Development of a BIM-based LCA Tool to Support Sustainable Building Design during the Early Design Stage

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Abstract: The vast majority of scientists, building industry representatives, and non-governmental organizations agree that a robust method in environmental load assessment of buildings needs to be implemented to reduce the environmental burden of the construction industry significantly and to meet the required environmental standards. So far, the industry utilizes the life cycle assessment (LCA) method to assess the environmental impacts of the detailed design; yet, the implementation of changes at that stage of development is often expensive and unadvisable. On the other hand, during the early design stages, the LCA method is restrained by the information provided by the design and the uncertainty of material decisions. To support sustainable design decisions during early design, the aim of this research study is primarily to investigate how the use of available methods and tools, such as Building Information Modelling (BIM), can facilitate the process of conducting LCA analysis. A literature review is conducted that enable us to establish a framework for BIM and LCA integration, which creates the foundation for the development of a new BIM-based LCA tool. The first prototype of the tool is demonstrated in this paper and empirically evaluated on a large case study of a residential building in Denmark.

Keywords: Life Cycle Assessment (LCA); Building Information Modelling (BIM); BIM-based LCA; Early Design Stage.

1. Introduction

Buildings’ production and operation stages are responsible for 35% of total energy use and 19% of energy-related to GHG (Edenhofer et al., 2014). To meet the sustainable development goals architects, engineers, contractors, together with other building stakeholders are not only obliged to work in the Building Information Modeling environment, but they also have to introduce the Life Cycle Assessment concept into their practices. Without ground methods for assessing environmental impacts of the building and exploitation of the benefits of reused materials, the process of achieving the sustainable goals will be significantly hampered.
Although the LCA has been widely accepted as a method to evaluate the environmental impacts of the buildings, the methodology, underlying data, and tools are still under development. The main disadvantages of the LCA are its complexity, time consumption, data collection, and issues with weighting. Due to those limitations, the design’s evaluation of environmental loads is often shifted after the design phase is completed—when all the necessary materials are available. Thus, both the possibility of influencing the design decisions made in the early design stage and the enormous potential for the reduction of the building’s life cycle impacts are abandoned (Basbagill et al., 2013; Häkkinen et al., 2015, Marsh, 2017). Moreover, Häkkinen et al. (2015) argue that there is a lack of not only design-integrated tools but also the process descriptions for designing low-carbon buildings.

Despite those limitations and incoherence in LCA studies, many researchers proposed solutions to introduce the LCA in the early design stage to enhance design abilities and sustainable decision making (Antón & Díaz, 2014; Basbagill et al., 2013; Bueno et al., 2018; Häkkinen et al., 2015; Kamari et al., 2018a,b,c; Meex et al., 2018; Röck et al., 2018; Soust-Verdaguer et al., 2017). The proper collection of data is key to the reliable and efficient environmental impacts assessment of the design. Since BIM allows a multidisciplinary collection to be imposed in one model, it creates a new way of incorporating sustainable measures throughout the design process (Azhar et al., 2011). As various disciplines are moving towards BIM application, it is beneficial to develop a BIM-integrated LCA methodology in order to take the aspect of environmental loads of the building into design decision making (Antón & Díaz, 2014; Chong et al., 2017; Hollberg & Ruth, 2016; Meex et al., 2018; Röck et al., 2018). The goal of BIM and LCA integration is to give AEC (Architecture, Engineering, Construction) industry a possibility to focus on conceptual design while, in parallel, being informed about the implications and potential effects of the material and design selection during the early design stage (Hollberg et al., 2018).

1.1. Problem statement

Since most of the available software on the construction market does not allow for interoperability between BIM environment, the most obvious solution is to integrate BIM and LCA and implement it in the early design stage to allow engineers and architects to identify hot-spots of environmental impacts and minimize their effects. Therefore, the main aim of this paper is to identify and investigate current LCA and BIM integration issues, and afterward, provide a holistic framework for BIM-LCA integration and to develop BIM-based LCA tool, which can be used in the early design stage. With decreasing the environmental loads from the operational stage, the building material selection starts to play a significant role in the total environmental impact of the design; thus, the LCA tool should facilitate the interpretation of the results to support design decisions regarding material choices. Moreover, the project aims to analyze the representativeness of the data, and the outcome of that research will be incorporated into the software’s architecture.

In particular, the developing tool is supposed to bridge the existing gaps in current practices, which were stressed by the EXIGO consultancy (a construction company located in Aarhus, Denmark), according to the two rounds of interviews we conducted with their LCA practitioners. Therefore, the developing tool in this paper should enable professionals, small architectural companies, students, and researchers to execute the calculation of the environmental loads of the building in the early design stage in a transparent, easy, and time-saving manner. The tool will allow for effortless quantity material take-off from the Revit model and, in contrast to other LCA tools, will allow for automated mapping of the materials to reduce the time needed to perform LCA calculations. This will lead to improving
sustainable design decision processes in the early design stage as well as to spread awareness of materials' selection and their production effect on the environment.

1.2. Research structure
The point of departure for this research is conducting qualitative research. Based on a literature review, the state-of-the-art within the current practices in the sustainable building design, the use of BIM and LCA methods, and the value of integrating these two approaches are outlined. In addition, the literature review is used to analyze current methods of the assessment of the environmental impacts within the construction industry and find the gaps in the existing LCA tools. Since the purpose of the tool is to being used within the BIM environment – the Autodesk Revit software is used as a BIM platform. The BIM-based LCA tool is developed using the Visual Basic Studio and C# programming language and utilization of the Revit API.

2. BIM and LCA – a framework for integration and design
The goal of sustainable design is to create a building with the lowest environmental impact while pushing economic and social development (Antón & Díaz, 2014). Many scholars reviewed several cases of BIM and LCA integration in the building industry and proved that through this approach, it is possible to gain quick and reliable results about the environmental impact of the building from the early design stages. However, there is still a long way to go in the process of eliminating current challenges in BIM and LCA integration. Both works by Häkkinen & Kiviniemi (2008) and Soust-Verdaguer et al. (2017) underline the variety of data requirements between BIM and LCA, which leads to the time-consuming nature and complexity of the whole process. According to the reviewed papers, the data contained in the BIM databases is not sufficient to perform LCA, which is the main reason behind the manual edition of the bill quantities and material properties by the end-users (Basbagill et al., 2013; Häkkinen et al., 2015; Najjar et al., 2017; Peng, 2016; Soust-Verdaguer et al., 2017).

Another critical issue is the lack of worldwide standards regarding functional units, system boundaries, and weighting methods. As Nwodo & Anumba (2019) stated, all inputs and outputs in the life cycle inventory and the life cycle impact assessment are related to the functional unit. The functional unit not only improves the comparison of the data but also plays a major role in assessing the environmental impact loads of the whole building system. Soust-Verdaguer et al. (2017) emphasize that many scholars assumed either complete building or 1 m² of the heated area as a functional unit in LCA, which might not be completely reliable while comparing different buildings. Soust-Verdaguer et al. (2017) suggest that functional unit should include building type (residential, office), relevant technical requirements (regulatory requirements, energy performance), a pattern of use (occupancy, usable floor area), and required service life. Another relevant issue is the variation in building life span and service life. Nwodo & Anumba (2019) state many studies on building LCA make varied standard assumptions on building life span and service life for material replacement, repair, and maintenance. These standard assumptions may lead to incorrect and unreliable LCA results. The authors suggest that pragmatic assumptions should be considered based on the science of building rather than common practice.

Besides, Nwodo & Anumba (2019) highlight that the lack of procedure for system boundaries is another challenge of building’s LCA, which needs to be tackled. As in the case of the functional units, the LCA standards do not provide any specific procedures to define system boundaries, which makes the comparison of the results difficult. According to EebGuide (2019), screening LCA should include A1-A3,
B6, B7, which corresponds to the production stage (raw materials supply, transport manufacturing) and use stage (only operational energy use and water use). The other stages are considered as optional because of minor relevance or due to potentially missing data, which is reasonable because in the early design stage, it is hard to define what will be emissions for the demolition or replacement phase. The simplified approach adds on top of that stage C3 and C4, which are waste process and disposal, and D stage, which is benefits beyond boundary. Complete, as the name suggests, includes all the life stages.

In terms of practical LCA assessment, it is a contentious issue whether the operational water use has to be included in the early design stage. Since the operational energy mainly depends on the building design, the water use depends only on user behavior. It is not related to the design at any degree, thus many researchers and screening or simplified LCA approaches omit that stage. Fufa et al. (2018) stated that the data from A4-A5, B, and C modules should be completely removed from the assessment of environmental impact, as they are based on scenarios given by the producers, but not by construction specialists. According to the interview with EXIGO A/S consultancy and the scientific resources, it is preferable to focus on the A1-A3 stages of the building design, which refer to the material production, since the uncertainty of the data in the use stage and demolition stage relatively high. Literature also echoes that selection of the final indicators is based on the scope of the LCA, the design location’s environmental problems, the intended audience of the research, and the practitioner’s preferences. However, literature shows that there is a common understanding of the importance of correct results’ presentation, which is a way to stimulate environmental awareness of society. In this case, proper selection of impact categories allows for flawless conduction of knowledge to the audience. To present different environmental impact categories results in a simplified unit first, they need to be normalized and weighted - which in accordance with the ISO standards, both steps are optional for LCA (ISO, 2006). However, since most of the building LCAs are used only in the building industry and their results are not publicly published, it is recommended to base the LCA on the environmental impact indicators included in BS EN 15978 standard (British Standards Institute, 2012).

The results should be presented in easy to evaluate way, preferably employing eye-catching graphs, charts, or by visualization of the impact categories BIM model (Kamari et al. 2020). It is recommended to avoid delivering broad environmental reports, which consists of many unnecessary data, especially during the early design stage, when the hot-spots have to be quickly identified and eliminated.

3. Demonstration of the BIM-based tool
The developed BIM-based LCA tool works linearly, which means that one activity needs to be finished before the other starts. The developed add-in automatically delivers the geometry extraction with the properties needed for further evaluation. After that step, the tool automatically links the elements from the material take-off with the material database created in the Microsoft Excel spreadsheet (developed by the authors). The whole process of assigning Revit materials to the material’s database takes less than a few seconds. Subsequently, the LCA BIM-based tool calculates the total environmental impact of each material during the production phase and saves up the results, which later are displayed in the form of tables and charts. The workflow is illustrated in Figure 1. It is worth mentioning that the process requires only one activity from the user, which is an initialization of the LCA tool by clicking on its plug-in icon in the Autodesk Revit software. The add-in automatically generates material quantity take-off and saves it up as a text file. This method was obtained by using the MaterialQuantities application provided by Revit SDK samples. However, the source sample provided in the Revit SDK was limited only to walls, roof, and floors, so it did not allow for full material quantity take off. The sample was customized with
additional commands targeting extraction of values for other Revit model elements, and removal of gross quantities calculator, which in that case was unnecessary. After the creation of the quantity take-off text file, the plug-in analyzes each material extracted from the model and links it to the data from the Material Database Excel file.

The material database developed by the authors is based on the ÖKOBAUDAT platform, which currently consists of 900 datasets in compliance with EN 15804 (British Standard Institution, 2014). The developed database follows the layout provided by the ÖKOBAUDAT platform and includes all the environmental impacts categories required by EN 15978 (British Standard Institution, 2012).

If the linking of the material quantity take-off and the material database was performed successfully, the add-on could calculate the environmental loads of each material used in the design process. The calculation process is as follows:

\[
EI_{x}^{A1-A3} = \sum_{i=1}^{I} (Q_{a}^{M} \times EI_{a}^{M})
\]  

(1)

Where:

- \(EI_{x}^{A1-A3}\) = environmental impact of category \(x\) resulting from product and construction stage (A1-A3);
- \(I\) = number of existing materials;
- \(Q_{a}^{M}\) = quantity of material \(a\);
- \(EI_{a}^{M}\) = environmental impact of category \(x\) resulting from production \(a\).

When the calculation process is finished, the LCA tool executes the normalization and weighting of the results. Normalization and weighting are used to simplify the evaluation process and to present the

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**Figure 1. LCA tool flowchart**
data more understandably. The normalization factors were derived from Global Normalization Factors (GNF) for the Environmental Footprint (EF) and the IMPACT 2002+ to match the environmental impact categories used earlier in the process. We acknowledge that this solution comes with high uncertainty. The weighting factors for the environmental indicators were mostly based on the DGNB weighting system with changes to Abiotic Depletion Potential elements and Abiotic Depletion fossil fuel categories.

The LCA tool displays the results in four ways. The first two are tables, which represent every element used in the Revit model and its impact category result, and the environmental category loads for the whole design. When comparing the different designs and their environmental contribution, the data displayed in the tables can be too specific, whilst used for decision-making, thus we introduced the other two methods: single score value and the pie chart. The single score determines the total life cycle impact of the Revit model as a normalized and weighted number. It supplements the first two methods and helps the design team to establish, in a transparent way, which design is better or worse. It serves as a benchmark system, to which other building projects can be compared. Since the GWP impact category is the most significant indicator responsible for climate change and the most common in LCA practice, we decided to add only the GWP pie chart. The pie chart, in this case, visualizes the contribution of each material in the GWP impact category.

4. Case study
The applied case is a residential project (see Figure 2), which was provided by the EXIGO consultancy. The case is used by the company to test new tools, software, and building scenarios. The project consists of one building, which is intended for residential purposes and includes all the systems necessary for operating a building. The building itself has five floors and a basement with a floor area of around 5500 m². The design is divided into four segments of different heights with separate staircases. The load-bearing structure of the model is designed as cast-in-situ and prefabricated concrete elements.

![Figure 2. The case study provided by EXIGO consultancy.](image)

4.1. Demonstration of the developed BIM-based LCA tool
To initialize the developed tool, the user has to select the tool’s plug-in from the External Tools group, which is located in Revit Add-Ins ribbon. The tool automatically performs the mapping and calculation process; the user does not have to manually intervene or import a material quantity take-off to the external application. After several seconds the add-in displays additional windows in the Revit software, presenting the results of the model the add-in is applied on (see Figure 3).

The first information displayed is the single score value, which later serve a design will team as a benchmark for the comparison of different design scenarios. The second data presentation method consists of a table displaying the environmental impact category results, which represent the total environmental loads of the production stage of the design. The next table represents all the materials
used in the project and their environmental loads. The last data presentation form that presents the results of the developed tool is the pie chart of the Global Warming Potential of the material’s composition. Due to the high number of materials used in the case study, the pie chart shows only the labels of the materials with the highest contribution with respect to the whole design. This was achieved by inserting additional conditions regarding the presentation of the data, and thus the boundary of 5% was implemented.

![Global warming, kg CO2e - materials](image)

**Environmental impact category results**

<table>
<thead>
<tr>
<th>Life Cycle Stage</th>
<th>GWP, kg CO2 eq.</th>
<th>ODP, kg CFC 11 eq.</th>
<th>POCP, kg Ethene eq.</th>
<th>AP, kg SO2 eq.</th>
<th>EP, kg (PO4)3 eq.</th>
<th>ADPE, kg SB eq.</th>
<th>ABDPE, MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1-4)</td>
<td>1.53617E+001</td>
<td>3.3692E+002</td>
<td>4.3416E+003</td>
<td>5.1341E+003</td>
<td>5.3058E+002</td>
<td>1.0809E+001</td>
<td>1.2741E+003</td>
</tr>
</tbody>
</table>

![SINGLE SCORE](image)

**Figure 3. Embodied environmental impact results generated by the plug-in.**

It means that all the materials with a contribution lower than 5% do not have their own label in the chart. Moreover, it is observed that the wooden materials have a negative GWP result. The reason for this is that timber is the only material that has the lowest embodied energy level, absorbs CO2, and produces oxygen during its growth. Thus, even though the processing emits some amounts of CO2, the benefit of timber to store CO2 outperforms its production several times, creating the negative value of GWP. This, in conclusion, is beneficial for the overall GWP result of the design. Although the timber has
a positive influence on the design, it creates the trivial problem of representing its value in the pie chart. The negative values cannot be shown in the pie charts, which means that those values have to either be omitted in the data representation or have to be included in the pie chart as the absolute values. Hence, we have decided to exclude them from the pie chart.

4.2. Discussion

The results of the implementation of the BIM-based LCA tool on the case study are presented inside the Revit software as an additional window. The fully automatic process delivers a reliable solution to enhance early design stage design by delivering the most valuable data identifying design hot-spots of an existing Revit model. The automatic mapping of the model elements with the material database together with the estimation of the environmental impacts take significantly less time in comparison to other existing software and does not require any input from the end-user.

As it was expected, the concrete based materials are responsible for $1.37 \times 10^6$ kg of CO2e, which is equal to 83% of the total embodied environmental load of the design. The concrete-based materials are followed by the metal and aluminum profiles used in the suspended gypsum ceiling, GWB walls, and railings, which together are responsible for the design contribution of 7% ($1.10 \times 10^5$ kg of CO2e). Furthermore, the production of the insulation and glass materials would emit $8.01 \times 10^4$ kg of CO2e and subsequently $5.15 \times 10^4$ kg of CO2e, which together accounts for 8% of the total global warming potential. What is worth to mention that the application of the wooden elements in floors, windows, and doors can reduce the global warming potential of the model by 7% ($1.12 \times 10^5$ kg of CO2e).

When it comes to the automatization and LCA assessment during the early design stage, the developed tool proves to be significantly faster than the similar LCA tools on the market and does not require any additional input from the user. Besides, the developed tool, despite its simplicity and its speed, delivers almost identical results to other available software as the process of the material take-off and the calculation process is the same. Furthermore, the developed LCA tool is free of charges, thus students, researchers as well as small and medium architectural, engineering companies do not have to stretch their budget to identify hot-spots in the conceptual BIM model.

5. Conclusion and future study

The study demonstrated that there is a large opportunity to utilize BIM to perform LCA. By combining those two methods and introducing them as a robust tool during the early design stage, the design team has a safety margin for defining the shape of the design – at this stage, possibilities to influence the design outcome are the best, while their costs are the lowest. Furthermore, the study showed that even with the low detail level of BIM, there is a possibility to perform LCA accurately enough to identify the design hot-spots.

The difficulties regarding the building life cycle in the current LCA practices can be easily omitted by introducing the tool focusing only on the embodied environmental impacts of the building materials. Moreover, by emphasizing the material-level LCA and the fact that the major embodied environmental impact corresponds to the building’s structure, it can be assumed that materials have the same life-service length as the building. It does not only eliminate inconsistencies throughout the design but also, as other studies indicated, it reduces the chance of delivering under-reported results.

Furthermore, by developing the LCA tool in the BIM environment, the problem regarding interoperability between the LCA and BIM is completely resolved. Because of that, there is no more
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need for manual calculation of material quantities; however, there is still room for improvement regarding the information which is obtained through the BIM model (material properties, e.g. U-value, density, weight, and environmental impacts).

The case study shows that the tool facilitates decision-making in an integrated design process. Moreover, it provides a reliable solution for a quick-assessment of the early-stage model, which excludes the manual input of the end-user. By that, the tool facilitates the comparison process but also reduces the time-consumption of the whole LCA process. Furthermore, in comparison to other existing software, the automatic mapping within the Revit platform does not require any manual input from the user; it thus takes significantly less time to obtain the results and increases the chance that environmental impacts are being considered during the design stage, as there is no additional work. Last but not least, the idea behind the development of the BIM-based LCA tool is to be used by everyone free of charges, so it can serve as an educational tool applied in University projects, consultancy companies, or in the architectural offices to support the design for the environment and educate people about the importance of material selection in the design process.

The tool still needs additional verification and improvement regarding the linking of the materials and the visualization of the results. However, the developed tool, as proved in the case study, serves as a reliable substitute for expensive LCA tools on the market. Moreover, due to its simplicity, the end-user to perform the embodied environmental impact assessment does not have to possess any knowledge about the LCA methods. Furthermore, the whole procedure of calculation of the embodied environmental loads takes significantly less time in comparison to other LCA software. This feature confirms that the developed BIM-based LCA tool can play a major supportive role in decision making during the early design stage of the project.

As concluded in the present paper, the BIM-based LCA tool seems to have a significant impact on decision making within the early design stage. However, there are still limitations regarding the functionality of the tool and the interoperability between LCA and BIM as follows:

Firstly, the proposed tool requires additional work in defining the model elements included in the assessment. So far, the results are displayed for each material, thus it would be more beneficial to implement element-based LCA to help designers identify where the material with the highest contribution to the environment is located in the model. Moreover, as was noticed in the case study, every material is accounted for as a new position. Hence, the solution to this is to improve the tool to identify the repetitive material and sum up its results. Regarding the data presentation, it would be profitable to include more data presentation forms, e.g. bar charts, bubble charts, etc. It would enhance the comparability of the results and improve the visual aspect of the final report.

Secondly, there is a need to create a function that would automatically export results to a Word file or Excel spreadsheet. By now, there is no such possibility, thus the user needs to take a screenshot of the results using an external snipping tool.

Last, in order to improve the mapping of the Revit materials with the Excel database, the AI could be introduced. It would increase the reliability of the linked materials, and the software by itself would learn which materials, based on the composition of the structure, should be included in the assessment.

References