Design optimization approach comparing multicriterial variants using BIM in early design stages

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Abstract

Building design processes usually follow similar workflows with different stakeholders and interdisciplinary design teams incorporating their individual domain knowledge. To improve the holistic performance of building designs considering economic and environmental qualities, design decisions based on simulations and analysis in early phases have a significant impact on the resultant design.

In this context, first, the advantages and limitations of the current approaches are analyzed with the help of a systematic literature review. Then, a framework for optimizing building designs is developed using Building Information Modelling (BIM) as a main source of truth for a multicriterial analysis. The framework compares multicriterial variants to support decisions during the early design stages, including the selection process and feedback communications of design changes. For a holistic variant comparison, several criteria are considered, with the main focus on life cycle assessment (LCA).

Keywords –

BIM, early design, design decision support, LCA, multicriterial optimization

1 Introduction

In modern societies, the built environment is essential in many ways. For example, the real estate industry is not only an important economic sector with 10% of the gross value added but is also responsible for 42% of the final energy consumption, 35% of the greenhouse gas emissions [1]. In order to improve the ecological impact of a building, life cycle assessments (LCA) are used to calculate the environmental impact along the entire life cycle of the building (embodied energy + operational energy). Up to now, these calculations have been carried out manually to a large extent, which is time-consuming on the one hand. On the other hand, the complete depth of information is only sufficiently available in the late planning phases. This leads to the fact that optimization potentials in the early design phases cannot be used so far [2]. With the introduction and development of new digital methods, such as Building Information Modelling (BIM), and uniform data standards for building models, technologies are available to the construction industry to optimize these LCA calculations. During the BIM process, a semantic data model is created during the planning phase, which provides all current information in digital form for all project participants and the building's entire life cycle. It makes sense to use this already bundled data for such a calculation of the LCA and thus to design the process efficiently.

Building design processes usually follow similar workflows with different stakeholders and interdisciplinary design teams incorporating their individual domain knowledge. Nevertheless, each building project is unique in its context, as national regulations, building owners, and the composition of design teams vary often. This means that design decisions differ from each project while the dependencies and relationships of their consequences in design quality remain the same. For example, decreasing the investment costs of a design may negatively influence the operational costs and environmental impact of the building. Therefore, a holistic consideration of several design qualities must be taken into account during the design decision process.

This paper aims to enable the holistic performance of building designs considering economic and environmental qualities by a model-based design decision approach based on simulations and analysis in early phases. After analyzing existing approaches, a robust framework is proposed based on the findings of the literature review.

2 Background and Related Work

To improve the holistic performance of building designs considering economic and environmental qualities, simulations and analysis in early design stages have a significant impact on the resultant design [3]. At the same time, the effort and cost of changing the design at these stages are relatively low. During the design process, several disciplines exchange different design information necessary for their specific needs, such as materials of construction elements for structural engineers or U-values for energy efficiency analysis. In this context, Building Information Modelling (BIM) is used as a main source of truth for a multicriterial analysis, while simulation-based on BIM helps the decision-making process in early design stages [4]. BIM facilitates the evaluation of design variants based on the same baseline design to optimize the different qualities of the building design, such as costs or environmental impacts [5].

Nevertheless, in conventional projects in practice, the main focus is still on the economic performance of buildings, while environmental qualities are not widely spread yet. This is the reason to approach the holistic multicriterial variant analysis, in the early design stages, based on existing approaches of BIM-integration strategies for LCA. Current approaches still have limits of fully automated workflow with open BIM models [6]. The main scope of this paper is focusing on the early design phases. To support the decisions at these phases, detailing decisions from more detailed phases are additionally analyzed. Based on the current approaches in the literature analysis, the findings are considered to further extend the approach in the sense of a holistic analysis that is adaptable for further criteria, for example Life Cycle Costs (LCC) or similar.

3 Literature Analysis

To analyze existing methods and identify their missing aspects in context of multicriterial variants using BIM in early design stages, a specific literature analysis is carried out.

3.1 Existing literature reviews

To avoid conducting similar literature reviews, existing ones are first analyzed considering their focus. While the research field of BIM-based simulation of operational energy in early design stages has been ongoing for more than ten years [7], the focus on real-time feedback, e.g., by Machine-Learning-based prediction [8], is getting more important. In the following, the focus is more on the multicriterial analysis, for example, a combination of embodied and operational energy or LCC.

Soust-Verdaguer et al. analyzed eleven papers from 2013-2015 in a structured literature review of the BIM-based LCA method and differentiated between Data input (BIM-LOD, LCA goal & scope, stages, and inventory), Data analysis (BIM software, Energy Consumption Calculation, LCA tool) and Outputs and communication of results (Environmental impact indicators, sensitivity analysis, embodied and operational CO2 emissions) [9]. Wastiels and Decuypere identified and compared five general different strategies on how to integrate BIM and LCA [10]. These five strategies contain the export of Bill of quantities, import of IFC surfaces, a BIM viewer for linking LCA profiles, an LCA plugin for BIM-software as well as LCA enriched BIM objects. Based on these findings, Potrč Obrecht et al.'s recent literature review is comparing more update approaches and classified them according to these five strategies [11]. Additionally, they divide each of them between manual, semi-automated and automated approaches which gives a holistic overview of the current state of approaches. Nevertheless, this literature review does not focus on the adaption of each approach for multicriterial variant analysis. Cavalliere et al. showed in their literature review the combination of BIM and parametric-based tools for LCA calculation, considering 25 publications between 2013 and 2018 [12]. Parametric-based LCA (PLCA) was first developed for the first time in 2016 by Hollberg et al. and entirely based on Visual Programming Language (VPL), in their case Rhino and Grasshopper, while no BIM-integration was considered [13]. Finally, Llatas et al. include in their systematic review also LCC and social LCA (sLCA) besides LCA and develop their own methodological approach based on their findings [14]. They generally reviewed 36 publications based on the integration of BIM and LCA, while just six approaches included both LCA and LCC, and none included sLCA.

3.2 Classification of literature analysis

Based on the classification and findings of existing literature reviews, a new systematic literature review was started in the field of BIM-based LCA in this paper. In total, 59 recent papers were reviewed, of which 25 from the years 2018-2021 were connected to the integration process of the BIM method for LCA calculations. Besides the described existing literature reviews, some papers have a deeper focus on specific subtopics, like visualization of LCA results, feedback communication into the BIM authoring tool, or LCA benchmarks and databases. To better overview and understand the advantages and disadvantages of the different approaches, a selection of 25 papers was investigated in more detail. A classification was established for better comparison and evaluation. The classification criteria are grouped as following (Table 1):

Table 2 Classification groups of literature analysis

Group	Subgroup	Classification
BIM	Design stage	Early Phase
		Detailed Phase

		Parametric (VPL)
		LOD
	Data exchange	IFC
		gbXML
		IDM/ BPMN
		ER/ MVD
BIM-LCA integration	Integration strategy	Bill of Quantities
		IFC-Import
		BIM-Viewer – LCA-Profiles
		LCA-Plugin
		Enriched BIM objects
	Feedback	Feedback communication
LCA	LCA Scope	Embodied Energy of Building Construction
		Embodied Energy of MEP/ HVAC
		LCA, including Operational Energy
		LCA including LCC
		LCA Phases
	LCA Inputs/ Goals	Functional Unit
		Case study
		Vagueness/ uncertainty
		Environmental impact categories
		Database

3.3 Findings

After evaluating the different approaches, it turns out that several are mainly focusing on the detailed design stages and do not have their focus on early design stages [5, 15, 16]. This fact does not support the optimization of building design when information is uncertain or missing. Rezaei et al. are suggesting a LCA-workflow for early design stages based on Autodesk Revit, but including an optimization process or other criteria [17].

For the exchange of the BIM models, there are different strategies. Most of the evaluated approaches use the open BIM format, Industry Foundation Class (IFC). In contrast, some use Green Building Extensible Markup Language (gbXML) as an exchange format when considering operational energy [18], others seem to use closed BIM, such as Autodesk Revit [19, 20] or Revit in combination with Autodesk Dynamo [21–25]. Other use VPL like McNeel Rhino and Grasshopper [13, 26, 27] or 3D modeling tools like Trimble SketchUp [28].

For the integration strategy of LCA into BIM workflow, the classification of five different strategies from [10] was investigated. As a finding, two main approaches are mainly implemented in the investigated approaches. While most approaches using authoring tools use the Bill-of-Quantities integration approach, which was already the tendency of [11], those using IFC for data exchange often enrich BIM objects using Property Sets (PSets) [5, 15, 29]. Lee et al. suggest a new approach giving a BIM template for authoring tools to avoid interface problems [30]. A few also use existing LCA-Plugins in Revit, such as Tally, eToolLCD or One Click LCA [18, 31–34]. Nevertheless, there are mainly two approaches that include a computer-readable feedback communication of the results back into the BIM model, so not just using the model for a down-streaming approach [35].

As this paper focuses on multicriterial design optimization, life cycle assessment of the building construction is not the only criteria, although all analysed approaches include it as a minimum. Kiamili just puts the focus on embodied energy of HVAC systems [22], while others include both embodied energy of building construction and HVAC [16, 26]. Other approaches even include embodied energy of building construction, HVAC as well as operational energy [18, 19, 36]. Another criterium which is relevant to consider next to LCA are Life Cycle Costs (LCC), which are also considered in some approaches [5, 15, 19]. In conclusion, no approach enables an integration of all criteria LCA for building construction and MEP systems, operational energy as well as LCC.

Finally, almost all approaches consider the whole building as a functional unit. But just a few also consider uncertainties [26]. Furthermore, most of the approaches include as environmental impact category Global Warming Potential (GWP), some are not only focusing on CO2-emission but even consider several more impact categories such as Ozone Depletion Potential (ODP), Photochemical Creation Potential (POCP), Acidification Potential (ADP), Eutrophication Potential (EP) and more [5, 28, 29, 32, 37]. Many different international databases were used, while the German Ökobaudat, ecoinvent and KBOB from Switzerland and product-specific Environmental Product Declarations (EPD) are the most common.

The literature analysis shows a significant potential for multi-criterial optimization in early design stages using BIM models, especially with IFC data. As well, a sufficient representation of a simplified calculation of embodied energy of HVAC is missing as usually it is generalized by 20% of the construction emissions according to the LCA calculation methodology of DGNB [38]. In addition, most approaches consider only one criterion (due to the chosen focus mainly LCA) for optimization using BIM. At the same time, the potential is the simultaneous comparison of costs and environmental impacts with real-time feedback. This shows the potential for further research on integrating several criteria in one holistic building optimization methodology using open BIM format. Having that in mind, an automated mapping of LCA and IFC data on component level is not developed or solved yet [39].

4 Proposed Methodology

The aim of this paper is to develop a framework for optimizing building designs based on component-specific design variants to support decision-making with the help of multicriterial analyses in early design phases. Necessary information for simulations is based on the same consistent variants and can be executed simultaneously. Furthermore, multiple optimization criteria are considered, while the main focus stays on life cycle assessment (LCA). In more detail, first, the advantages and limitations of the current approaches are analysed with the help of a systematic literature review. Then, a new methodology that facilitates a multicriterial variant comparison and feedback communication of design changes is developed. For a holistic variant comparison, several criteria, including embodied energy, operational energy as well as capital and operational costs, are selected.

The methodological approach shall include open BIM data exchange in early design stages, multicriterial variant analysis (primarily environmental and economic impacts of construction, operation, and End-of-Life phase of buildings), as well as an automated mapping of relevant information from the model. Therefore a robust implementation should take different modeling approaches (planers & software products) into consideration. Furthermore, adding individual cost benchmarks and EPDs (Environmental Product Declarations) shall be addable in a later stage. First drafts of the conceptual and methodological developments are shown in the following.

4.1 General Framework

To perform these criteria, engineers require a set of information to be present in the model. However, typically, a lot of information is still missing or uncertain in the early design stages, which influences the conducted simulations and analysis results. Therefore, a standard component database that couples all relevant information for the LCA calculation and other criteria, which is subsequently mapped to the corresponding building component, is developed. The database can support exploring the different variants when any information, such as elements or properties, is missing or uncertain by offering a set of possible options or range of values. Accordingly, the performance of the different design variants can be evaluated according to the influence of the incorporated uncertainties on the economic and environmental qualities. In the end, the selected design changes are communicated back to the BIM authoring software to implement them in the design. The proposed methodology leverages the open BIM standards, the Industry Foundation Class (IFC), and model view definitions (MVD) for the exchange of building models and the specification of simulation requirements.

In the first stage, a robust methodology is presented in theory (Figure 1), which already considers all the mentioned work packages. It consists of a use case selection process before the planning starts. This defines which use cases and analysis types should be calculated later on. Necessary exchange requirements are handed over to the planers/ BIM modelers. The next step includes mapping the relevant IFC data to a standard component database (also see Figure 2). In the following steps, different criteria, such as Embodied Carbon (LCA) and others are automated calculated. In the last step, the results are visualized, and design variants are compared for better decision support, including relevant benchmarks. When the final configuration of variants is chosen, the changes of the selected variants are communicated backward as feedback for the planer or BIM modeler.

4.2 Standard Component Database

The standard component database, based on components, elements, layers and materials, shall contain all information, which are relevant for holistic calculation of different criteria and missing in the IFC model. The systematic of the standard component database contains

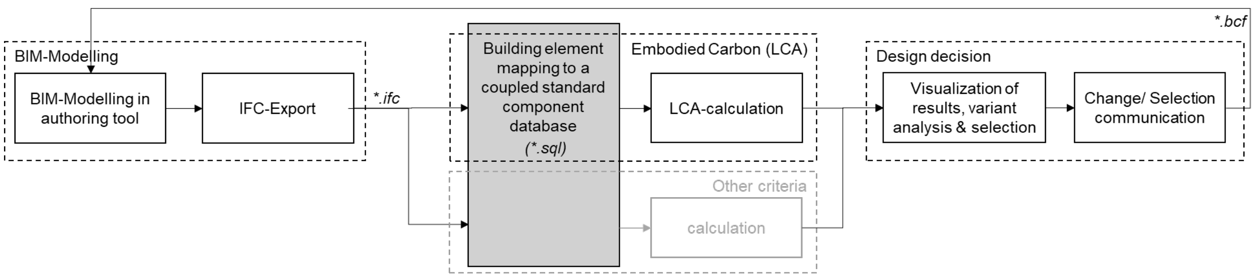

Figure 1: General Framework of the proposed methodology with the focus on LCA

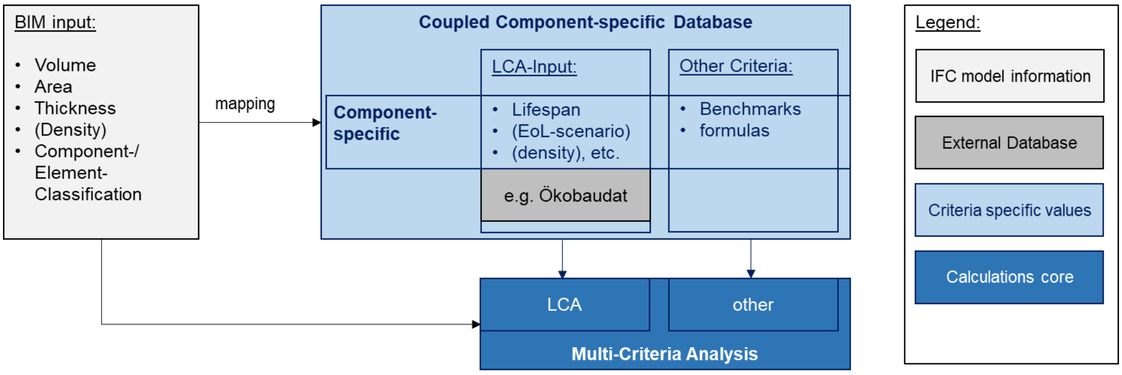

Figure 2. General Strategy for a standard component database for multi-criterial variant analysis

a link with different external databases for example for environmental criteria (Ökobaudat, etc.) (Figure 2). One challenge is to provide all necessary input information for a holistic and correct calculation and analysis, which might be missing in an early BIM model or the IFC schemata. Another challenge is to combine the external databases with different input information representing the domain knowledge of multiple criteria analysis. International databases can be added to the database using this methodology as well as material/product-specific Environmental Product Declarations (EPD) can be linked, too.

The component database provides on a material or component level additional information necessary for a sufficient calculation, like the lifespan of a component, End-of-Life scenarios if missing in the dataset, or densities if missing in the BIM model. The database itself is structured similar to the German Cost Grouping DIN 276 on the third level but provides a material-specific level of different component layers. Different combination possibilities of material layers for each building component are referenced for the variant selection process. By this one, the one-hand side domain knowledge can be represented, and on the other side, deviations of the materials consider semantical uncertainties in the early design phase. Other criteria information like cost values or U-values (if missing in the model) for calculating operational energy are stored on the material level of the standard component database as well. This ensures that a change of the variants leads to a change in all criteria calculations and shows the complex dependencies of the multi-criterial design decision process.

4.3 Automated Mapping Method

The automated mapping is necessary to avoid time-consuming manual mapping of the BIM components with its correlating components from the database for correct analysis and calculation. The challenge is to correctly map them and find a robust workflow that considers multiple ways of modeling and exporting the BIM model with IFC. The proposed method includes several steps (Figure 3). At first, IFC data are classified using their IFC class types (e.g., ifcWall/ isExternal, etc.). These classifications lead to different groups of standard components in the database, which is oriented to the German norm of cost groupings (DIN 276). According to the German cost grouping (CG) schema, there are two

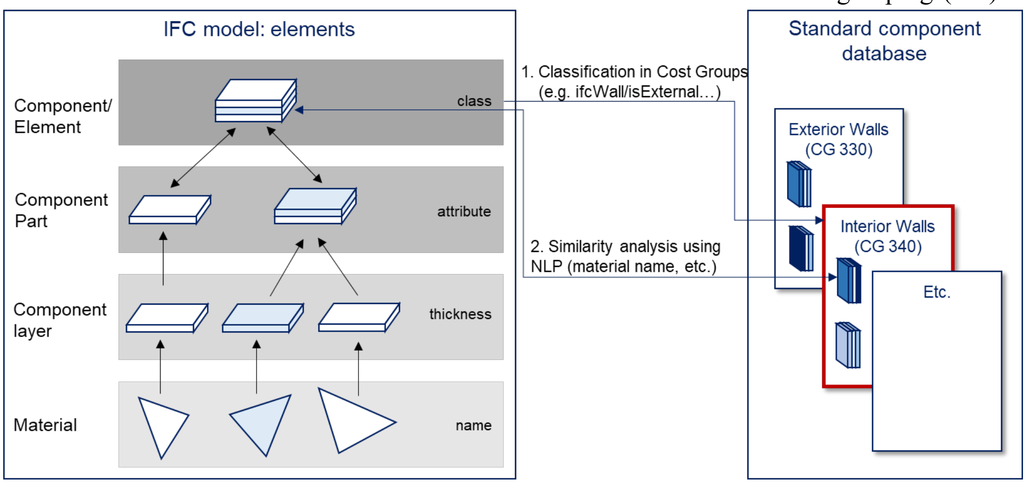

Figure 3. Proposed steps for an automated mapping method of IFC models and the standard component database

options to guarantee a correct classification of all components according to German cost grouping (CG) schema: either it can be defined according to a specific categorization of IFC exchange requirements, or it needs to be automatically clustered algorithmically. In some use cases in Germany, a CG classification already occurs so that it can be used as a byproduct for this framework. If this is not the case, an algorithm can help to cluster relevant components and elements based on their IFC class types automatically to the CG classification to ensure the first step of the automated mapping method with the standard component database.

In a second level, the modeled component layers with their material attributes are mapped to an environmental dataset of the used database. In late design stages, conventional mapping methods usually have a manually mapped UUID for each IFC material from existing databases, like Ökobaudat, as an attribute [16]. Another approach by Georg Reitschmidt follows also automated mapping on material level [40]. In a first step, material names of IFC are tokenized, while every token is searched in the environmental dataset of Ökobaudat resulting in a hit list. In a second step, the listed hit with the smallest the Levenshtein-Distance is chosen as the mapped dataset, if it fulfills a certain threshold to ensure a correct result. All these approaches expect, that all necessary information of all LCA-relevant component layer is modelled which is usually in detailed design stages the case.

In early design phases, information about material layers and their combinations are approximate or missing. An approach for gradually deciding on a specific material value is by defining a material group (according to existing classification system) and evaluate the individual materials within each group [41]. Therefore, instead of checking the similarity between textual words (the same as Reitschmidt 2015) or manually mapping them to existing materials, we propose employing Natural Language Processing (NLP) techniques to measure the “semantic similarity” between materials. Measuring the semantic similarity involves converting the text of every material type to a vector representation (A vector is a list of numerical values, where the combination of them represents the overall meaning) [42]. Afterwards, the similarity between vectors can be measured using the cosine similarity. Accordingly, the similarity of Brick to Terracotta is expected to be higher than the similarity to Concrete or Glass. Measuring the similarity between the numeric vectors has performed remarkably well in different domains [43]. A promising implementation of the state of the art in the field of NLP is the pre-trained neural network model spaCy [44], which represents every word with a vector of 300 dimensions and includes 685k unique vectors in its corpus. In this regard, we will evaluate and extend the existing model provided by spaCy to deliver an automatic mapping of material layers an evaluate the proposed methodology.

5 Conclusion & Future Work

With the help of a systematic literature review, the key potentials and limitations of current approaches of BIM-based LCA in early design phases were investigated, such as multi-criterial analysis based on open BIM format for holistic building optimization. A new adapted methodology based on open BIM format and a standard component database was proposed based on these findings. The component database is flexible to extend for several criteria like LCC and embodied as well as operational energy and contains missing detailed information of early BIM models based on domain knowledge. For an automated mapping, two different steps were suggested. The first one is to classify each component according to German cost grouping, either manually as an exchange requirement or algorithmically. In a second step, similarity analysis of layers and materials helps to identify the BIM component in the component database automatically with the help of NLP.

As future work, this theoretical approach needs to be validated with a real-life case study. Therefor, the different steps need to be implemented prototypically and tested with several IFC models for validating the robustness. Also, the mentioned standard component database needs to be implemented and validated for further research. Another focus will be on the design decision process. On the one hand side, an intuitive visualization of the results and variant comparison helps for the selection process. On the other hand, the selected variants and changes need to be communicated back to the BIM modeler with a computer-readable interface to the authoring tool.

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