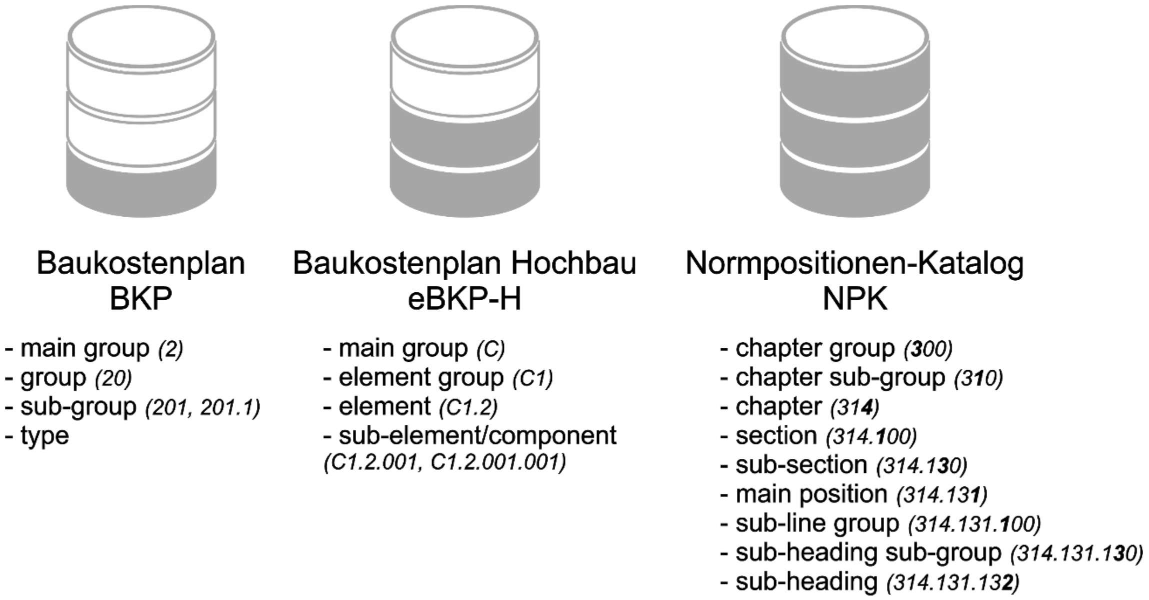

Figure 31: BKP Baukostenplan (Cost-plan), eBKP-H Baukostenplan Hochbau (Cost-plan Building) and NPK Normpositionen-Katalog (Standard positions catalog) (crb, 2012; Crb, 2018; crb, 2017)

For the development of the LCA, database proposed, the eBKP-H – Baukostenplan Hochbau (Cost-plan Buildings) structure is adopted since it provides information regarding building components in Building Phases 1-3. The Main Group, Element Group, Element, and Sub-Element categories are taken into account and related to the existing Building Phases (SIA 112, 2001). The relation between the different categories and the Building Phases is explained in the next section of this report[27].

5.2.3 Building phases

As mentioned in section 2.4.3 of this report, LODs and existing Building Phases are strongly related. For the development of the new LCA Database, the different LODs and the related Building Phases are mapped on top of each other, while pointing out their relation to the LOG and LOI (Figure 32)[28].

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[27] Described in part 5.2.3 LCA Database: Building phases, of this report.

[28] As shown in Figure 32, Building Phase 1, Strategic Briefing, can be associated with the Pre-LOD. The building area and the concept by planners regarding the LOI are defined in it. Building Phase 2, Preliminary Studies, is mapped to LOD100. It is associated with defining the room areas and further definition of the concept by specialists and planners. Building Phase 3, Project, is connected to LOD200 and associated with the definition of the components and building elements regarding their position, size and material. Building Phase 4, Invitation to Tender, LOD300 is about specification, quality and design of the building components. Building Phase 5, Construction, LOD400 requires a set of all execution details, while Building Phase 6, Facility Management, LOD500 is about certifications and product documentations.

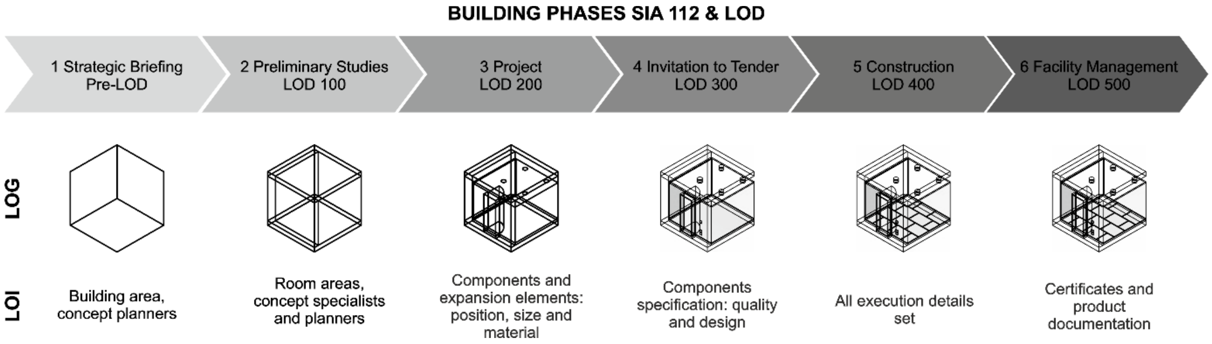

Figure 32: Building Phases (SIA112) and related LOD, LOI, and LOG (SIA 112, 2001; Curschellas et al., 2018)

Through the development of the new LCA Database, the building process is divided into two parts. From Building Phases 1 to 3, a Simplified component-based approach is considered (Figure 33), while from Building Phase 4 to 6, a Detailed material-based approach is taken into account (Figure 34).

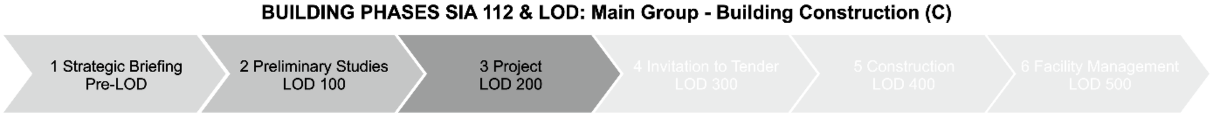

Figure 33: Simplified component-based approach for LCA related to the building process

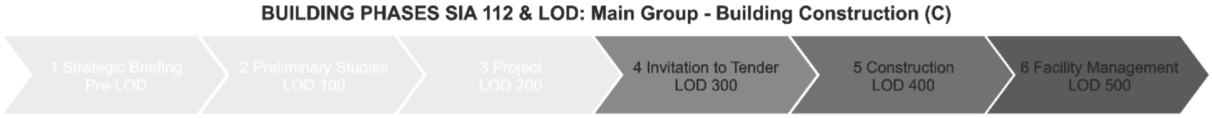

Figure 34: Detailed material-based approach for LCA related to the building process

The LOG and LOI can be associated with the different categories composing the eBKP-H structure for the Simplified component-based approach. For the Detailed material-based approach different information regarding the building materials can be taken into account. In that way, the whole building process is evaluated, providing a method for LCA that is applied continuously over the entire building process. Decision-making metrics (SIA2032&Minergie-ECO) both on Element and Building Levels are implemented at every Building Phase (SIA112) by using code structure existing in BIM (eBKP-H) (SIA, 2018; MINERGIE, 2014; SIA 112, 2001; crb, 2012).

Figure 35 below shows an example for the eBKP-H Main Group C – Building Construction[29].

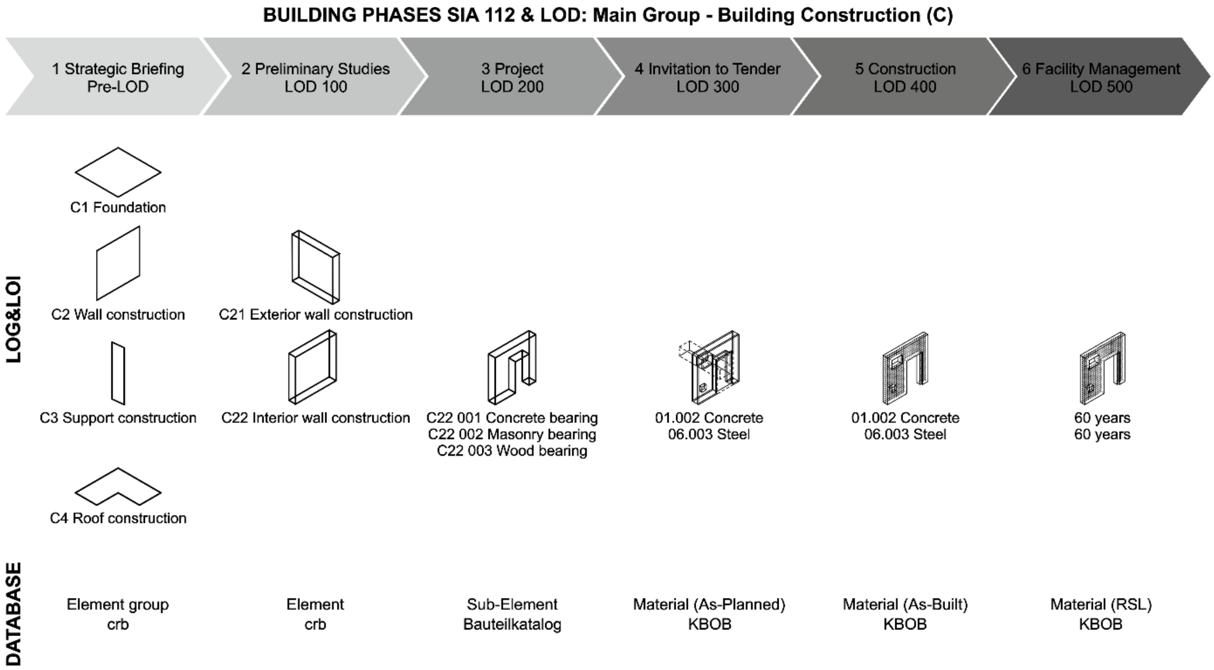

Figure 35: eBKP-H categories mapped over the Building Phases, LODs, LOG, and LOI

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[29] The Simplified component-based approach for LCA is applied from Building Phase 1 to 3 (Figure 35 and 36). In Building Phase 1, Strategic Briefing, since there is not enough available information, the Element Groups, namely C1 Foundation, C2 Wall Construction, C3 Support Construction and C4 Roof Construction are considered. Focusing on Element Group C2, Wall Construction, in Building Phase 2, Preliminary Studies, the Elements it is composed of, C21 Exterior Wall Construction and C22 Interior Wall Construction, are taken into account. In Building Phase 3, Project, specific Sub-Elements are examined, since in that Building Phase there is more clarity about the future development of the project. Since the materials these Sub-Elements are composed of are known, they can be evaluated with the help of the material-based database KBOB, on which the component-based database Bauteilkatalog is structured according to (KBOB, IPB and Verein, 2016; Bauteilkatalog, 2016). For the composition of the LCA Database, the Bauteilkatalog, which provides information about building elements based on the KBOB database, has been taken into account. In that way, an average value of the Sub-Elements, part of Building Phase 3, Project, can be calculated, giving an input for the evaluation of the Elements in Building Phase 2, Preliminary Studies. Then, taking an average value for the Elements part of Building Phase 2, Preliminary Studies, an average value for the Element Groups in Building Phase 1. Strategic Briefing, is calculated (Figure 36). That provides the possibility for all the Building Phases from 1 to 3 to be evaluated.

In Building Phases 4 to 6 the Detailed material-based approach is considered (Figure 35). In Building Phase 4, Invitation to Tender, information regarding the materials as-planned is taken into account and related to the KBOB database (KBOB, IPB and Verein, 2016). In Building Phase 5, Construction, information about the materials as-built, and in Building Phase 6, Facility Management, information about the Reference Service Life (RSL) of materials is considered and again associated with the KBOB database (KBOB, IPB and Verein, 2016).

Figure 36: Simplified component-based approach for LCA related to the building process - evaluation

5.3 Testing on the Case study

The Dynamic parametric tool for LCA and the related workflow developed by the author of this study have been applied and tested on the project Case Study described in section 4.2[30].

In Figure 37, results derived after running the Dynamo scripts on BIM models from Building Phase 22, 31, and 32 with different LOD LCA Levels are shown.

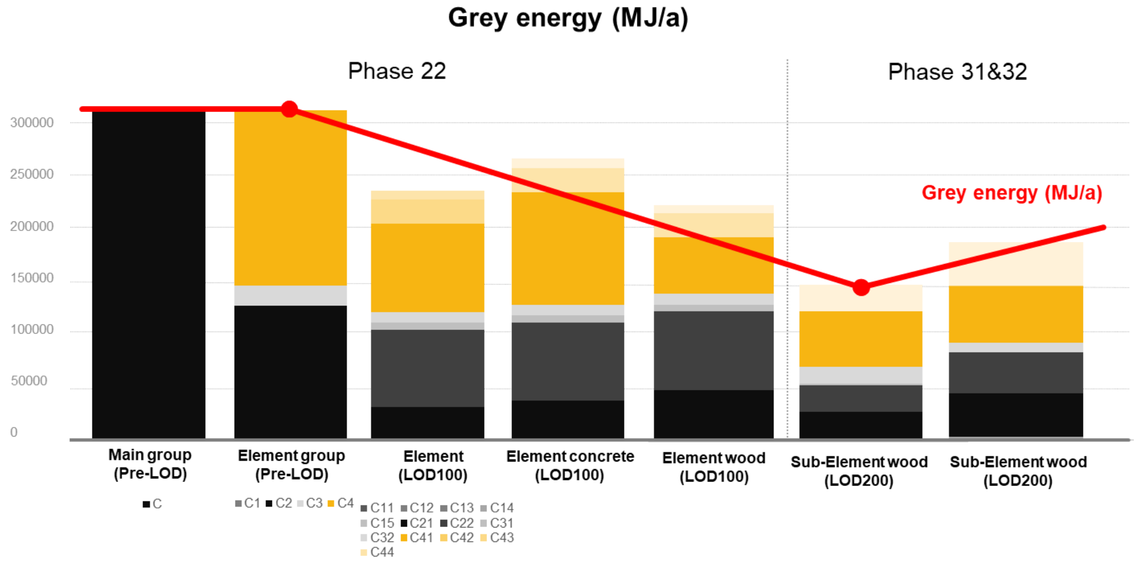

Figure 37: Case Study Results

On the BIM model from Building Phase 22, LCA LOD Levels for Pre-LOD/Main Group, Pre-LOD/Element Group, LOD100/Element, and LOD100/Element Material are extracted from the newly created LCA Database. Once the LOD is better defined, there is a base for better decision-making. Changing the Level of Development from Pre-LOD to LOD100 different Elements are distinguished from the different Element Groups, providing more precise information regarding each Element.

It should be noted that these results are highly dependent on the Elements' quantities, represented by their surface areas. In that sense, the Dynamic tool for LCA would provide quick observation regarding LCA Values during the preliminary studies.

Already in LOD100, the impact of different Element materials can be highlighted. In figure 37, the results of LOD100/Element Material Concrete and LOD100/Element Material Wood are compared to LOD100/Element. The higher impact of LOD100/Element Material Concrete is easily distinguished. However, it should be pointed out that not each Element can be associated with LOD100/Element Material Concrete from the LCA Database. This is due to the limited Building components provided by the current version of the Bauteilkatalog. In that sense, LOD100/Element Material Concrete is a combination of building components composed of concrete and building components with a general material that is not specified. Still, the idea of defining different material groups can provide valuable input for the future development of the building project.

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[30] For that purpose, three BIM models are used, from Building Phase 22, Building Phase 31 and Building Phase 32. The models are collected as IFC files and later loaded in Revit. The Dynamo scripts are applied on each of the BIM models, while extracting information on Pre-LOD/Main group, Pre-LOD/Element group, LOD100/Element, LOD100/Element material and LOD200/Sub-Element levels from the LCA Database. The detailed LCA reports based on running the scripts are part of the Appendix A.4 of this study.

The Dynamo scripts are run on the Revit models from Building Phase 31 and 32 with the extraction of LOD200/Sub-Element Material Level. For that purpose, specific wooden building components with low LCA Values from the LCA Database are chosen. In that sense, the lower values for grey energy can be explained with the usage of bio-based sustainable material.

6 Discussion

After applying the Dynamic tool for LCA and the related workflow on a case study, it is shown that the entire building process could be continuously assessed in terms of embodied energy impacts. As the building process evolves the variability decreases since the LOD is better defined. Different LCA Parameters, like Grey energy and greenhouse gas emissions, can be continuously accounted for throughout the building project development while applying LCA Benchmarks associated with them. In that way, there is a possibility for continuous decision-making metrics.

Still, the results provided in the LCA Report rely strongly on the consistency of the LCA Database used. In the case of this study, the newly developed LCA Database uses LCA Values from the Bauteilkatalog. This catalog does not provide such a wide variety of building components, leading to results that are affected by the limited number of catalog elements. This issue could be overcome by adding additional information to the database. The catalog used for the development of the newly formed LCA Database involves mainly typical industrialized building solutions. In that sense, it is useful for mass construction, but not for innovative, unique building projects. Again, the issue can be improved by adding innovative, bio-based building components to the database.

The element-based database developed by eco-bau and Intep AG[31] provides the potential to overcome these issues. The database is composed according to the cost-planning structure provided by crd. For that reason, its implementation in BIM has high potential. The database provides more than 600 building components, meaning the outcome can be more precise.

The results presented in figure 37[32] showing lower values of Grey energy can be explained with a decision-making metric chosen with the idea of using more sustainable building materials with less embodied energy. Another reason for the lowering of the grey energy in that specific case is the reason that when the LOD is better defined, the LCA Values are more precise and lower, leading to the reduction of the grey energy. Still, that is partly due to the specific choice of building components. Comparing Building Phase 31 and 32, an observation about the growth of grey energy can be pointed out. This rise can be explained by the fact that the Level of Geometry has been developed.

The case study used as a research method in this master thesis provides information about element code structure up to LOD100 (eBKP-H codes, Element[33]). The LOI provided by these codes does not let different elements be distinguished from the group they are part of. For example, all exterior walls are considered to be from the same type, as well as all interior walls, all stairs, floors, columns, etc. For a better LCA evaluation, a higher level of detail in the code structure implemented in BIM should be provided.

It should be noted that the results derived with the help of the Dynamic tool for LCA give information about different LCA Values and a possibility for decision-making at both the Element and Building Levels.

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[31] Described in part 5.2.1 LCA Database: Decision-making support, of this report.

[32] Described in part 5.3 Testing on the case study, of this report.

[33] Described in part 5.2.3 LCA Database: Building phases, of this report.

There is a discussion related to the BIM approach adopted for the development of the Dynamic tool for LCA and the related workflow. This discussion can be associated with the idea of using a closedBIM or an openBIM approach. The terms closed and openBIM are associated with information exchange, a basis for which are the Industry Foundation Class (IFC) files, provided by buildingSMART International (Santos *et al.*, 2019). For the development of this thesis, an IFC file is used and converted into a Revit model. Afterward, this Revit model is taken as a basis for the creation of the Dynamic tool for LCA and the related workflow, together with the parametric program Dynamo. In that sense the specific approach would work for companies using these software tools and having BIM and LCA experts in place. However, once there is a need for information exchange, the building model should again be converted into an IFC file. This would lead to the impossibility of the use of the Dynamic tool since for it a Revit model is needed. Still, the information exchange would be possible with the help of the IFC files, meaning an openBIM approach could be achieved. In this regard, it should be noted, that the proposed methodology is useful for applying decision-making metrics while modeling the building.

7 Conclusion, limitations and future potential

7.1 Conclusion

Reflecting on the research questions, the main question that this study aims at addressing is:

How could BIM support LCA over the entire building process?

A methodology for Swiss construction companies to perform LCA continuously over the entire building process (SIA112) is proposed. The methodology provides decision-making support (SIA2032&Minergie-ECO) both at the Element and Building Levels at every Building Phase (SIA112) and their associated Level of Development (LOD). For its implementation, an existing code structure (eBKP-H) applied in BIM is used, so that the re-entertaining of data is prevented.

Answering the sub-questions that follow from the main research question:

What digital tools and related workflows can support a BIM-based method for LCA? How can they provide decision-making support?

The digital tools used for the development of the Dynamic tool for LCA are an IFC file converted to a Revit BIM model that is connected to an LCA Database via a parametric tool called Dynamo. The parametric tool connects the BIM model and the LCA Database, calculates LCA Values, and returns the results in the BIM model. After the results become part of the BIM model, they are compared to the LCA Benchmarks part of the LCA Database on Element and Building Levels (SIA2032&Minergie-ECO). That leads to decision-making support through color distinguishment of different building elements, while associating them with the Energy Reference Area (ERA).

What LCA-related data can be embedded into a BIM model? Which databases can be linked to a BIM model?

The LCA-related data embedded in the BIM model provide information about different LCA Parameters associated with different building elements. The database linked to the BIM model is a newly created LCA Database that combines existing LCA databases and groups the information provided by them according to different Building Phases and their associated LODs.

How can the re-entering of LCA data into the BIM model be prevented? Is there a common code data structure existing in BIM that can be used?

The re-entering of LCA data into the BIM model is prevented by composing a new LCA Database. The database uses an existing structure for cost-planning that is widely adopted in Switzerland. The LCA Parameters, part of this new LCA Database, are automatically accounted for through the application of the Dynamic tool for LCA. After that, through the application of the workflow, the information is first returned to the BIM model, and then an LCA report based on that data is created. The Method developed in this thesis provides evaluation and optimization, as well as time-saving opportunities and reliability while implementing visualization criteria.

7.2 Limitations

IFC-REVIT compatibility

For the application of the case study adopted as one of the research methods during the development of this master thesis, IFC files are used. These files are loaded in a BIM environment, represented by the software program Revit. The conversion between the first file format to the second one has led to a limitation in the provided geometry, respectively their visualization and associated decision-making metrics. The reason for that is because some parameters are not readable for all the building elements. Consequently, the information they contain could not be used.

BIM Models

- ***Incompleteness of BIM Models***

The first limitation in BIM models is related to their incompleteness, as well as the incompleteness of the IFC files used for their creation. Two general trends can be identified in that sense. The first one is related to missing building elements (HVAC elements) and building sub-elements (finishing plaster within a wall element). The second one is for missing parts of the BIM geometry as well as information assigned to such geometry (different parameters or eBKP-H codes). These limitations lead to an incomplete BIM model and incomplete BOQ.

- ***BIM models' LOD***

The second limitation is related to the BIM models' LOD. It is about the fact that some building elements (structural elements) are defined before others (claddings). These issues lead to variability between the LOD of different components. Another important fact in that sense is the fact that even if structural elements are defined, still the materials they are defined with do not represent the same LOD as the BIM model. For example, composite walls composed of concrete and steel are modelled with only concrete as a material. That means that if such elements are evaluated in terms of grey energy and other LCA Parameters based on their material content, such evaluations will not represent the actual LCA Values. In that sense, it can be concluded that the usage of some materials in BIM is rather related to a group of materials than to a particular single one.

- ***BIM Models' modeling methodology***

The concept behind the Dynamic tool for LCA and the related workflow developed in this master thesis are strongly related to the modeling structure used in BIM models. The main idea adopted from this methodology is that different building elements in the BIM model are distinguished according to the Swiss cost-planning structure for buildings developed by crd (eBKP-H)[34]. These element codes are later mapped to an LCA Database structured according to the same code system. That means that if the BIM methodology doesn't incorporate such code system, this mapping wouldn't be possible unless such codes are assigned manually in the BIM model before its LCA Evaluation. In the case study part of this master thesis, the LOD of the codes assigned in the BIM model is LOD100. For that reason, the codes from this LOD are used for the evaluation of LCA in LOD200 as well. That lead to the fact that different Sub-Elements levels couldn't be identified in different Elements level. For example, all interior walls are considered to be from the same type, since they all had the same code assigned. In that sense, better code distinguishment would lead to more detailed results and better decision-making metrics.

LCA Databases

- ***Newly created LCA Database***

There is an issue related to using average values for the creation of the new LCA Database[35]. Using average values for Elements and associating them with Element Groups complies that different Elements are equally distributed in different Element Groups. For example, Element Group C2 Walls is composed of Elements C21 Exterior Walls and C22 Interior Walls. Taking the average value of these two Elements would mean that the Element Group C2 Walls is composed of 50% interior and 50% exterior walls, which is not precise. Still, for an early estimation when there are not enough details about the further development of the building project, such simplification can be taken into account for LCA estimation.

- ***Existing LCA Databases***

A limitation exists concerning LCA Databases. The main issue with LCA Databases is that the databases don't declare LOD, leading to the possibility of their imprecise application time, as well as LCA results. Another issue is the fact that LCA Databases are inconsistent in terms of variability of proposed building components and materials used in them. For example, most databases focus mainly on traditional building components and neglect the usage of more sustainable and/or bio-based materials. There is also variability in the units used in the databases. For instance, some building materials described in the KBOB database are in kg, others in m^3. Regarding BIM-LCA integration, the biggest challenge associated with LCA Databases is their structure and its difference when compared to the BIM modeling structure.

Dynamic tool for LCA and newly created LCA Database

The Dynamic tool for LCA and the newly created LCA Database that are parts of this thesis have been developed for Building Phases 1 to 3: Simplified component-based approach for LCA. The reason for that is that the LOD of the case study reviewed during their development doesn't evolve after Building Phase 32. IFC files from Building Phases 41 and 51 were reviewed, but the LOI they possessed had the same level as the IFC files from Building Phase 32.

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[34] Described in part 5.2.2 LCA Database: Code structure, of this report.

[35] Described in part 5.2.3 LCA Database: Building phases, of this report.

Human factor

Since the BIM-LCA integration is not fully automated and digitalized, there is a potential for errors related to the human factor. The main issue about the human factor is associated with the potential of the inconsistency of the BIM models. That may lead to an incomplete list of parameters for BIM elements and a lack of information for LCA evaluation. Another issue might be the entering of LOD levels in Dynamo player since it requires a manual input as well. Still, this can easily be tracked with the Dynamo player itself.

7.3 Future potential

BIM model structure

There is a need for a common modeling structure to be recognized and adopted by different specialists when they are developing different building projects. This structure should be associated with different LODs and the related LOI and LOG that are part of them. If a common structure is used with different project needs, that will provide its easier implementation, as well as easier evaluation of the building elements it is applied to. For that reason, researchers and specialists working in different areas part of the building industry should find common ground for standardization of common building components, elements, and sub-elements.

The method applied in this master thesis strongly relies on the information provided and the structure implemented in the case study developed by the Swiss construction company Implenia AG. For the method to be better assessed, case studies from other construction companies of the same scale should be reviewed, so that the different approaches can be compared. Case studies from different planning companies, e.g., architectural offices, should be considered as well. The method is also strongly dependent on the existing databases and cost-planning structure in Switzerland. For better evaluation, the application of databases and structures from other countries must be taken into account.

openBIM

As noted before, the approach adopted for the development of the Dynamic tool for LCA and the related workflow part of this thesis can be identified as an openBIM one. Still, the approach can be improved by adopting the following trends:

- Trend 1: Incorporating LCA Parameters in the methodology for the BIM model creation (Figures 38-41);
- Trend 2: Using IFC files for LCA evaluation (Figures 42).

For the first trend, LCA Parameters should be part of the methodology during the project creation (Figures 38-41). If LCA Parameters exist in the model from its very beginning that would allow for different specialists involved in the building process to evaluate them in the desired software environment. This would also remove the need for importing LCA Database in a later phase of the building process. There are several ways in which that can be accomplished. One way is for the LCA Database to be incorporated in the form of an IFC file, which could be used for the beginning of the design process (Figure 38). Another is to map certain LCA Database to existing Native BIM libraries (Figure 39). The BIM libraries can also be created based on existing LCA Databases and used as a source for BIM creation (Figure 40). The Application Programming Interface (API) of a certain BIM software program can also be used for the incorporation of LCA Databases (Figure 41). This trend can be associated with the provision of decision-making metrics while modeling the project.

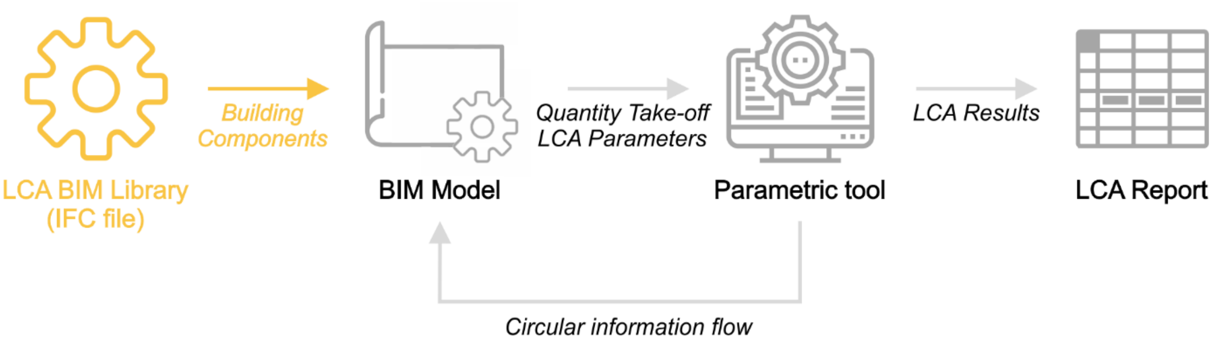

Figure 38: Trend 1: Incorporating LCA Parameters in the methodology for the BIM model creation: LCA BIM Library (IFC file)

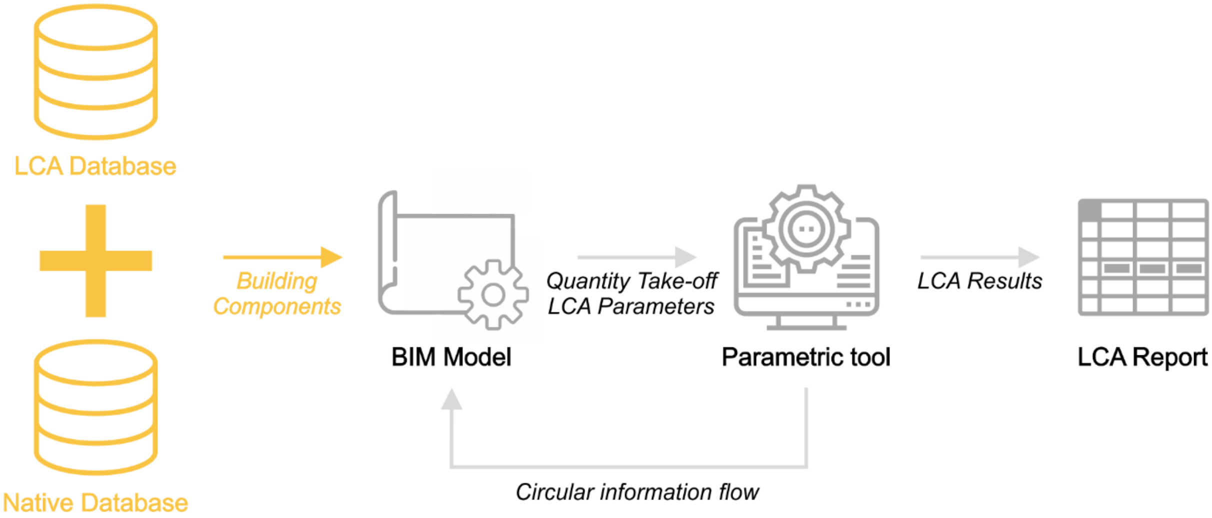

Figure 39: Trend 1: Incorporating LCA Parameters in the methodology for the BIM model creation: LCA Database mapped over Native Database

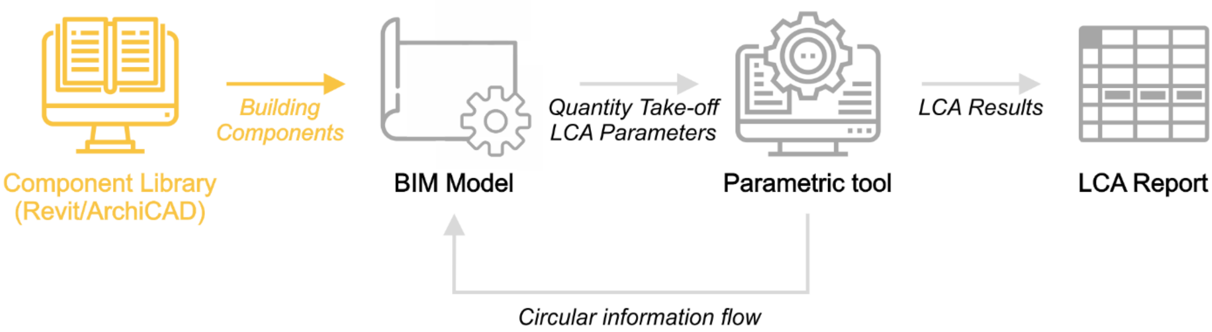

Figure 40: Trend 1: Incorporating LCA Parameters in the methodology for the BIM model creation: LCA Component Library in a specific BIM software

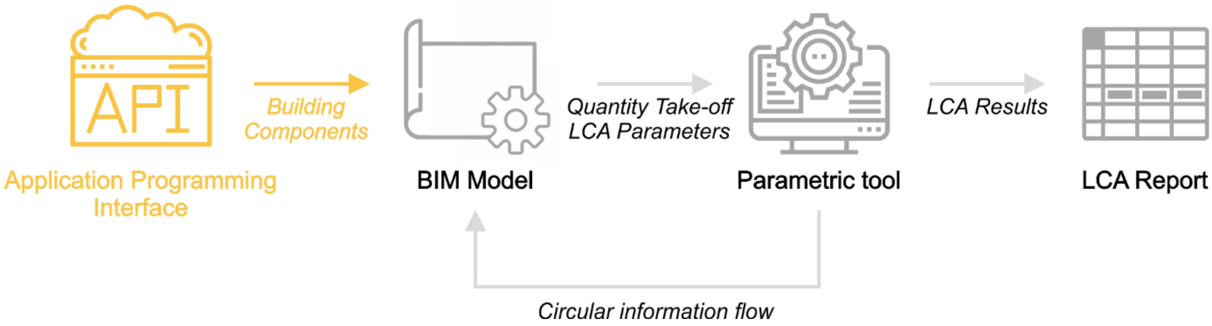

Figure 41: Trend 1: Incorporating LCA Parameters in the methodology for the BIM model creation: API manipulation

For the second trend, IFC files could be used for LCA evaluation (Figure 42). That would allow for the BIM model to be created in a desired BIM software program and then exchanged in the form of IFC. Several criteria are identified related to that approach:

- BIM Library requirements, a BIM guideline and a Model View Definition (MVD);
- An IFC file model checker to ensure that the IFC file contains all the relevant information;
- An IFC Viewer Plugin or a newly developed software tool that performs the LCA Evaluation.

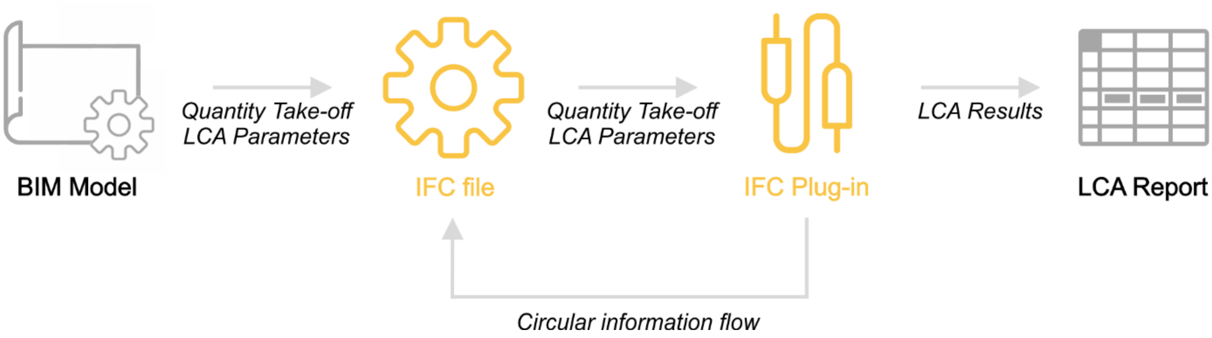

Figure 42: Trend 2: Using IFC files for LCA evaluation

Still, for the creation of an IFC-based tool for LCA evaluation, a specific IFC Viewer software program should be used. That again implies to the fact that an approach for BIM-LCA integration is associated with the exchange of information between different software programs. The trend can be pointed out as an approach providing consultancy on the project since the project's geometry can't be remodeled.

LCA Databases

Future potential can be identified with further development of LCA Databases. Existing LCA Databases can be restructured so that different building phases and LOD Levels are pointed out. The Databases should adopt a common generalized code structure, that is related to different LOD Levels for their easier implementation in BIM. LCA Values should be incorporated in existing Building Components and Libraries, Revit families, Pre-fabricated Elements, Technical Equipment, etc. LCA Parameters should be distinguished using a standardized LCA dictionary, which provides keywords associated with LCA so that a common understanding is achieved.

The newly developed LCA Database part of this thesis relies on information from databases, which consist of only traditional components and materials. In that sense the proposed method is useful for mass construction, but not for innovative construction solutions. Development of databases for bio-based materials, as well as recycled and innovative materials, should be considered for their easier implementation in buildings and for construction companies to have a higher motivation to use them.

Dynamic tool for LCA and newly created LCA Database

Since the Dynamic tool for LCA and the newly created LCA Database part of this thesis are developed until Building Phase 3, Project (SIA112), there is a future potential for their development in Building Phases 4 to 6, adopting Detailed material-based approach for LCA[36]. There is also a potential for the development of a tool with a specific approach for Building Phase 1, Strategic Briefing, since, in that phase, there is usually no BIM Model. This tool can be developed using the software program Grasshopper in combination with modeling software tools like Rhino or ArchiCAD, which are usually associated with providing decision-making metrics during conceptual design phases.

The proposed dynamic tool and workflow for LCA evaluation account only for embodied energy. An operational energy impact is not considered. However, the same logic can be applied for the future development of a tool and workflow for evaluation of operational energy. Still, it is important to highlight, that in newly developed energy-efficient buildings, the impact of embodied energy often exceeds the one from operational energy (Azari and Abbasabadi, 2018). In that sense, the Dynamic tool and the related workflow, part of this thesis, provide an instrument to account for the contribution of a type of energy in a building, which has a higher overall impact.

Decision-making

The results derived after running the Dynamic tool for LCA provide only concrete numbers, based on the quantities of the building elements and the building's gross floor area. There might exist other indicators that can be taken into account. For example, if a building element's LCA Values are above the associated LCA Benchmarks, this element can still be better when related to the whole building than two elements with LCA Values at the LCA Benchmarks. This issue is partly addressed by the provision of decision-making metric on Building Level, taking into account all building elements and associating them with the whole building. Still, there exist other possibilities to provide more sophisticated decision-making metrics, for example, by implementing Artificial Intelligence opportunities and Machine Learning. In that sense, Artificial Intelligence opportunities and Machine Learning can be pointed out as a way to address decision-making metrics during the building process in the future.

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[36] Described in part 5.2.3 LCA Database: Building phases, of this report.

General

There is future potential in developing similar tools by adopting similar workflows for different purposes, for example, for evaluating operational energy or Life-Cycle Costing (LCC). The scripts can be optimized, and their computation done on a cloud source so that the time for their evaluation is reduced. Machine learning is another general approach that can be used for future improvement of the method, for example, for smart mapping of components, elements, sub-elements, and materials.

BIM integration in different parts of the building process is a powerful approach through which various areas of the process can be optimized. Many specialists, part of the AECO industry, are unfamiliar with the benefits provided by digitalization in their practices. Methodologies, similar to the one developed in this master thesis, can be generated to improve specific areas of specialists' daily work. These methodologies can be applied in different case studies providing a proof of concept with different purposes. Information regarding different use cases can be formed according to LODs and an algorithm for their implementation in BIM provided. This information should be simplified and standardized for its easier assessment. In that sense, simplification and standardization of the building process through its digitalization have the potential to improve its overall sustainability.

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