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Consistent BIM-led LCA during the entire building design process

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Abstract. Life Cycle Assessment (LCA) is a suitable method to analyse the environmental impact of buildings' design choices. However, the nature of the building design process leads to a dilemma when applying LCA in early phases. LCA can be fully performed only in the later design phases when complete information is available, but it is too costly to make changes. As a result, LCA is scarcely employed as a decision-making tool. Building Information Modelling (BIM) can assist LCA during the design process. So far, two different approaches are usually adopted to perform the BIM-based LCA of buildings. The first approach concerns performing LCA with a detailed BIM at the end of the building design process. The second approach involves simplified methodologies for early design stages with uncertain data. This study proposes a novel approach for applying a consistent BIM-led LCA from the early design stages to the detailed ones based on lower to higher level of accuracy. Since the BIM elements are specified with increasing level of detail in each design phase, the method uses different LCA databases for the Level of Developments (LODs) of the building elements. Accordingly, LCA calculations are based on mixing the databases in every design phase. This is possible as long as the databases use identical background data. The framework helps to provide consistent information for decision-making throughout the whole design process, both in the later design phases and early ones with a simplified BIM.

1. Introduction

The building sector consumes a large amount of natural resources [1], contributing to their depletion and to the emission of a significant amount of greenhouse gases (GHG) [2]. The growing interest in environmental issues has led to several studies based on Life Cycle Assessment (LCA) since it is recognized as a powerful tool to predict the overall environmental impacts of buildings [3,4].

Over the last years, several studies have combined Building Information Modelling (BIM) with the LCA methodology to investigate the environmental performance of a building element or of a whole building. On the one hand, BIM supports integrated design and improves data management and collaboration between the different stakeholders. BIM also provides an effective way to investigate the options for the reduction of GHG emissions with regards to the materials processing, delivery, and construction methods [5]. On the other hand, LCA is a suitable method for assessing the environmental performance of buildings during their whole life cycle.



However, methodological challenges on the BIM-based LCA can be found in the literature. For example, existing studies focus on a specific stage when conducting BIM-based LCA calculations without referring to the entire design processes. Moreover, most papers on BIM-based LCA methods do not declare the Level of Development (LOD) which the BIM model refers when conducting the LCA [6]. The LOD concept is crucial for BIM-led LCA. It defines the minimum content requirements for each BIM element at different progressively detailed levels of completeness.

The aim of this paper is to provide a framework which empowers LCA to be used as a consistent decision-making tool during all phases of the design process. The novel approach considers the available information in the BIM with as much accuracy as possible in each stage. This way it is possible performing continuous LCA over the entire building design process by using the data provided by BIM. Different LCA databases are employed with regards to the LODs of the BIM elements. Since different types of BIM elements are modelled with different LODs in each design phase, the LCA is performed by consistently mixing the LCA databases. This is made possible as long as the databases use identical background data. This approach has not been considered by any of the published studies before and helps to provide information for decision-making throughout the whole design process, both in the early design phases and later phases with a more detailed BIM.

2. Literature review

The use of the BIM-based sustainability assessment tools is increasing together with the studies focused on methods for the environmental impact assessment. The development of methods that integrate BIM and LCA is dramatically growing.

In general, two different approaches exist to perform the LCA of buildings based on BIM. The first trend concerns performing detailed LCA with specific building performance simulation tools. However, it requires linking LCA with a detailed BIM and can only be applied in the advanced design stages because of the lack of data in the early design stages. Additionally, only experts can use the method and designers find difficult to apply it at the early design stages due to the number of variables and tools involved. The second trend refers to simplified approaches only for early design stages. This simplified approach cannot match the complex data available in detailed BIM in advanced design stages.

The existing literature for both trends is summarized in Table 1. As can be seen, all reviewed papers only refer to a single trend, without considering the entire design process. Furthermore, only few studies set the LOD of BIM elements. Ajayi et al. [7] and Röck et al. [8], for example, set the LOD 200 to support their early analysis. Also LOD 300 was declared in two cases by Lee et al. [9] and Yang et al. [10] to support detailed analysis.

The main problem is that these trends are not linked and they require different tools, databases and assumptions. To overcome these limitations, this paper proposes a framework to link both trends by performing continuous LCA calculation through the entire design process.

3. Method

The framework is based on the authors' previous work and it is developed for the Swiss context, but it could be applied for other countries as well [11]. The approach is based on the application of different LODs for the LCA calculation depending on the design process phase. The method is depicted in Figure 1.

The first step is the definition of the LOD evolution. For this paper, the design process is divided into five phases that correspond to the phases 31 to 52 as defined in the Swiss Order for services and fees of architects SIA 102:2014, namely Project Planning (PP), Project (P), Building Permit Application (BPA), Tendering (T), and Construction (C). Then, the LODs are defined in four steps, from low information content (LOD 100) to the highest one (LOD 400).

Table 1. List of BIM-based LCA studies.

Ref.	Trends 2nd 1st	LOD	Tools	Impact	FU	DB	LCA phase
[12]	•	–	Revit, Navisworks, Excel, API	ECOE; EE	Complete building	ICE	–
[7]	•	200	Revit, GBS, ATHENA Impact Estimator, Excel	GWP; HH	Complete building	ATHENA Impact Estimator	A1-A3, A4-A5, B1-B7, C1-C4
[13]	•	–	Dprofiler, CostLab, eQUEST, SimaPro, ATHENA EcoCalculator, Excel	EIF	Complete building	Athena Eco Calculator	A1-A3, B1-B7
[14]	•	–	Revit, Dynamo, Excel	ReCiPe indicators	Walls and roof	Ecoinvent	–
[11]	•	100 to 400	3D model, Excel	GWP	Complete building	Swiss building db, KBOB, Bauteilkat	A1-A3, B4, C3, C4
[15]	•	–	Revit, Excel	ECE	1 m ² of GFA	EPD	A1-A3
[16]	•	–	Revit, Excel, SIMIEN, SimaPro 7.3	ECOE; OCOE	1 m ² of HFA	Ecoinvent Version 2.2	A1-A3, B1, B4, B6
[17]	•	–	Grasshopper, Rhinoceros	PET; PERT; PENRT; GWP; EP; AP; ODP; POCP; ADPE	Complete building	ökobau.dat, EPDs	A1-A3, B4, B6, C3, C4
[18]	•	–	Revit, Excel, SIMIEN, SimaPro 7.3	ECOE; OCOE	1 m ² of HFA	Ecoinvent Version 2.2	A1-A3, B4, B6
[19]	•	–	BIM tool (N/S), Excel	ECOE; OCOE	Complete building	ICE	A1-A3, B6
[20]	•	–	Revit, Ecotect, IESVE, Excel, Athena Impact Estimator	AP; EP; GWP; HH; ODP; PEC; PCSP; REP; WRRU	Complete building	ATHENA Impact Estimator	A1-A3, B6
[21]	•	–	Revit, Athena Impact Estimator, Excel	ADP; AP; EP; GWP; ODP; POCP	Complete building	Korean LCI	A1-A3, B1-B7, C1-C4
[9]	•	300	Revit, Korea LCI database	ADP; AP; EP; GWP; ODP; POCP	Complete building	Korean LCI	A1-A3, A4-A5, B1-B7, C1-C4
[22]	•	–	Grasshopper, Design Builder, DIVA, Ladybug, Galapagos, Octopus, Rhinoceros	GWP	1 m ² of HFA	EPD Norway, Ecoinvent	A1-A5, B4, B6
[23]	•	–	Revit, Revit DB link, MS Access, Athena Impact Estimator, Excel, Visual Studio	CO ₂ ; SO ₂ ; PM; EP; ODP; PSP	Complete building	ATHENA Impact Estimator	A1-A3, A4-A5, B1-B7, C1-C4
[24]	•	–	Revit, Tally, GBS	AP; EP; GWP; ODP; SMP; PET; PERT; PENRT	Complete building	GaBi database	A1-A3, B1-B7, C1-C4
[25]	•	–	Revit, Revit API, External db	EE	Complete building	ICE, Chinese handbook	A1-A3, A4-A5
[26]	•	–	Revit, Insight	GWP; AP; EP; ODP; ADPele; ADPfoss; TETP FAETP; HTTP; MAETP; POCP;	Complete building	EcoHestia	A1-A3, A4-A5
[27]	•	–	Revit, Ecotect, Excel	COE	Complete building	ICE	A1-A3, A4-A5, B1-B7, C1-C4
[8]	•	200	Revit, Dynamo, Excel	GWP	1 m ² of GFA	Ecoinvent	A1-A3, B4, C3-C4
[28]	•	–	Revit, Power Pivot, FME, Google Maps API	EE	External wall	EPD database	A1-A3, A4
[29]	•	–	Revit, Dynamo, MySQL, Grasshopper, Slingshot, Archsim, Octopus, EnergyPlus	EE, OE	Complete building	ICE	A1-A3, B1, B4, B6, B7
[30]	•	–	Revit, Excel	ECOE	Complete building	ICE	A1-A3, A4
[31]	•	–	ArchiCAD, Excel	COE	Complete building	Korean LCI	A1-A3, B1-B6
[10]	•	300	Revit, Excel, Glondon BIM5D, eBALANCE, Designbuilder,	GWP	Complete building	Chinese db, Ecoinvent, ELCD	A1-A3, A4-A5, B1-B7, C1-C4

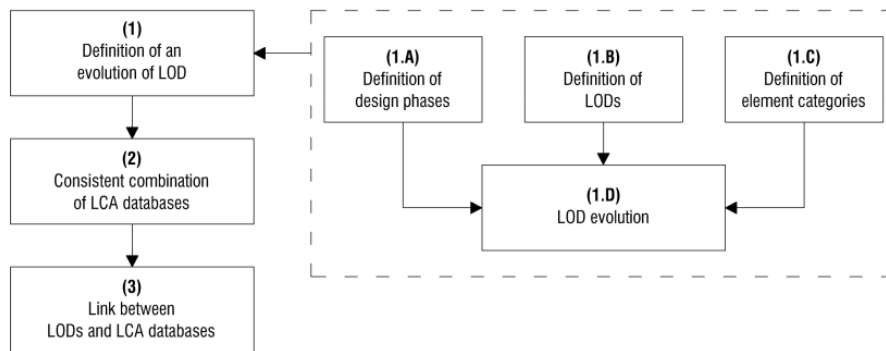


Figure 1. Schematic workflow of the proposed method.

The LODs of different BIM elements do not always simultaneously evolve across the design process, but refer to the aim of the different design phases. While general decisions such as the size and the shape of the building are usually already fixed in the PP phase, decisions on material choice are taken along all the different phases. For example, the load-bearing elements are typically defined with a higher detail in the early design phases while the finishing may only be defined late during the construction phase. Therefore, the different construction categories have a different LOD evolution. For that reason, the Swiss building element classification scheme for cost estimation e-BKP-H SN 506 511 is used to identify the building parts. It is depicted in Figure 2. The scheme considers the building as composed of eleven *building elements*. Each *building element* consists of several *building components*, which have different functions, and belong to different *construction categories*. For this paper, four construction categories are defined according to this scheme, namely *Structure* (all load-bearing parts), *Envelope* (façade and roof covering), *Interior* (non-load-bearing walls and floor finishing), and *Technical equipment*.

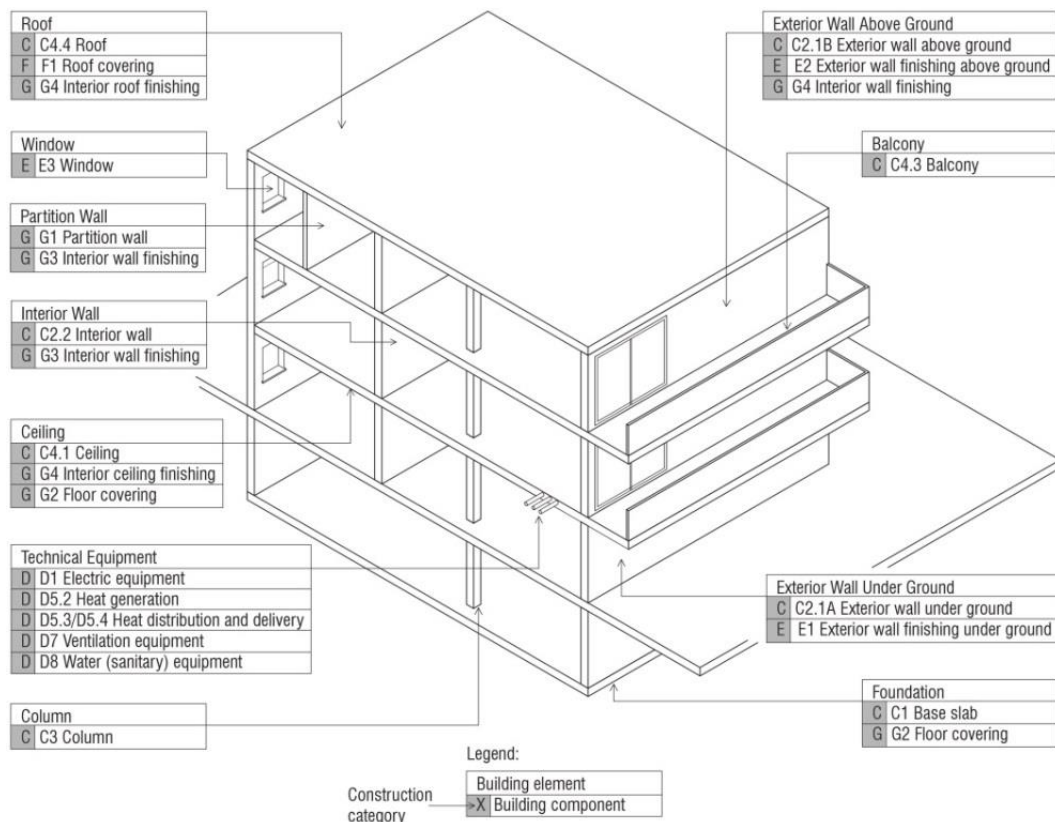


Figure 2. General description of the building, building elements, building components, and construction categories.

Here, it is assumed that all building components belonging to the same construction category are developed at the same LOD at a specific design phase. The LOD evolution is shown in Figure 3.

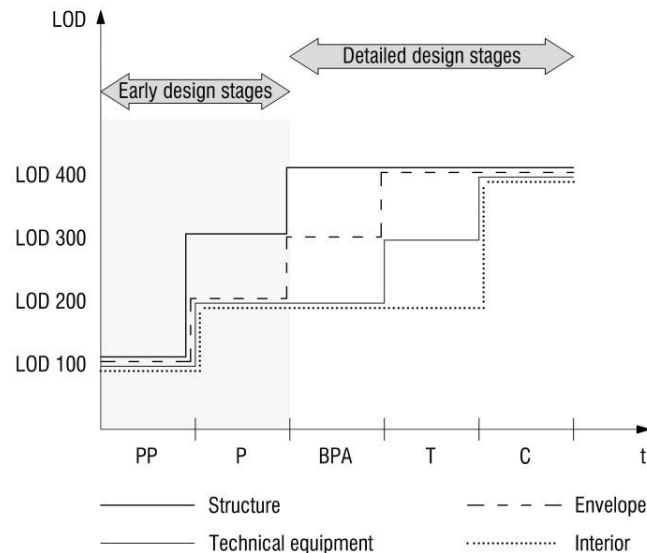


Figure 3. Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction.

The second and the third steps of the framework aim at proposing a consistent combination between different LCA databases and linking them to the LODs. Here, various LCA databases are employed. In Switzerland, LCA data for building materials are provided in a list called *KBOB Ökobilanzdaten im Baubereich*, but to facilitate the application of this data, the building component catalogue *Bauteilkatalog* has been developed by providing the environmental impact of pre-defined typical Swiss constructive solutions according to the Swiss building classification system. Both databases are based on the same background data (Ecoinvent 2.2) and they can be consistently mixed.

The LCA databases are linked according to the LODs as shown in Table 2. Before the design process starts there is no BIM. At that stage, only the square meters of floor area could be known. Therefore, it can be called pre-LOD. Hence, the environmental impact is calculated using the average impact per m² of floor area.

When LCA databases are used averaging the values (e.g. Pre-LOD, LOD 100 and LOD 200), the minimum and maximum values can be calculated to show the LCA variability. In fact, in the early design stages the exact final technological solutions of the building elements are unknown.

Table 2. LCA databases used for different LODs.

LOD	Database	Use of Database
Pre-LOD	Swiss Buildings Database	Average value at building level
100	Bauteilkatalog	Average value at building element level
200	Bauteilkatalog	Average value at building component level
300	Bauteilkatalog	Specific value at building component level
400	KBOB	Specific value at material level

4. Results

The method is applied to a real building called *WoodCube*. All material properties are obtained from a published LCA report [32]. Quantities information of different materials and components are extracted from the 3D model to an excel spreadsheet. These are then used to perform the LCA according to the

method. The building elements and related building components are provided by Cavalliere et al. [11]. The functional unit of the performed LCA is the whole building with a reference study period of 60 years according to SIA 2032:2012 [33]. Regarding the system boundaries, the LCA is performed focusing on the cycle modules A1-A3, B4, C3 and C4 [34].

The life cycle impact assessment provides results using the GWP in kg CO₂-equivalent as the environmental indicator. The values are provided per year.

When performing the analysis at the building level, the LCA results show a general coherence throughout the design process. From the PP phase to the C phase, the GWP in each design phase is within the variability of all the previous phases. The use of the Swiss buildings database at the Pre-LOD leads to a consistent result until the BPA phase. The results in the T and C phases do not fall within the variability of the Pre-Design phase. This is due to the limitation of the Swiss buildings database because it is based only on fifteen residential buildings resulting in a limited variability range.

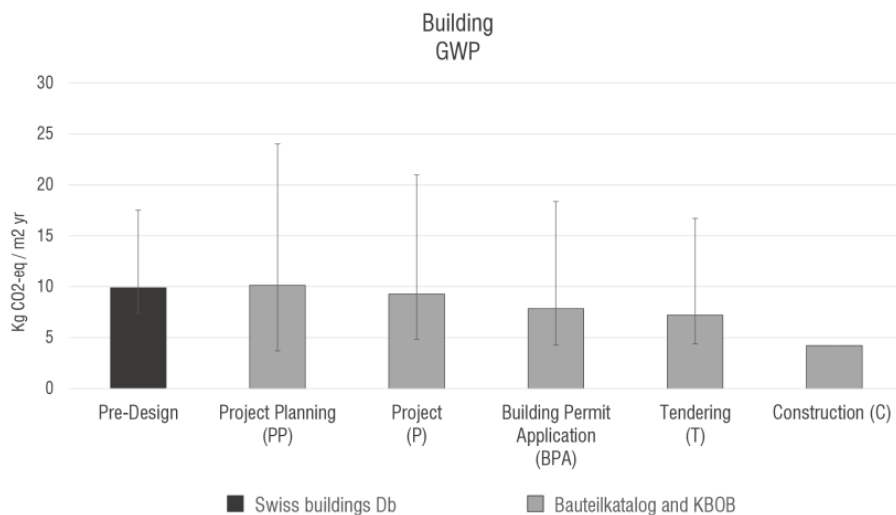


Figure 4. GWP of the building during the design process

Here, the LOD evolution of building elements is based on the typical Swiss architecture practice. Actually, LOD evolution for the building components can be different, because design teams could adopt different LOD evolutions according to their own design best practices. Therefore, different scenarios concerning the LOD evolution have been considered (see Table 3). This allows testing the sensitivity of the method towards the LOD evolution.

Table 3. Evolution of LOD during the design phases depending on the scenario

Building components	Design phases				
	PP	P	BPA	T	C
Structure	LOD 100	LOD 300	LOD 400	LOD 400	LOD 400
Envelope	LOD 100	LOD 200/300	LOD 300	LOD 400	LOD 400
Technical equipment	LOD 100	LOD 200	LOD 200/300	LOD 300/400	LOD 400
Interior	LOD 100	LOD 200	LOD 200	LOD 200/300	LOD 400

The results considering the different scenarios show a general coherence throughout the design process phases and a low sensitivity to the assumed LOD evolution. As can be seen in Figure 5, bottom and top values do not change much as well as the value after the tendering phase, but they can change the decision choice in the PP phase.

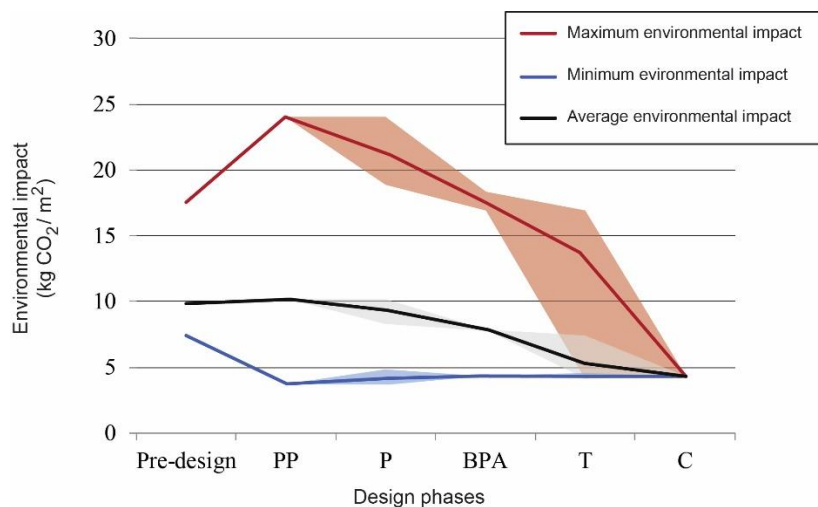


Figure 5. Variability of top/bottom values and LCA results for all scenarios considered.

5. Discussion

The application of the proposed method demonstrates one way to solve the dilemma of applying LCA in the design process. Within the information processes at the different design stages, it is crucial to define which information is needed and how detailed it must be. BIM objects are modelled with different LODs depending on the BIM uses and the project milestone, which usually grow reflecting the project progression. Hence, as the project grows, BIM elements are modelled with more information in order to support more detailed analyses.

The proposed method and its application to a real case-study building show that it is possible to continuously perform the BIM-based LCA throughout the whole design process by mixing various LCA databases, which is possible as long as they use identical background data. The previous work carried out by the authors shows that the LCA results are consistent in general in terms of variability of the different building elements [11]. Minor inconsistencies for individual elements are not visible in the overall results. In fact, the environmental impacts of the case-study building in a specific design stage fall within the variability range of the previous one. Furthermore, it could be shown that results have a low sensitivity towards the assumed LOD evolution, allowing the method to be adapted to the individual workflow of the design team.

The method should evolve in the future. The study is mainly based on the embodied impact calculation since it will become more relevant when referring to very energy efficient residential buildings as demonstrated by recent studies [35]. To further improve the proposed framework, the operational impact should be included and additional case studies should be investigated since the general approach of the methods is identical. The study was applied to the Swiss context by using Swiss databases and standards, although different LODs scenarios were evaluated. Further investigation could be integrated in the future with the reference to different national contexts.

6. Conclusion

BIM-led LCA is recognized to be a powerful approach to reach sustainable building projects. However, it is currently difficult to apply the LCA during the entire building design process because the necessary data are only completely available in the latest phases. The proposed approach divides the building into functional elements, which consists of several building components. Then, the building components have different functions, and belong to different construction categories because they are typically modelled at different LODs in different planning stages. The LCA is consistently performed by mixing the LCA databases according to the LOD of the building elements at different design stages. By involving the use of different databases that match the LOD of the BIM elements, LCA can be conducted with the maximum level of information available at the current design stage,

providing a continuous workflow over the building design process. Hence, the LCA results are as accurate as possible at all times.

As demonstrated by the case study, it is possible to forecast the final environmental impact from the early design stages. According to the method, the results show that the variability of the environmental impact decreases from the early design phases to the final one because estimations are performed from lower to higher accuracy based on increased LOD. The environmental impact in a certain design stage is within the variability of the previous one, confirming the reliability of the proposed method. As a result, the method enables the use of LCA as a decision-making tool to reach more sustainable solutions from the early to the detailed design phases.

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