BIM-integrated LCA - model analysis and implementation for practice

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Abstract. Ecological impacts of buildings can be quantified using the method of Lifecycle Assessment (LCA). With the help of digital methods and semantic building models (BIM), those impacts can be reduced by investigation of variants and their LCA comparison. However, there is a large deviation in the results due to inaccuracies in the modeling and the calculation tools. This paper proposes an improved workflow of BIM-integrated LCA avoiding those inaccuracies. As a first step, various sources of error are identified using a model analysis, which is examined with 25 models focusing on geometry and materiality. Thereby different workflows are investigated, modeling recommendations are derived based on the error analysis, and the findings are implemented in a prototype. Through an optimized calculation process, the semi-automatic calculation of life cycle assessments becomes faster, more consistent and more accurate due to the improved integration in BIM.

1. Introduction

Since ancient times, buildings have great importance for society. Today, they account for most of humans' daily lives and, according to the broad definition, real estate accounts for 19% of total gross value added [1], making it an important economic sector with many jobs. However, the construction industry also contributes significantly to climate change and other environmental problems. According to the European Commission, European buildings account for 42% of final energy consumption, 35% of greenhouse gas emissions and 50% of materials produced in their production, use, and dismantling [2]. Also, they are responsible for 30% of water consumption and a third of all waste [3]. This increases the need to identify and reduce the environmental, economic and social impacts of buildings. A promising approach lies in the formal assessment of a building's environmental footprint. Individual analyses and, since the 1990s, holistic approaches such as the sustainability certification of buildings, which are also known as Green Buildings, are an important step forward.

In a proposal for discussion for the new "Building Energy Act" (GEG) from February 2018, the German Sustainable Building Council (DGNB) proposes that in future the resulting CO2 emissions should be balanced rather than primary energy consumption. "Embodied emissions (production, usage, and maintaining, recycling) will also be accounted for from 2025 so that in future the entire life cycle will be covered" [4]. This approach, which has been extended to include embodied energy, is intended to create a goal-oriented, holistic approach.

In this respect, there are great opportunities to benefit from the ongoing digitization of the construction sector to cope with the environmental challenges. This means that in the long term it is desirable to automate criteria for sustainability certificates, such as life cycle assessments (LCA), to the

greatest extent possible using the BIM method [5] which includes a comprehensive digital representation of a building.

The integration of the BIM method into the LCA calculation is intended to simplify the work process and thus make it possible to optimize the LCA in earlier planning phases. Also, increased efficiency regarding time and complexity can reduce the workload and thus contribute to broader dissemination of the performance of life cycle assessments.

Although there are already existing software products which try to use the BIM method in the LCA calculation, the use of the BIM method in the LCA calculation is not yet optimized. However, the quality of BIM models is not yet thoroughly mature due to the short application time. Therefore, there are still different problems with the application of these programs, which should be analysed in more detail.

The paper presents an experimental study that shows that problems and requirements of the BIM-integrated LCA considering different workflows and model requirements, to make the data transfer between architect and Green Building Auditor or the life cycle assessment experts smoother in the future and to minimize the loss of data. On the basis of this results, the concept for an improved workflow was developed. It has been implemented in a software prototype that is discussed in detail. Using the prototype, it was possible to show that errors were significantly reduced.

2. Related work

In this section, a short overview of the state of the art is shown. The major challenge is the semantic linking of the BIM model with the LCA model. BIM programs can be used to determine areas and masses automatically. The goal, however, is a fully automated LCA process that can be realized with the help of an integrated BIM and LCA model. This increases data consistency, makes the verification process for sustainability certificates more accurate and increases efficiency by shortening the processes.

García-Martínez et al. compared different integration approaches in their paper "Critical Review of BIM-based LCA method to buildings" [6]. They find that there are major difficulties in mapping all life cycle phases, especially the use phase and end-of-life phase, in the calculation. In most studies, manual adjustment and addition of mass constellation and material properties were required. Therefore, they call for further research to improve and standardize the BIM integration of LCA and propose user-friendly handling of the calculation tools.

Furthermore, Díaz and Álvarez Antón have investigated different approaches to LCA calculation in the planning process [7]. It becomes clear that through BIM integration a BIM model is already available in early phases, which leads to early optimization of the results through automated calculations. Furthermore, a real-time calculation is desirable to reduce the time required for an LCA.

Díaz and Álvarez Antón distinguish between two approaches, how such integration can look like [8]. The first method presented contains an automatic inventory analysis linked to LCA datasets. To ensure a consistent calculation, the BIM model must be created and maintained without errors. This avoids the repeated manual input of data for the LCA. A further disadvantage is the lack of research into the compatibility between BIM models and LCA tools as well as errors in IFC (Industry Foundation Classes) export and import.

The second approach provides for the implementation of environmental impact information in BIM objects. This means that the impact categories and environmental impacts can already be displayed when the architects and planners select materials. However, this method requires training of the designers so that this information can be evaluated correctly. To counteract an excessive demand, Schlenkrich suggests alternatively listing only selected categories [9]. This method can already be applied in the earliest planning phases and thus actively intervene in the decision-making process of material selection. However, this approach has the disadvantage that material alternatives are compared and the quantities of materials in the comparison are neglected. Thus, the estimation is less precise than an LCA that addresses the complete building model [8].

As early as 2003, Neuberg developed a "software concept for the Internet-based simulation of the resource requirements of buildings" [10]. As part of his dissertation, he realizes an ecological assessment of buildings with the help of the IFC data format. In addition to a life cycle assessment, he also

implements an integrated energy demand calculation by German energy efficiency regulations of building (EnEV). "The implementation of these dynamic component properties takes place as a module for extending the AutoCAD database" [10]. At that time, not enough LCA databases were available, and life cycle assessments were mainly carried out for research purposes. In addition, impact categories other than those established today, such as cumulative energy consumption and cumulative material consumption, were taken into account. Neuberg's method makes use of an open interface, where the parameters of the materials can be individually adapted and extended by external data sets. However, the addition of additional component layers afterwards and the assignment of end-of-life scenarios or the consideration of composite materials is not possible. For these reasons, his approach not fully applicable for today's practice.

Tsikos and Negendahl have developed a method using *Revit*, *Dynamo,* and *Excel* to calculate an LCA using an Integrated Dynamic Model (IDM) [11]. Their aim was to achieve a fully automated work process. Material allocation is carried out with the aid of a "permanent link" between an external *Excel* database and the materials in *Revit*. The encoding is performed according to the Danish system BIM7AA [12]. Although LCA calculation results are generated within one minute, the quality depends strongly on the BIM model, the accuracy of the database and the take-off method implemented in Dynamo [11]. Inaccuracies of the BIM model can be adjusted later in the model, although this procedure seems cumbersome. On the contrary, this paper is intended to make a specific contribution to optimizing the compatibility between BIM models and LCA tools and to find a consistent and transparent calculation approach.

3. Methodology and procedure

The aim of this chapter is investigate different workflows and occurring problems of BIM-based LCA. The general workflow of the model analysis consists of three stages. The first stage is the creation of models based on the catalog of the investigated BIM-models. The models are modeled with two BIM-capable authoring tools, *Revit 2018* by Autodesk in "Revit" data-format (RVT) and *ArchiCAD 19* by Graphisoft in "Plan" data-format (PLN) and exported into the vendor-neutral IFC data format. Then *Solibri Model Viewer* is employed to check the data quality of these models and adapt them so that the models have identical masses and materials if necessary.
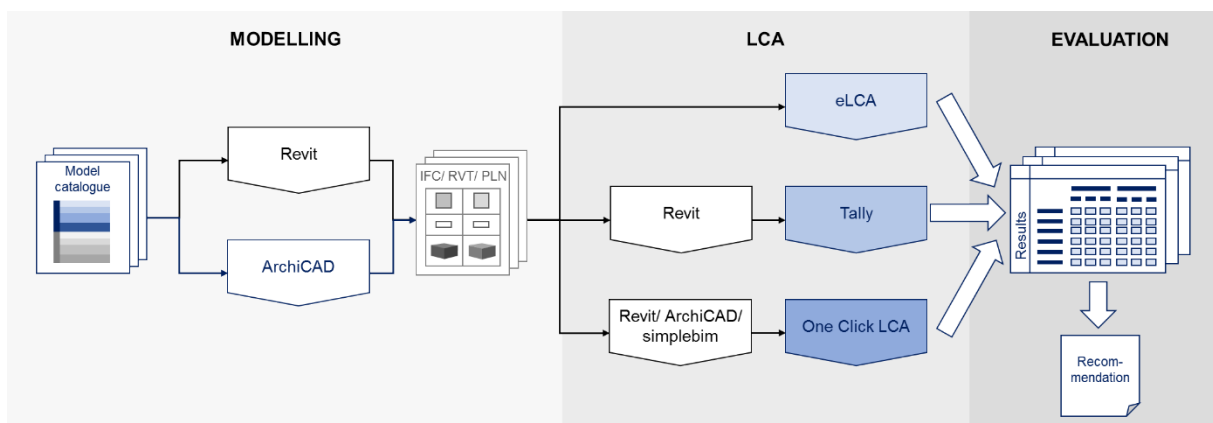

Figure 1. The procedure of the model analysis of BIM-integrated LCA workflows

The second stage is the actual life cycle assessment. This consists of the application of the three different work processes. The tool for the conventional workflow used is *eLCA*, which draws its mass balances based on the models created in *Revit*. In the semi-automatic working process, the data models are imported into *Revit* and calculated with the LCA tool *Tally*. In the fully automated working process, the models are loaded into *ArchiCAD*, *Revit,* and *simplebim,* and the life cycle assessment is calculated there using the *One Click LCA* plug-in.

The third stage consists in the evaluation. All results of the respective eco-balancing with *eLCA*, *Tally* and *One Click LCA* result in a result matrix for each model. These are analysed, and problems and conspicuities are described to formulate general and specific findings finally and to derive recommendations from these. The different work processes, as well as the results of the respective programs and data exchange formats, are taken into account. As the different result of each LCA-software are not compareable with each other due to different databases, the results of each LCA-Software have their own Ground truth which are investigated in the error analysis [13].

3.1. Boundary conditions

The investigation presented here does not aim at improving the LCA results through different material or design choices of the models, but helps finding the best possible implementation of BIM-integrated life cycle assessments about the work process and data requirements. Clear framework conditions are the prerequisite for a reliable evaluation and preparation of recommendations.

Initially, the same databases and an identical approach should be defined for all LCA tools. Due to large data gaps in building technology, this topic is not addressed in this paper. However, for the LCA calculation of the models according to the calculation system of the German Sustainable Building Council (DGNB), the energy consumption in the use phase according to the current German regulations (EnEV) is required, which is not available for the individual models. Here, the focus is on the building construction in the manufacturing (A1-A3) and end-of-life phase (C3-C4), as well as module D. Operational energy, plant technology, and transport are neglected.

Due to the great diversity, ÖKOBAUDAT serves as the common database for all life cycle assessments, which is based on GaBi data records. The impact categories considered are Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP) and Primary Energy, differentiated into non-renewable (PENRT) and renewable (PERT) depending on the LCA calculation program. The service life of the structures is set to 50 years.

3.2. Case studies

Table 1 + 2. Model catalog for Case studies of the model analysis, grouped by Form and Material.

Form	Modellgroup		Model	
	F1	Ground floor	angular	F1e
			round	F1r
	F2	Multistory	suspended ceiling	F2z
			galery with cloumns	F2g
	F3	Sloping walls	outside inclined straight wall	F3ag
			outside inclined round wall	F3ar
			inclined inside straight wall	F3ig
			inside inclined round wall	F3ir
	F4	Roof	saddle roof	F4s
			saddle roof with corner	F4e
			hip roof	F4z
			pent roof	F4p

Material	Modellgroup		Model	
	M1	Monolithic	reinforced concrete	M1s
			brick wall	M1m
			timber	M1h
	M2	Multi-layer	reinforced concrete + EPS	M2s
			brick wall + XPS	M2m
	M3	Construction	mullion-transom facade	M3p
			wood frame construction	M3h
	M4	Windows/ doors	wood frame	M4h
			aluminium frame	M4a
			plastic doors	M4k
	M5	Roof	warm roof (flat)	M5s
			brick covering (saddle roof)	M5z
			sheet metal cover (pent roof)	M5b

To produce a valid and meaningful evaluation of the data requirements for a successful BIM-integrated life cycle assessment, a wide range of applications using BIM models is required. Table 1 + 2 show the model catalog, which was first created and then converted into BIM models using *Revit* and *ArchiCAD*. They are then made available on the proprietary and the IFC data exchange format. In the model catalog, different complex geometries, materials and building constructions are covered. The model catalog differs in the two groups "shape" (subdivided in the groups "ground floor", "multistory", "sloping walls" and "roof") and "material" (subdivided in "monolithic", "multi-layer", "construction", "windows/doors" and "roof").

The nomenclature of the individual model groups results from the initial letters of the group's form and material, the sequential numbering depending upon the complexity of the investigation as well as

the clearly characteristic model abbreviation. The basic form has a square ground plan (10.00m x 10.00m), which is slightly modified depending on the study model. The height of the floors is 3.00m with a clear room height of 2.80m for the most part. The outer walls of the models are 30cm thick, the ceiling 20cm.

3.3. Results

Table 3. Comparison of the results of the model analysis.

LCA-Software	Tally			One Click LCA									●	◆	■
LCA-Plug-In	revit	revit	revit	revit	revit	revit	simplebim	simplebim	archicad	archicad	archicad				
File-Format	RVT	IFC	IFC	RVT	IFC	IFC	IFC	IFC	IFC	IFC	PLN				
BIM-Software	revit	revit	archicad	revit	revit	archicad	revit	archicad	revit	archicad	archicad				
F1e	●	●	●	●	●	●	●	●	●	●	●		11	0	0
F1r	●	●	●	●	●	●	◆	◆	●	●	●		9	2	0
F2z	●	●	●	●	●	●	●	●	●	●	●		11	0	0
F2g	●	◆	●	●	●	●	●	●	■	●	●		9	1	1
F3ag	●	●	●	●	●	◆	■	●	●	●	●		9	1	1
F3ar	●	■	■	●	■	■	■	■	●	●	●		5	0	6
F3ig	●	●	■	●	■	■	■	◆	●	●	●		6	1	4
F3ir	●	●	■	●	■	■	■	■	●	●	●		6	0	5
F4s	●	■	■	●	●	■	●	●	●	●	●		8	0	3
F4e	●	■	■	●	●	■	●	◆	◆	●	●		6	2	3
F4z	●	■	■	●	●	■	●	●	◆	●	●		7	1	3
F4p	●	■	■	●	●	■	●	●	◆	◆	●		6	2	3
M1s	●	●	●	●	●	●	●	●	●	●	●		11	0	0
M1m	●	●	●	●	●	●	●	●	●	●	●		11	0	0
M1h	●	●	●	●	●	●	●	●	●	●	●		11	0	0
M2s	●	●	●	●	●	●	●	●	●	●	●		11	0	0
M2m	●	■	●	●	●	●	■	◆	■	●	■		6	1	4
M3p	●	■	■	●	●	●	■	■	●	●	●		7	0	4
M3h	●	◆	■	●	●	■	◆	◆	●	■	●		5	3	3
M4h	●	◆	■	●	■	■	■	■	●	◆	●		4	2	5
M4a	●	■	■	●	■	■	■	■	◆	●	■		3	1	7
M4k	●	■	■	●	■	■	■	■	■	●	●		4	0	7
M5s	●	●	●	●	◆	●	◆	●	●	●	●		9	2	0
M5z	●	■	■	●	■	■	◆	◆	■	■	●		3	2	6
M5b	●	■	■	●	■	■	◆	◆	■	■	●		3	2	6
●	25	11	11	24	16	10	13	10	17	20	24		181		
◆	0	3	0	0	0	2	4	9	3	2	0			23	
■	0	11	14	1	9	13	8	6	5	3	1				71

Legend: ● correct result
◆ slight deviation
■ strong deviation

Table 3 shows a matrix of all 275 LCA calculations categorized by models and its BIM Authoring software, data format, LCA-Plugin and LCA-Software. The results are divided into the categories "correct", "slight deviation" and "strong deviation".

Most errors occur during the software-independent export into the IFC file format [13]. Also, IFC imports in the respective BIM programs also result in deviations of the model about geometry and material assignment. The more complex the original model, the higher the error rate. There are major problems and thus optimization potential especially with unconventional geometries, such as sloping walls, as well as window and door components and multi-layer roofs.

The causes for the calculation deviation are mainly because of differences of quantity take off in ArchiCAD and Revit and their IFC im- and export and missing or incorrect building components or material layers. One of the reasons are different geometric representations of connecting walls in ArchiCAD and Revit. IFC models of more complex models are missing components like roofs, walls, windows or component materials and layers.

The LCA software Tally couldn't calculate the construction phase of reinforced concrete for the Revit models. Also incorrect IFC-export of dummy-material in ArchiCAD leads to deviations in the

LCA results. One Click LCA has partially calculated all layers of multi-layer component structures (IFC models) together.

In general, it can be stated for all BIM-integrated life cycle assessments that these can only be as accurate as the BIM model was generated. In current practice, the BIM models should not be assumed as complete. Even in the analysis of simplified models, even minimal differences in modeling had a strong impact on the results. Missing parts or component components lead to poor calculation results without being recognized at first glance. It is sometimes only possible with great effort to adjust the missing information for the calculation afterwards since the programs usually lack the necessary transparency in the calculation steps.

Also, there is no interface in the LCA programs where specific data records, such as EPDs (Environmental Product Declaration), can be individually and easily integrated into the specified database. This is desirable if specific products are used for which EPDs are available. The datasets are partly based on different sources, so that large differences in the results also arise here. For the German market, Ökobaudat has established itself, which is available transparently to everyone and can be supplemented with individual EPDs.

As far as the working process is concerned, it can be said that the conventional method of operation is extremely time-consuming, especially when drawing up the mass balance. This problem intensifies by large, complex construction projects and is impracticable in the long run. Therefore, an automated component-specific material setup with subsequent manual or automated material assignment should be preferred and is associated with considerable time and cost savings.

A fully automated work process is not necessarily more effective than a semi-automated. Smaller errors in the model and the material allocation are not noticeable at first in full automation and have to be searched for afterward. In a semi-automated process, all materials are assigned manually, whereby missing component layers or components can also be adapted directly in a single step.

Although the promise of a fully automated LCA calculation sounds convincing, transparency and comprehensible adaptability suffer from this. With an ideal BIM model, the results can achieve a high degree of accuracy. Nevertheless, to skip the step of material allocation or its control would be negligent, since it sometimes leads to considerable error divergences. A check of the component-specific building materials for completeness and quantity is therefore urgently recommended, as is precise post-processing of the material take-off through correction and additions.

A semi-automatic work process is therefore recommended. A component-specific allocation of the materials allows these to be allocated exactly even in the case of inaccurate models with missing information's. A unique, direct assignment of the same materials is desirable. Faulty components should be marked as such to correct them during post-processing. Also, specific information such as layer thickness, composite content, service life or end-of-life scenarios of the building materials can be adapted in more detail.

4. Improved workflow with a prototypical implementation

We propose a workflow whose aim is to enable complete transparency and the possibility of exerting influence in the LCA calculation process, in which the data for calculation and allocation are presented in a comprehensible manner. Adjustments for individual parameters can be made easily, quickly and precisely using *Excel* interfaces. This includes the modification of layer thicknesses, composite proportions, lifetimes or end-of-life scenarios of building materials. With this approach, however, the real-time calculation is still not possible. Also, this interface is only intended for *Revit* models, so no qualified evaluation of an IFC model is created. Although the planned procedure is more cumbersome than the fully automatic calculation, it can ensure sufficient quality of the life cycle assessment with exact results.

4.1. Procedure

As with all life cycle assessments, a distinction is initially made between three parts: the model, the life cycle inventory analysis and the impact assessment. For this reason, any model is first created or loaded

in *Revit*. In the next step, the Life Cycle Inventory Analysis, Dynamo Player is opened, and the *Excel* file is linked to create the material allocation. The Dynamo Player is a reduced application that makes it easier to execute Dynamo scripts without having to open them. All you need to do is specify all the required input parameters in the *Excel* sheets.

Once the Dynamo script has been executed, the *Excel* file opens to check the boundary conditions, such as net-space area, project lifetime, LCA phases, etc. The following parameters can be checked. Subsequently, the components and the corresponding materials are checked and adjusted if necessary. In the last step, the Life Cycle Inventory, the energy sources, and the electricity and heat requirements are set up using German regulations (EnEV).

During the impact assessment, the LCA calculation file is opened in Dynamo Player, and the completed material allocation and the still empty output *Excel* file are linked to export the LCA calculation. The dynamo player file is then executed, and the LCA results are automatically inserted into the *Excel* template provided for this purpose.

4.2. Implementation of the prototype in Dynamo and Revit

After a comparison of relevant component groups in the calculation according to DGNB, LEED, *Tally,* and *One Click LCA*, a selection was made for the prototypical implementation in *Dynamo* for *Revit*. First of all, a distinction is made between volume components, which include walls, ceilings, roofs, and foundations. The second group is referred to here as element components and consists of windows, doors, stairs, facade elements and posts as well as ceilings. Structural elements such as columns and girders also form a relevant group but are initially left out due to their implementation in *Revit*. The plant technology includes all mechanical, electrical and plumbing (MEP) components and forms the last grouping.

First, all component-specific materials are summarised, different information, like component name, area, volume and quantity is queried and compiled and finally exported to an *Excel* template for the Life Cycle Inventory. For the sake of simplicity, problems with the geometry export of windows, facade posts and stairs are no longer taken into account for the rest of the process and can be further developed as the prototype is further developed.

The subsequent *Excel* export contains the folders boundary conditions, material assignment, component overview, and energy requirement. Under boundary conditions, the net space area calculated from Dynamo as well as the pre-defined information on the observation period, relevant life cycle phases and calculation methods according to DGNB can be adapted. When assigning materials, the individual materials must be referenced to an LCA data set, and the values of density, service life and composite materials can be adapted or supplemented. All components can be adapted in the component overview folder. This includes the addition of layers, geometric checking of the volume, the characteristic length, the area or the number. In the last folder, the energy requirements and any missing MEP components are supplemented with the respective data sets.

The impact assessment is then calculated automatically. The calculation follows the formulas of the DGNB calculation system using the information of the *Excel* sheet Boundary Conditions, the references from the material allocation and the datasets of the structural and MEP components. The results are shown for the whole project grouped by construction, equipment, and usage, subdivided by production, preservation and deconstruction.
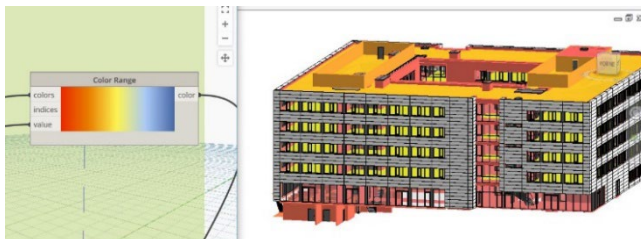

Figure 2. Visualisation of component specific results with colour coding in *Dynamo* and *Revit*

On another *Ex*cel sheet, the results are shown component-specific, which can be used to color code the Revit Model according to their total impact on the embodied energy (Figure 2). This visualization

helps to identify optimization potential during the planning phase and has a positive effect on the optimization workflow.

4.3. Validation of the prototype

In the following, the prototype will be quantitatively validated. For this purpose, the model M1s is calculated as an example reference object. The calculation method corresponds to the life cycle assessment according to the DGNB system 2018. The service life of the building was assumed to be 50 years. The data basis is Ökobaudat 2013.

The error deviation of 1.13% results from the more accurate mass determination through BIM integration. The actual volumes of the component-specific materials are determined, whereas in conventional balancing the calculation is based on the product of component area and layer thickness. Besides, with the own prototype, the approach of density accumulation can be bypassed by the method of the specific assignment of composite materials and thus a more exact calculation can be achieved. The correct results of the own prototype validate the calculation method and functionality of the prototype.

5. Discussion and Outlook

This work aimed to investigate BIM-integrated life cycle assessment about its operability and weaknesses. Initially, model analyses were carried out with existing software programs.

The calculation results show that even with simple models of the IFC files there are large deviations in the results. This leads to the conclusion that the "open BIM" approach is error-prone and often leads to incomplete and incorrect BIM-integrated LCA.

In general, a more precise nomenclature of materials with qualitative name affix is recommended to guarantee a correct, component-specific material allocation. For example, this can be the minimum compressive strength class for concrete, the tree species or material type for wood, or the type and processing of metals.

Therefore, the core of this approach was to develop a separate concept for an LCA calculation tool using *Autodesk Dynamo* and *Excel* interfaces. It realizes a compromise between the automation of the component-specific materials and subsequent adaptability according to the given component catalog. All components relevant for the LCA calculation are read out via dynamo, whereby problems still arise with the geometric export of stairs, windows, and doors, facade elements as well as beams and supports. In contrast to existing programs, this approach ensures a precise and transparent LCA calculation even for imperfect, complex projects. Due to the open interfaces, it is possible to make comprehensible adjustments to the materials. However, programming complex models with *Dynamo* and Python scripts are still computationally complex and was just used to prototypical implementation. Together with the exact geometric mapping, this offers further optimization potential.

The modeling recommendation for an effective BIM-integrated LCA is the naming of the components according to the component catalog and a precise nomenclature of the building materials, which also includes qualitative material properties. Post-Processing of the mass installation as error correction is necessary to ensure a correct and complete life cycle assessment.

For future work, a workflow with real-time calculation would be the next step. This way of feedback of BIM-based design decision support helps optimizing the design according to its ecological impacts in early design stages. The difference to Hollberg's Parametric Life Cycle Assessment [14] would be that BIM models could be used for existing semantic information about the building constructions and materials.

Another focus of future work in this field of BIM and sustainability is to supplement Life Cycle Assessments with the aspect of life cycle costs (LCC) to take the economic dimension into account. Further BIM-compliant criteria according to green building certificates are available in the areas of socio-cultural and functional quality as well as technical quality. After a general potential analysis, which criteria are suitable for a BIM-integrated verification, it is necessary to integrate the different calculation criteria into BIM programs.

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