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TOWARDS LIFE CYCLE ASSESSMENT OF TECHNICAL BUILDING SERVICES IN EARLY DESIGN PHASES USING BUILDING INFORMATION MODELLING

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Abstract

In order to reach the goal of a net-zero carbon society, the construction industry plays a significant role. Optimising the performance of new buildings in early design phases requires the analysis and evaluation of environmental impacts by life cycle assessment (LCA). The semantic building model can be employed to automatically derive necessary information for LCA to reduce the manual calculation effort. Existing approaches using Building Information Modelling (BIM) for LCA mainly take the operational and the embodied impacts of the building construction materials into account. Still, they do not consider technical building services (TBS), especially in early design phases. However, the embodied carbon of TBS has a significant impact (up to 30% for office buildings) on the whole building LCA and is generally underestimated. Usually, it is considered as a factor of the total LCA but rarely calculated in detail.

To identify the research gap, this paper first presents a literature review on existing approaches of the research field of BIM-based LCA of building services. There are just a few approaches in this field, and none of the BIM-based ones are applied in early design phases. The literature review classifies publications in different aspects, such as design phase, TBS Scope, LCA scope, and BIM integration. In a second step, a new methodology focusing on early design phases is presented. As in early design phases, we assume not to have a TBS model yet, an energy demand analysis and pre-dimensioning of TBS components are included in the methodology. Afterwards, LCA is calculated for the main TBS components based on the quantity take-off of the pre-dimensioned components.

Introduction

The European Commission proposed along the actions of the European Green Deal and the EU Taxonomy new actions regarding climate and energy policies of the construction and building sector, which will tighten the requirements on energy efficiency, use of renewable energies, and life cycle thinking. Greenhouse-Gas (GHG) Emissions from the production, deconstruction, and recycling of buildings are considered for the first time. To assess a building's GHG emissions, LCA is used. However, the TBS, defined by Heating- Ventilation and Air-Conditioning (HVAC) electrical and plumbing systems, are usually only included in a simplified way or, more often, are entirely neglected. Therefore, the extent of the environmental impact of building services is generally underestimated, and the savings potential in terms of emissions and other environmental impacts is not recognised. The main reason for this is that the effort required to determine the necessary data basis for an LCA of TBS is very high.

The BIM method and the Industry Foundation Classes (IFC) data exchange format offer a high potential to perform LCA significantly more efficiently and comprehensively by enabling the full consideration of TBS materials.

State of the Art

This section introduces the four main interfacing topics BIM, LCA, HVAC, and Early Design Phases, and their combination by analysing the synergies of the combination of two main topics (Figure 1).

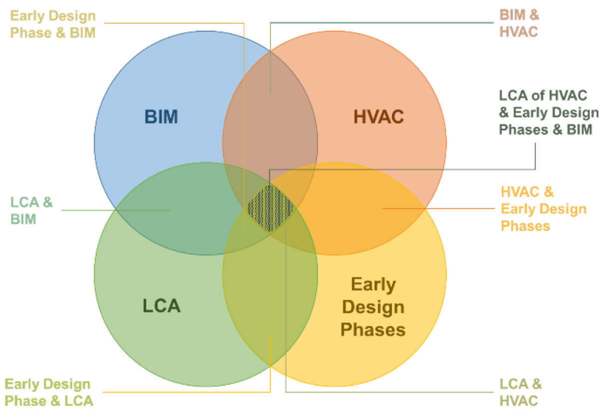

Figure 1: Overview of interface topics BIM, LCA, HVAC, and Early Design Phases

HVAC and LCA

The consideration of HVAC in LCA is still an underestimated area. Although the standard DIN EN 15978 provides an exemplary specification in its supplementary Annex A, where besides the main elements of the building, TBS is also included, current LCA calculation rules of green building certification systems allow to simplify or neglect the consideration of environmental impacts. However, a few studies show that TBS is responsible for a high share of embodied impacts for new constructions of non-residential buildings

(Alexander et al., 2010). Notable in this regard is that TBS only has a material mass share of usually around 1–4% of the total building. For example, in the case of GHG emissions CO2 emissions are significantly higher than 20% or 30% (Lambertz et al., 2019; Schneider-Marin et al., 2019). Within TBS, HVAC becomes a key role as it consists of materials like metals and plastics, which cause high material-related environmental impacts due to energy-intensive manufacturing processes and short service life. Therefore, there is a high necessity to consider TBS in assessing embodied carbon in a more integrated and coherent way with the building design.

Early Design Phase and BIM

Building design processes usually follow similar workflows with different stakeholders and interdisciplinary design teams incorporating their personal domain knowledge. To improve the holistic performance of building designs, e.g., considering economic and environmental qualities, design decisions based on simulations and analysis in early phases significantly impact the resultant design (Abualdenien et al., 2020). At the same time, early design phases of building projects are those, which are most complex to understand, carry out and manage (Knotten et al., 2015).

There are several advantages of a BIM-based planning process, such as the automatic derivation of views, floor plans and sections from the model without contradictions, collision checks between the models of different disciplines, and the connection to calculation and simulation programs or for checking compliance with various regulations (Borrmann et al., 2018). Furthermore, BIM can be used to precisely determine quantities in order to calculate costs or as a basis for calculating a life cycle assessment.

As in early design phases, most information is uncertain. The assignment of a (low) LOD to a model or a component is necessary to make the lack of reliability transparent. LOD in the BIM method is understood as an acronym for Level of Development and is the analogous concept to the scale drawings of conventional design. Level of Development specifies the degree of completion, maturity, or elaboration. The U.S. representative of buildingSMART International BIMforum has defined the individual Levels of Development (BIM Forum, 2020).

Furthermore, Level of Information Needs (LOIN) describes similar content like LOD (geometry and alphanumerical information). Still, it supports a particular use-case and was introduced by the European Standardization Organization (CEN) (DIN EN 17412). LOD is known as the sum of Level of Geometry (LOG) and Level of Information (LOI) (Borrmann et al., 2021).

Abualdenien developed a meta-model approach where multi-LOD data represent buildings at different design phases (Abualdenien and Borrmann, 2019). It is based on BIMForum's LOD definitions and introduces a new concept, Building Development Level (BDL). As LOD usually defines specific components, the BDL concept defines the maturity of the overall building model with individual LODs for each element type.

Early Design Phases and LCA

In today's industry practice, most of the LCA calculations are executed in the detailed design phase (Braune et al., 2018). One reason is that all necessary information is available in later design stages, and collecting all of them is usually time-consuming, so it is generally done once. Nevertheless, an important goal of calculating embodied environmental impacts is to optimise the design, while the most significant impact on the performance is mainly early design stages. Dotzler et al. showed the potential of a combined analysis of LCA and LCC in early design phases in the research project Design2Eco (Dotzler et al., 2018). The paper identifies strategic parameters for both LCA and LCC and derives recommendations for optimising the building performance. The final proposal recommends that both LCA and LCC should provide data on a component level, allowing to holistically analyse both simultaneously.

Alexander Hollberg's PhD thesis approached the optimisation potentials of LCA in early design phases with the help of parametric tools using the Visual Programming Language (VPL) Grasshopper with Rhino (Hollberg, 2016). This approach, called Parametric LCA (PLCA), is implemented by CAALA (Caala GmbH, 2022). This software start-up was founded with the aim of integrating LCA more seamlessly in early design phases.

Another approach of calculating LCA in early design phases is based on whole building LCA benchmarks of previously calculated LCA of already realised buildings (see discussion in section 4.1). Hollberg et al. discuss the question of top-down or bottom-up approaches, and benchmarking help evaluating LCA in early design phases for design optimisation (Hollberg et al., 2019).

Gantner et al. suggest a successive detailing of benchmarks, based on several design phases such as occasion and initialisation, where building types and systems are decided, demand planning and basic concept phase, where functional systems are selected, design and approval planning, where element systems are chosen, and more detailed design phases (Gantner et al., 2018). In the first phase, benchmarks are derived from fully developed buildings and in the second phase from typical building elements.

When calculating LCA in early design phases, certain geometry and material choice information are still uncertain. To better understand the uncertainty, sensitivity analyses have been carried out and received greater attention in recent research. Goulouti et al. extend their analysis to LCA and LCC and show the importance of building elements' service life (Goulouti et al., 2020). Schneider-Marin et al. propose a method where designers are guided to parameters with the highest uncertainty to optimise the design (Schneider-Marin et al., 2020). Harter adds operational energy besides the embodied energy in his uncertainty analysis (Harter, Singh et al., 2020).

HVAC and Early Design Phases

In the Early design, only the concept of the TBS and the main routes for the ducts, pipes, and electrical trays are known. Therefore, some level of estimation is needed in this project phase. Two main approaches are used: (1) algorithmic estimation of the rest of the routes (Böckle, 2021), calculation of their Bill of Quantities (BoQ), and their environmental impacts. Another option is (2) a rough estimation of the environmental impacts of the TBS based on the conceptual solution of the systems and experience of the assessing person.

In the literature, the usual value is to add 10-20% on top of the embodied environmental impact of the building. This value can vary according to the building typology and its specific use. Passive solutions of the air ventilation can decrease impact significantly. On the other hand, special buildings, such as hospitals or laboratories, can have an impact of the TBS up to 50% on top of the building itself. As buildings become more complex and technical, it can be estimated that the environmental impacts of the TBS will increase. Nevertheless, there is currently no standardised method available for estimating TBS in early design stages, which raises a number of research questions and needs.

BIM and HVAC

The modelling of TBS with BIM takes place in several BIM specialised models. In general, Heating, Ventilation and Air Conditioning, as well as plumbing and electrical systems, are modelled as separate BIM models.

The BIM Manager of TBS combines the separate models of the TBS into a combined model for checking clashes, correct distances, or fire protection requirements. The specialised model of TBS is then used by the overall BIM coordinator in a BIM project (usually the architect), for example, to perform the clash detection of the architectural and structural models. As a rule, non-proprietary data exchange formats, such as IFC, must be used for this purpose.

The combined specialist models can be used as a basis for a whole building LCA, meaning full consideration of HVAC materials. However, only a few studies have done this (Theißen et al., 2020). The current approaches, in which BIM and LCA are combined to assess environmental impacts of HVAC, generally export data from the BIM model for the Life Cycle Inventory (LCI) or follow a closed BIM solution (Kiamili et al., 2020).

LCA and BIM

The integration of LCA calculation in the BIM workflow is an emerging field in research and practice (Schumacher et al., 2021). Several literature reviews have been recently conducted, which will be partially presented in the following section.

Wastiels and Decuypere analysed five different integration strategies (Wastiels and Decuypere, 2019):

- Bill of quantities (BOQ) export
- IFC import of surfaces
- BIM viewer for linking LCA profiles
- LCA plugin for BIM-software
- LCA enriched BIM objects

Based on these strategies, Potrč Obrecht et al. analysed and compared several recent approaches and classified them according to the integration strategy. Nevertheless, in their systematic literature review, the authors identify that HVAC systems are not always included in the scope of LCA (Potrč Obrecht et al., 2020). Furthermore, the analysis differentiates between manual, semi-automated and automated approaches, which is a significant benefit.

Safari and AzariJafari identified a list of challenges and opportunities of LCA and BIM in their research and also identified the history of trends in the research field (Safari and AzariJafari, 2021). While in 2017, the consideration of LODs was described as a key point of BIM-LCA studies, in 2020, the development focused more on the dynamic approach of integrating LCA with real-time feedback directly into BIM models.

Llatas et al. investigated in their systematic literature review not only the environmental dimension of sustainability but also the economic and social ones in the context of BIM integration. From the analysed 36 papers, all included LCA, but only six included LCC as well, while no approach already included a social LCA (Llatas et al., 2020).

Forth et al. identified six approaches, including the embodied energy of TBS or HVAC systems in their process, although none were in the early design stage (Forth et al., 2021). This leads to a more detailed literature analysis in the following section.

Literature Analysis

Classification of Literature analysis/ Criteria Matrix Selection

Each paper was analysed according to previously defined criteria to analyse the identified literature in a structured way. These criteria were selected by groups according to the major topics of this paper, which are the design phase, building services scope, LCA and BIM integration. To provide a better overview and allow to understand the advantages and disadvantages of the different approaches, a selection of twelve papers was investigated in more detail.

A classification was established for better comparison and evaluation. The classification criteria are grouped as follows (Table):

Table 1: Classification groups of literature analysis

Group	Classification
Design Phase	Early Design
	Detailed Design
Building Service Scope	HVAC
	Electrical equipment
	Plumbing
LCA Scope	Service Life
	Impact Category
	LCA data source
	Replacement period
	Source of replacement rate
BIM	Integration available
	Closed or open BIM approach

Evaluation

Most of the analysed approaches use office buildings as building typology of their case study, while others use laboratory and research buildings (Hoxha et al., 2021), single-family homes (Weißenberger, 2016) or healthcare buildings (García-Sanz-Calcedo et al., 2021). Furthermore, only three approaches include early design phases in their methodology (Harter, Willenborg et al., 2020; Stoiber, 2018; Weißenberger, 2016). Most of the others focus on detailed stages, while Hoxha et al. include both design phases (Hoxha et al., 2021).

When addressing building services, we can distinguish between the subgroups of HVAC, electrical equipment and plumbing. While all approaches include HVAC in their scope, just three methods also include electrical equipment (Hoxha et al., 2021; Weißenberger, 2016; Ylmén et al., 2019) and four others include additionally also plumbing (Eberhardt et al., 2019; Fraunhofer IRB Verlag, 2010; Pohl, 2014; Theißen et al., 2020).

As the buildings' service life mainly depends on the building typology and scope of LCA, most papers set it to 50 years. Only the research project 6D BIM-Terminal assumes the whole building life to be 100 years (Figl et al., 2019). Considering module B4, most approaches took the replacement rate into account, mainly using the BNB data for construction elements (BNB, 2021) and the element service life for building services according to VDI 2067-1. Kiamli et al. included the replacement period of manufacturers and used the ASHRAE standard (Kiamili et al., 2020). Only Rodriguez et al. excluded the replacement periods in their approach (Rodriguez et al., 2019).

When analysing the considered environmental impact categories of the LCA, all approaches include Global Warming Potential (GWP), except Harter et al., who focus on the primary energy demand (Harter, Willenborg et al., 2020). Other approaches also include other impact categories such as Ozone Depletion Potential (ODP), Photochemical Creation Potential (POCP), Acidification Potential (ADP), Eutrophication Potential (EP) (Pohl, 2014; Weißenberger, 2016; Ylmén et al., 2019) or more. Due to the fact that most research was carried out in central Europe, the most common data sources which were used in the analysed projects are Ökobaudat and Ecoinvent. Kiamli et al. additionally used KBOB, while Figl et al. included IBO Bauteilkatalog and Baubook and García-Sanz-Calcedo used BEDEC in their approach.

As a BIM integration into the LCA calculation process of building services is still not commonly used, only three papers are found in the literature. Two of them even integrate an open BIM approach (Figl et al., 2019; Theißen et al., 2020), while the third implements the calculation in a closed BIM approach (Kiamili et al., 2020). All three approaches consider a detailed design phase when usually BIM models include information about building services. Furthermore, one method includes early design phases but uses GIS models with the open CityGML exchange format instead of BIM (Harter, Willenborg et al., 2020).

Conclusion

As previously shown, there is no approach documented in the literature which is calculating the LCA of a building, including the building services in an early design phase based on BIM models. Nevertheless, the literature review using its classifications shows two main patterns in approaches, which scope:

- Life Cycle Assessments including building services in early design phases (without BIM integration), as well as
- Life Cycle Assessment including building services in detailed design phases based on a BIM integration.

Therefore, a new approach will be introduced in the next section, which enables a holistic whole building LCA calculation, including building services already in early design phases based on an open BIM approach. As already mentioned, in the early design phases, there is not sufficient information about building services from the planners or even TBS models, there are several problems identified. One of them is that there is no dimensioning of HVAC systems available, making it hard to approximate the LCA results. Another problem is that generally, only a few LCA datasets are available for building services, making it more time-consuming to approximate the missing information with raw LCA data.

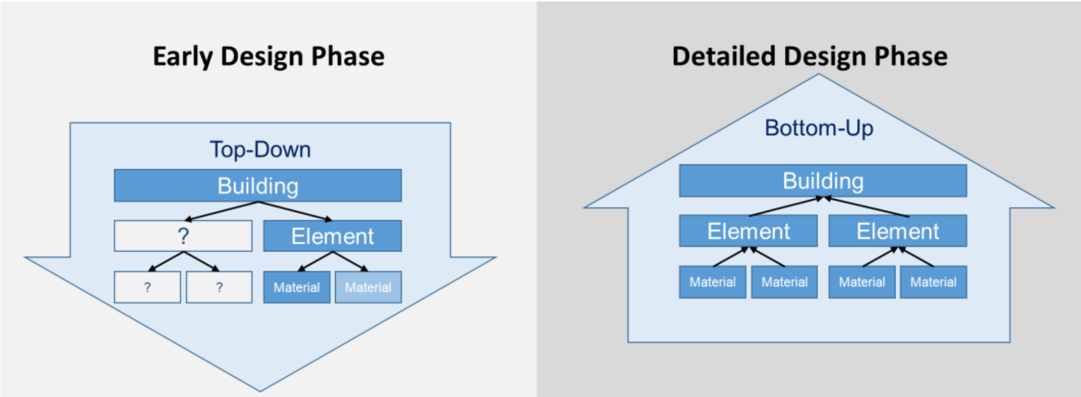

Figure 2: Comparison of Top-Down and Bottom-Up approaches

Proposed Methodology

Top-Down vs. Bottom-Up

While in this case, Top-Down approaches get their input from several previously assessed reference buildings, Bottom-up approaches are derived by a number of detailed materials and components. Figure 2 illustrates the Top-Down and the Bottom-Up approach, both of which have advantages and disadvantages. The Top-Down approach has been used predominantly in early design phases using benchmarks of previously conducted LCA. Chuchra et al. suggest a building service configurator for calculating LCA in different design phases, also based on Top-Down benchmarks on different system levels (buildings, functions, elements) (Chuchra et al., 2020). CIBSE recently published first benchmark results on element level in their project TM65.2 "Embodied carbon of HVAC systems in offices" (CIBSE Journal, 2021).

In the Bottom-Up approach, the whole-building LCA calculation is conducted in detailed design phases. As discussed previously, Kiamli et al. as well as Theißen et al. have used this Bottom-Up approach for calculating LCA of HVAC systems based on BIM models (Kiamili et al., 2020; Theißen et al., 2020). Nevertheless, these high LODs are not available in the early design phases, when significant design decisions about building services are made.

As already shown in section 2.3, Hollberg et al. call for benchmarks on element level but differentiate between different material choices (Hollberg et al., 2019). While they promote the "dual benchmark approach by combining Top-Down and Bottom-Up, they base their method on LCA benchmarking and focus on residential buildings but do not include building information models.

Proposal for a mixed approach

As previously discussed, the level of development of the individual domain-specific sub-models is often diverging. For example, an HVAC planner starts detailing the concept based on the architect's model. In this case, the LODs of the architectural and HVAC elements differ. For this reason, the Top-Down approach for LCA in early design phases is not working, as LODs are not consistent for all elements. Furthermore, the previously proposed concept of Building Development levels is relevant (Abualdenien and Borrmann, 2019).

On the other hand, calculating a holistic LCA of HVAC in early design phases needs to consider the complexity of the domain knowledge. Dependencies between different design decisions are complex and cannot be simplified by benchmarking. For example, radiators and area heating systems are classified in the cost group "423 Space heating surfaces". Here, a benchmark based solely on the cost group would result in greater imprecision, as the material needs differ significantly between radiators and panel heating systems. Furthermore, space heating surfaces can be installed either in the floor, in the ceiling or in the walls. Another factor is the choice of material. Usually, multilayer composite pipes are used to transfer the heat to the room. However, this system can also be implemented, for example, with copper pipes. This illustrates the complexity of creating benchmarks for HVAC.

For these reasons, we generally propose a mixed approach for early design phases. The missing details of each specific domain's elements are compensated with domain knowledge. These will be formalised in a knowledge database, as described in detail in section 4.3. Based on this database, a holistic whole-building LCA calculation based on materials and elements is enabled, as shown in Figure 3.

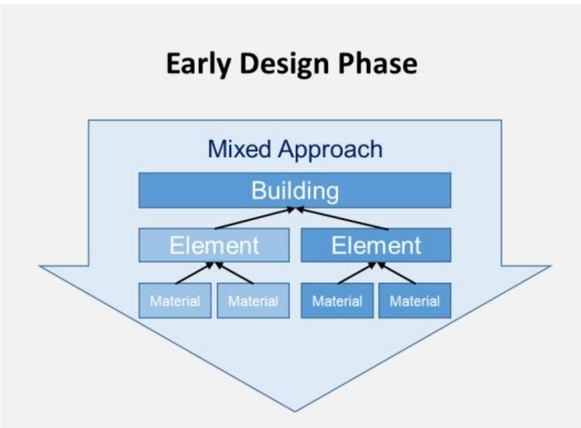

Figure 3: Proposed Mixed approach in the early design phase

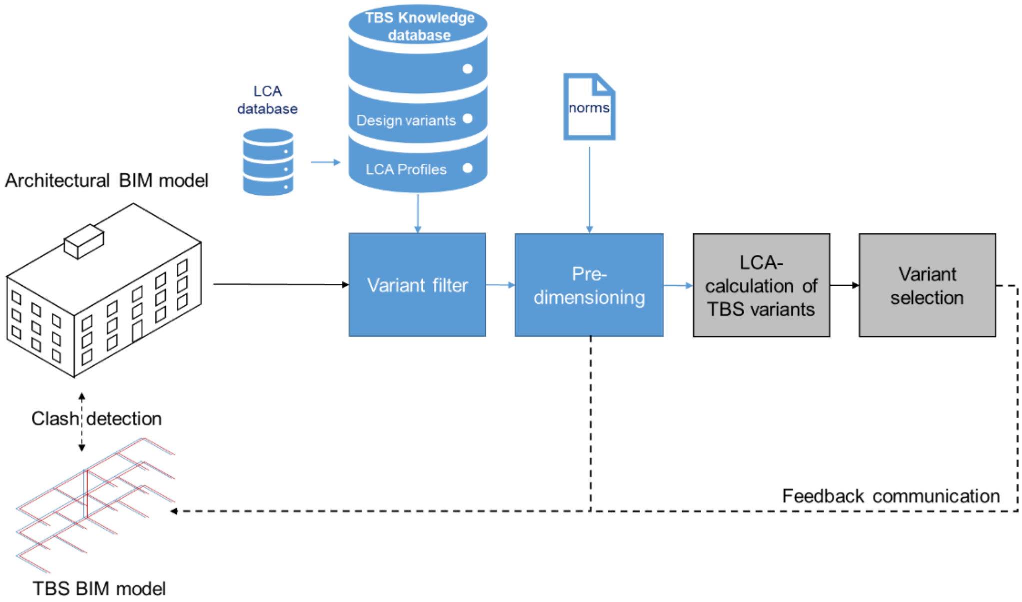

Figure 4: Proposed Methodology for LCA of TBS in early design phases using

Methodology

In the early planning phases, no detailed information on materials, quantities or masses is available, so there are high uncertainties and low levels of information, making it difficult to perform an environmental assessment, especially for TBS. Therefore, a method is needed to make a whole-building LCA applicable based on the little information available (Figure 4). To make this possible, a hierarchical knowledge database serves as a basis. The database is based on benchmarks, and higher levels can be used instead of building product or material levels, which are only known in late planning phases.

The benchmarks are based on the evaluation of finished building projects as well as on the derivation of climate policy goals. Regularities and repeating factors within a planning process are identified, which simplifies the derivation of benchmarks. Through a pre-assessed database structure, the different impacts between disciplines are considered, as illustrated in the example described earlier. For this purpose, the interfaces between the different disciplines within HVAC are investigated. Especially interdisciplinary aspects and the existing causalities between the individual disciplines are considered. For deriving the benchmarks, different dimensions (e.g. GWP or sound insulation requirements) are not weighted one-dimensionally but multi-dimensionally. Thus, multidimensional benchmarks are applied here, which should enable a holistic analysis. This has the advantage that environmental data can be linked to less information available at an earlier stage in the planning process. For example, the type of use and area of a room are known quite early. In addition, this also allows conclusions to be drawn about the personnel functions and other basic requirements for the space, function and equipment needs of a room and the HVAC performance. This means that by providing a minimum amount of information, further information can be added consistently based on standards until a profile is created that can be linked to benchmarks.

As a starting point, however, a BIM model of the architecture is required, in which design parameters are already available. Once the BIM model has been linked to the database, a filter can be used to minimise possibilities. For example, CO2 intensive designs can be excluded, or preferred system variants can be highlighted. In the subsequent step, the pre-dimensioning of the components takes place. This allows, for example, different pipe materials to be compared with each other. Without pipe dimensioning based on DIN 1988-300, a direct comparison can lead to falsified results since the internal diameter of a pipeline depends on several factors. Thus, the necessary pipe diameters and masses can differ depending on the material. After the rough dimensioning, the LCA of the HVAC variants can be carried out, followed by the selection of the preferred design. As a result, it becomes possible to perform LCA of variant comparisons through a minimum level of information that is available in a standardised way. With rudimentary building models, this procedure can be used to realise early whole-building LCA, including the building services within the framework of the open BIM method.

Conclusions & Outlook

This paper investigates the topic of LCA of technical building services in early design phases using the BIM methodology. First, the state of the art of the four interface topics showed the complexity of this research field. A structured literature review showed relevant approaches and their limitations in the next step. Based on these findings, a new methodology was proposed.

It can be generally found that there are little data for TBS available and if only of limited quality. Furthermore, there are no methods and tools available yet, considering LCA of TBS in the early design phases. The BIM method was identified to enable an automated and integrated approach. Current approaches, such as the one from DGNB with a simplification adding 20% of the construction impacts to consider the LCA of TBS, could be found as not sufficient and useful for variant analysis and optimisation of the LCA results in early design phases. Additionally, the benchmarking approach on building or German cost group levels was identified as insufficient either, so an integration of LCA profiles was suggested in the proposed methodology.

As next steps, we are suggesting to further detail, prototypically implement and validate the proposed methodology by creating LCA profiles based on existing designs. Furthermore, an evaluation of the method with case studies is required. Finally the methodology will be extended for the briefing or demand planning phase according to (Forth et al., 2022) and connected to the approach of LCA for building construction by Forth et al. (Forth et al., 2021).

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