Life cycle-oriented decision making based on data-driven building models

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Abstract –

The integration of BIM and sustainability is a key success criterion for sustainable planning, construction and operation and maintenance. Actually, various research is conducted to integrate the economic, environmental and social aspects in the BIM method. Especially, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are subjects of research. Although the integration of the various aspects has made significant progress in recent years, the complete life cycle is not regularly considered, but rather individual life cycle phases (such as design and construction). This is particularly due to the fact that building components consisting of different components are regularly included in the LCA and LCC calculation as a single component. The layered structure of the individual components (e.g. a wall with load-bearing elements, insulation, plaster and others) is thus not included in the respective calculations. However, it is a relevant criterion, since the conversion and renovation of buildings and the associated emissions and costs are strongly dependent on the layered structure and the deconstructability. Against this background, this paper presents a BIM- and data-based simulation of LCA and LCC to enable an optimized and realistic estimation of costs and emissions over the life cycle of building. The layered structure of building components is used to simulate the findings in a Proof-of-Concept (PoC). This paper shows, that BIM is a success criterion for the simulation of LCA and LCC and improves the construction and real estate industry's ability to implement sustainability concepts more effectively. It also indicates success factors for life cycle-orientated decision making as processes or definitions for the quality of information.

Keywords –

Building Information Modeling (BIM); Life Cycle Assessment (LCA); Life Cycle Costing (LCC); Data-driven Decision

1 Introduction

Sustainability defines a concept that aims to meet the present needs of a generation in a way that does not limit the opportunities of future generations [1]. In the current research and literature sustainability combines social, economic and environmental aspects [2,3]. In addition to that, the sustainability certification systems, as Leadership in Energy and Environmental Design (LEED), the Qualitätssiegel Nachhaltige Gebäude (QNG) or Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) combine these three aspects [4,5].

The combination of sustainability and digitization leads to new perspectives in the solution of current economic, social and environmental challenges [6]. Especially in the construction and real estate sector it is necessary to use all existing possibilities to solve sector-specific challenges, especially the reduction of costs and the carbon footprint of buildings [7]. 37% of global CO_2 emissions are due to the design, construction and operation & maintenance (O&M) of buildings [8]. To reduce the carbon footprint of buildings, the costs and benefits of new materials like wood (e.g. [9,10]), sustainable insulation materials (e.g. [11,12]) or carbon concrete (e.g. [13,14]) are researched. Furthermore, the technical equipment, like heating, cooling or ventilation, becomes more effective, e.g. due to big data analytics and the connection to the Internet of Things (IoT) [15].

To get a holistic view of efficiency and carbon footprint, it is necessary to collect, process, analyze and store all relevant data throughout the life cycle. With the help of a holistic and fully comprehensive data usage it is possible, to reduce waste, to minimize the energy consumption of buildings, to increase recycling and to support circularity [16–18]. In addition to that and due to new technologies, various data is generated by Building Automation Systems (BAS), sensor technologies and IoT devices. This data could also be used to identify actual usage, actual consumption and optimization potentials [19,20].

This large amount of data, new technologies and new building materials leads to the fact, that structured data collection is necessary to manage the complex requirements for sustainability aspects. Building Information Modeling (BIM) is one essential component for structuring, analyzing and storing sustainability data throughout the whole life cycle and to make it usable for all relevant stakeholders [21,22].

This paper aims to combine economic and environmental sustainability aspects. It shows a solution to perform a BIM- and data-based simulation of LCA and LCC to enable a weighted and result-based decision for Design, Construction and O&M variants in early life cycle phases. Variables (e.g., a CO_2 tax) that may result in a change in LCA and LCC will also be included. The paper uses the layered structure of a wall as an example to illustrate the results.

2 Literature Review and related work

BIM as a method - that links various disciplines throughout the life cycle with the help of a digital building model enables transparent data exchange – also offers advantages to support sustainable design, construction and O&M [21,23]. Various research is actually conducted to combine BIM and sustainability aspects. Mostly, only one aspect of sustainability is focused (e.g. environmental criteria). A distribution of the research of BIM in the respective sub-aspects of sustainability is shown in Figure 1. Here, published papers on the sub-aspects are considered. Especially, the preparation for LCC, LCA, Simulations and Material Passports is supported by the integration of BIM and sustainability.

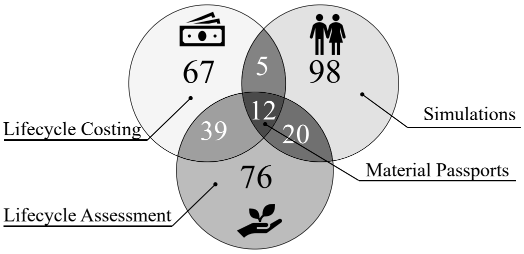

Figure 1. Application of the BIM method in the field of sustainable construction (number of publications mentioned) [24]

The analysis that forms the basis for Figure 1, serves as a basis for further literature analysis with regard to the link between BIM and sustainability. This further literature analysis considers in particular the integration of BIM with LCA and LCC, that are relevant research topics for the linking of BIM and sustainability. In this context, previous literature analyses were also included in the literature review (e.g. [25–29]). On the basis of these publications, a further literature analysis was carried out with three keywords “BIM *AND* LCA”, BIM *AND* LCC” and “BIM *AND* LCA *AND* LCC”. These keywords were searched in various research databases (e.g. SCOPUS, ScienceDirect, Springer, MDPI or google scholar). In this literature review, the years 2013 – 2023 were considered. In addition, attention was paid to the main focus of the publication, which means that publications that only mention a keyword in the text but do not have this as their focus were not included in the evaluation. Figure 2 shows the published papers during the years 2013 – 2022 (status as of 29 December 2022).

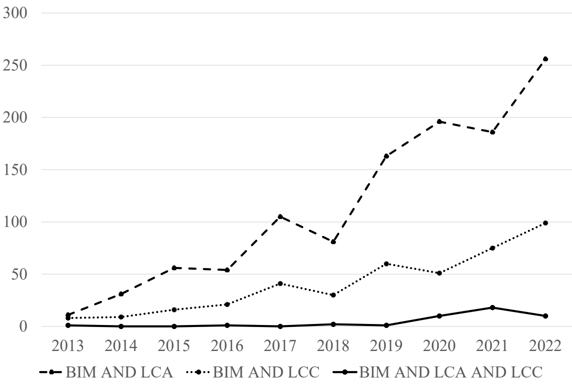

Figure 2. Literature review of the integration of BIM, LCA and LCC as of 29 December 2022.

As can be seen in Figure 2 most of the publications were published in the recent years. The main focus of the research was on papers about BIM and LCA. The research about the integration of BIM, LCA and LCC falls significantly in comparison to the other two research fields. The literature review also showed, that there is a lack of cross-life cycle comparison and thinking by using the BIM method for integrating LCA and LCC. The majority of the papers only focusses on one life cycle phase of the building. But to get a holistic view of the life cycle of a building, it is necessary to integrate various data and to get to know the relationship between the building components.

In particular, an evaluation of the layered structure of the individual components is rarely performed and is regularly incomplete. Instead, only the individual components (e.g. concrete, insulation) are considered. The layered structure, which leads to the fact that components can be deconstructed with different efficiency, is regularly not considered.

3 Integration of BIM-based LCA & LCC

For the integration of LCA and LCC it is necessary to consider all relevant cost and environmental aspects. Figure 3 shows the course of the developed method from uploading an IFC file to evaluating the results of the LCA and LCC. Based on the IFC-upload and a model check, three steps are passed through to calculate the LCA and LCC of the used materials, the building components and finally of the entire building.

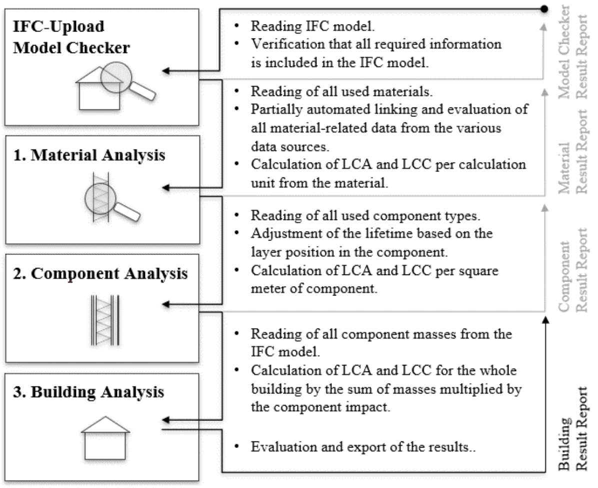

Figure 3. Course of the developed method

The following sections explain the steps 1-3 more in detail. Here this paper refers to the relevant databases (3.1), the calculation of the lifetime of building components (3.2), the calculation of LCA (3.3) and the combination of LCA and LCC (3.4). The upload and the model check are assumed to be established processes.

3.1 Relevant Databases

To calculate LCA and LCC it is necessary to use data bases. These databases have various purposes and may support by conducting LCA, Material Passports (MP), LCC or Simulations (Sim). An overview of German databases is shown in Table 1.

Table 1. Relevant German databases in sustainable construction [21]

Data base	LCA	MP	LCC	Sim
ÖKOBAUDAT	X	X		X
WECOBIS	X	X		X
EMMy	X	X		
Building material scout	X	X		X
IBU.data	X	X	X	X
Material library	X	X	X	X
DGNB Navigator	X	X	X	X
Cradle to Cradle certified	X		X	
BNB service lives	X	X	X	X

In addition to that, there are many more databases, as the data base of the Energy & Environmental Building Alliance (EEBA) [30]. Furthermore, it is necessary to integrate data of the lifetime of building components, what can be found in the data bases of the Informationsportal Nachhaltiges Bauen and the Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR). [31]

3.2 Calculation of the lifetime of building components

To evaluate the sustainability of a building structure or system (e.g. a Wall), it is necessary to calculate the lifetime of that component. Building components may consist of various layers (e.g. a wall consists of an Insulation layer, a reinforced concrete layer, plaster layers, etc.). In addition to the layer structure of the wall, the maintenance strategy of the building component in particular influences the life cycle costs. [32] Figure 4 shows that context using the example of a wall.

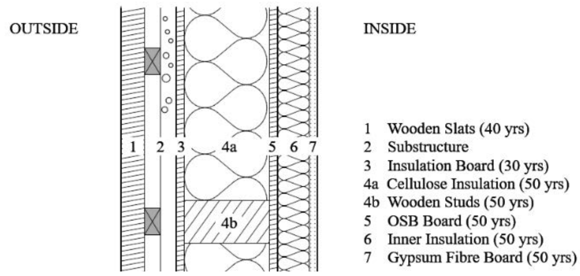

Figure 4. Lifetime of layers in a building component using the example of a wall (here: wall of a residential building in Cologne-Junkersdorf)

To calculate the sustainability of a building component, it is necessary to develop a concept for the visualization of the service life between the individual layers. Here, a distinction must be made between two variants:

1. If all component layers are detachable from each other, the components can be considered individually.
2. If the component layers cannot be detached from each other, the service life is limited by the lowest expected service life of the underlying layer groups [33]. This is to be considered as an attribute in the model

To model that, a function was developed to visualize and determine the course of the service life of the layer structure. Firstly, all multi-layer components (e.g. Ceilings, Walls) are detected using *IfcOpenShell*, a Python-based open source software library for working with Industry Foundation Classes. The *IfcRelAggregate* entity is used so that these can be read out from the IFC file previously uploaded to the browser app. With the help of the entity *IfcRelAssociatesMaterial*, which describes the relationship between components and their material components, the materials of the individual layers can be read out from the IFC file. [34] In the next step, the entity *IfcRelDefinesByProperties*, which allows the assignment of a property set to a single or multiple objects [35], is used to read all properties of the materials and filter them by "Component Properties". This property set stores information about the layer structure.

To structure the layers, a code is used to show whether the layer is a core layer or not. If it is a core layer, a “1” is appended to the list. If it is a non-core layer, a “0” is appended to the same list. (e.g. [0,0,1,0]). Afterwards, a layer number is assigned to each layer. Three different cases have to be differentiated. (e.g. [0,1,2,1]):

1. The first *IF*-loop considers the case that the component contains a core element. In that case, first the index of the core element is determined. Then, for each layer, it is checked whether its index is smaller than that of the core layer. In this case, the index can be kept. However, if it is larger, the numbering should decrease again, which is why one counter per layer is reduced by one.
2. In the second *IF*-loop the layers of components are numbered with an odd number of layers. First the number of layers must be determined for this. Then for each layer it is checked whether its index is smaller than half of the number of layers. In this case, the index can be kept. If the index of the layer is greater than or equal to half of the number of layers, the numbering should decrease again.
3. The *ELSE*-loop considers the remaining case, of a component without a core element with an even number of layers. This loop works in the same way as the one for the odd number of layers, except that the counter for counting down does not have to be reduced by one beforehand.

Figure 5 und Figure 6 show the results for two components. If the result is assigned with a “+”, the lifetime decreases from the core to the outside. If the result is assigned with a “-“, the lifetime increases from the core to the outside and adjustments might be required.

```
Component Typ 1
Layer:
        - Wooden Slats
        - Substructure
        - Insulation Board
        - Cellulose Insulation
        - Wooden Studs
        - OSB Board
        - Inner Insulation
        - Gypsum Fibre Board
Core element:               [0, 0, 0, 0, 1, 0, 0, 0]
Layer position:             [0, 1, 2, 3, 4, 3, 2, 1]
Lifetime of layers:         [40, 'x', 40, 50, 50, 50, 50, 50]
Valuation for adjustment:   ['+', '+', '+', '+', '+', '+', '+', '+']
Adjusted lifetime of layers: [40, 40, 40, 50, 50, 50, 50, 50]
```

Figure 5. Results of the lifetime of layers in a building component (lifetime decreases from the core to the outside)

```
Component Typ 2
Layer:
        - Wooden Slats
        - Substructure
        - Insulation Board
        - Cellulose Insulation
        - Wooden Studs
        - Insulation Board
        - Inner Insulation
        - Gypsum Fibre Board
Core element:               [0, 0, 0, 0, 1, 0, 0, 0]
Layer position:             [0, 1, 2, 3, 4, 3, 2, 1]
Lifetime of layers:         [40, 'x', 30, 50, 50, 30, 50, 50]
Valuation for adjustment:   ['+', '+', '-', '+', '+', '-', '+', '+']
Adjusted lifetime of layers: [30, 30, 30, 50, 50, 30, 30, 30]
```

Figure 6. Results of the lifetime of layers in a building component (lifetime increases from the core to the outside, adjustment might be required)

With the help of another function, the lifetime of the material is read out (e.g. by using databases as the BBSR tables [36]). By using the entity *IfcMaterialProperties* all PSets of a material can now be read out. In this way, the *IfcProperties* can also be identified with the unique IDs of the datasets of the databases. Using these IDs, information requests can be sent to the databases, connecting them to the browser app. In this way, the lifetime data of a material can be queried. In the next step, this function is applied to all materials of a component and all lifetime dates are stored in a list to compare these dates which each other. The consideration must always be made from the inside to the outside. Thus, it is started with the layer with the highest layer number, which represents the core layer of the component. In the next steps, it is checked whether the adjoining layers have a higher or lower lifetime. If the layer has a lower lifetime, it can be retained. If the layer has a higher lifetime than the lower layer, the lifetime must be adjusted to the lower layer.

3.3 Calculation of LCA

In order to be able to correctly offset the masses and life cycle assessments against the lifetime, the masses per component must be read out. In this case, all units are read from the IFC model so that the correct reference unit can be selected during LCA. If a bulk density for the material is stored in a database (e.g. ÖKOBAUDAT), this is used from the database rather than from the IFC file, because the bulk density and the LCA data belong to the same data set in this case and the building material data in the IFC model are often also very poorly maintained. As the bulk density is not mandatory in the case of the ÖKOBAUDAT database, the IFC model is used if it is not available. However, the building material masses are completely read out from the IFC model.

The following process was developed to integrate this data. First, all materials (of ceilings, roofs and walls) of the multi-layer components were determined by using the entity *IfcRelAssociatesMaterial* as already mentioned in 3.2. In the next step, all PSets of the materials can be identified by using the entity *IfcRelDefinesByProperties*, from which the PSet *Component Quantities* can now be filtered. In this PSet all data concerning the masses of the materials are stored. After that, the *IfcSingleValue* can be sorted by surface, volume and weight and attached to the corresponding property lists.

1. The volume has the entity *IfcQuantityVolume*.
2. The weight has the entity *IfcQuantityWeight*.
3. Since the Pset "Component Quantities" stores different surface areas, the component surface area cannot be filtered by the entity, but must be matched with the *Layer/Component Surface Area* label.

As this is done for each component layer, a list is obtained with all the square meters of the layer surfaces, all the cubic meters of the material volumes and the weight in kilograms of each layer. To access the masses of a material in a component, only the index of the material is needed.

The last step is to link the material amounts of the IFC model to the databases by using a semi-automated process to connect the UUIDs. For this purpose, however, the materials must have a unique designation and be described and categorized as characteristically as possible. But the research showed that the connection between IFC and the databases regularly does not work properly. Especially a lack of standardization into the databases (e.g. ÖKOBAUDAT) complicates the connection. For this reason, a function was developed which creates a material preselection for the user. In this way there is at the same time a quality control by the user. For this purpose, in this function the columns "UUID", "Name (en)", "Category (original)" and "Raw density (kg/m³)" are first read out from the databases and stored in individual lists. In the next step, the database is reduced to the essential information for data processing, so that each material is no longer listed per life cycle phase but is reduced to one line. Based on the user's selection, the LCA can then be determined.

Figure 7 shows the example of a material selection parts of the developed interface for two exemplary materials. The interface displays all material-related data from the various data sources for the respective material.

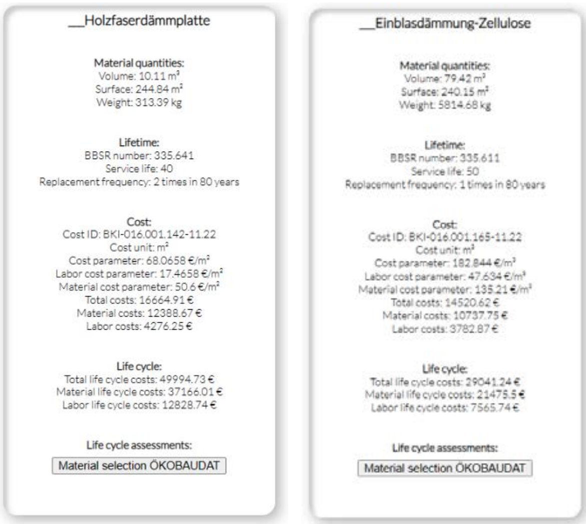

Figure 7. Example for material evaluation and material selection (left: Insulation Board, right: Cellulose Insulation)

Only the LCA data still has to be linked to the material data using the drop-down menu manually.

3.4 Calculation of LCA and LCC

Based on the service life of the materials in each component, the manufacturing costs and LCA can be calculated for the entire life cycle of the building. With the help of that calculation, the best solution for the life cycle can be simulated. For this purpose, the LCA results from the different phases are calculated according to DGNB or QNG. Because of the partially insufficiently maintained databases, the focus here was placed on the manufacturing phase including raw material provision, transport and production (A1-A3), the replacement in the use phase (B4), in the disposal phase on waste treatment and landfilling (C3, C4) and finally on the recycling potential (D). The data basis of the manufacturing phase can be rated as quite good and since the replacement is calculated as new manufacturing according to DGNB, this phase is also covered by good data. The data for the disposal phase and the recycling potential, on the other hand, are partly incomplete. If the database does not provide a value for these phases, a "0" is set at this point, which is critical. While missing data for the recycling potential does not improve the value, missing values in the disposal phase even embellish it. Finally, the LCC can be calculated with the help of the cost parameters of the building materials. An example for the Global Warming Potential (GWP) is shown in Figure 8.

```
Global Warming Potential (GWP):
    Material name:
        - Wooden Slats
        - Substructure
        - Insulation Board
        - Cellulose Insulation
        - Wooden Studs
        - OSB Board
        - Inner Insulation
        - Gypsum Fibre Board
    calculation unit: ['m3', 'm3', 'm3', 'm3', 'm3', 'm3', 'm3', 'qm']
    Production (A1-A3): [-721.74, -738.94, -198.4, -73.37, -654.77, -753.0, 40.31, 1.36]
    Replacemen (B4): [0, 0, 0, 0, 0, 0, 0, 0]
    Waste (C3,C4): [809.71, 796.78, 270.0, 99.08, 815.1, 967.0, 1.12, 0.13]
    Recycling (D): [-351.38, -349.48, -184.5, -30.51, -288.65, -549.0, 0, 0]
    DGNB: [-263.41, -291.64, -112.9, -4.8, -128.32, -335.0, 41.43, 1.49]
    BNB: [87.98, 57.84, 71.6, 25.71, 160.33, 214.0, 41.43, 1.49]
```

Figure 8. Section of the calculation of the LCA per material of a building component (GWP)

Using the example of the wall, this can mean that a different wall construction, which at first glance appears to be more favorable in terms of LCA and LCC without considering the layered structure of the wall, has a worse life cycle balance in the life cycle due to the longevity of materials. In order to estimate the cost development for the LCC, figures from the Baukostenindex (BKI, german for Construction Cost Index) are used. The BKI represents the price development for construction projects in Germany and can be used as a basis here, as it allows an estimate of the price development for the future dismantling or replacement costs of components [37]. It is necessary to take into account not only complete components (e.g. a wall), but also the layered structure as described above, as this can lead to price differences. These price differences occur especially due to the fact, that the period of the adjustment of components is influenced by the life time of its layers.

In addition, the cost parameters of the building materials must be differentiated into labor and material cost parameters for a correct calculation of the LCA and LCC. The distinction between labor and material cost is necessary, because the price increase rate differs for these parameters

4 Validation based on an example project

The concept presented in Section 3 was validated in a Proof-of-Concept (PoC) application to determine its practicality. For this PoC a residential building in Cologne was used. The building is located in Cologne-Junkersdorf, has a gross floor area of 410 m² and was designed by “Klara Architekten BDA”. This project is shown in Figure 9.

Figure 9. PoC – 3D model of the validation model by "Klara Architekten BDA"

To validate the findings of the previous sections, the building was modelled with BIM and without BIM to calculate the LCC and LCA. Especially due to the material selection, the LCC and LCA could be calculated easily and optimizations were evaluated. An example for the result of the calculation of the GWP and LCC for a wall are shown in Figure 10 and Figure 11.

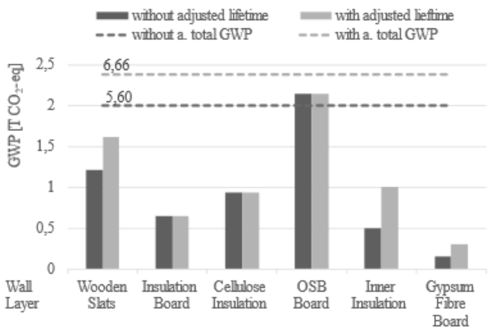

Figure 10. Effect of adjusting the lifetime on the GWP (calculation with BNB method).

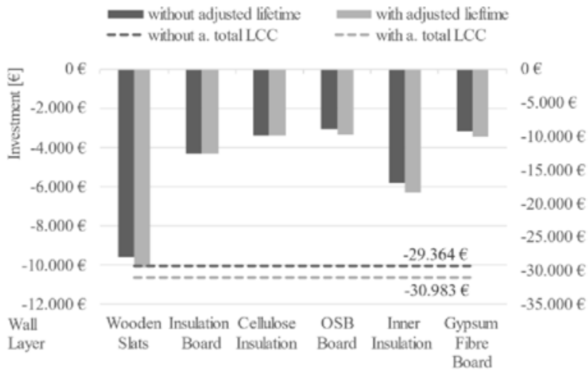

Figure 11. Effect of adjusting the lifetime on the LCC (calculation with the present value method)

Besides the results of the calculation of the LCC and the LCA, this validation shows especially five main factors that are relevant for successful implementation to integrate BIM and sustainability aspects:

1. All relevant data must be maintained even more precisely than in projects in which no application of LCA and LCC is carried out with the BIM method. In particular, data such as density (e.g. of the different concrete grades) must be maintained precisely, as they cannot always be retrieved unambiguously from the databases.
2. Furthermore, a differentiation of the materials for different types of building components is necessary. In the IFC model, for example, a different material should be used for mineral wool used as insulation between rafters than for mineral wool used in wall construction, since the expectation of its service life is different.
3. It is necessary that the user (e.g. the architect, technical equipment planner, construction management, sustainability planner) can intervene in the process via a user interface. The intervention is necessary because only a partially automated process is possible when linking the databases because of the missing standardizations. However, this also enables quality control by the user, as well as a high level of transparency and influence. In the test project Haus-Blu in Cologne-Junkersdorf by “Klara Architekten BDA”, for example, the quality classes of the concrete were not clearly marked, which is why manual linking became necessary.
4. Another point to consider is that the building components have to be built as a whole multi-layered building component. In the PoC, there was initially the problem that a differentiation was made between facade, shell and extension components This is due to the construction process, tendering and the intersection of components. However, it is not possible to recognize the coherence of the component

and thus also not to adjust the service life on the basis of the position of the component layer in the component, since in this case façades, shell and extension components are considered individually instead of as one coherent component. To calculate the LCA and LCC of the component, it was necessary to remodel the wall construction in the PoC. In the future, it will therefore be necessary to ensure during modeling that the elements are classified as facade, shell and extension component and their layers can be assigned to a component via a parameter.

5. Components that are not modeled in the multi-layer component are neglected in the layer-by-layer analysis, e.g. timber frame, steel girders or profiles. In this case, it is also necessary to consider the corresponding parameters.

The findings from the PoC show that it is necessary to create clear processes and definitions regarding the relevant data. This requires clear Exchange Information Requirements (EIR) that map the requirements with regard to the calculation of LCA and LCC. Especially with regard to the layered structure of the components, a clear definition of the EIR, a high-quality modeling and an attribution of the relevant parameters is necessary.

5 Conclusion and Future Work

This paper presents a solution for calculating LCA and LCC that considers the layered structure of components. The validation carried out in the course of the research shows that the presented method offers a possibility to optimize the reliability of the calculations. Thus, the concept presented in this paper contributes to the construction and real estate industry's ability to implement sustainability concepts even more effectively, helping to reduce CO_2 emissions from the construction and real estate industry.

Although this paper takes various aspects in account, it considers only the service life of the materials due to the structure, which is considered the most favorable in design and construction. In the future, with regard to LCA and LCC, the costs for facility management must be priced in over the life cycle. For example, technical facilities that at first glance appear to be more costly and emission-intensive can become more cost-effective in the further life cycle if the facility management processes are optimally adjusted to these facilities.

In addition to that, it is necessary to specify the processes for the integration of BIM and sustainability regarding LCA and LCC. Especially the EIR needs to be specified by all technically involved people. These are two aspects that are being explored in the context of research at the University of Applied Sciences in Cologne.

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