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Continuous BIM-based assessment of embodied environmental impacts throughout the design process

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Abstract

Life Cycle Assessment (LCA) is a suitable method to analyse and improve the environmental impact of buildings. However, it is complex to apply in the design phase. Building Information Modelling (BIM) can help to perform LCA during the design process. Current BIM-LCA approaches follow two trends. Either they use complex models in detailed design phases, when it is late for major changes, or they are based on simplified approaches only applicable in early design stages. This paper proposes a novel method for applying LCA continuously over the entire building design process to assess the embodied environmental impacts by using the data provided by BIM with as much accuracy as possible in each stage. The method uses different LCA databases with different levels of detail for the specific level of development (LOD) of the BIM. Since different building elements are not modelled with identical LODs in each design phase, the assessment of embodied environmental impacts is conducted by consistently mixing the LCA databases, which is possible as long as the databases use identical background data. The method is applied to five design stages of a building case study. The results show that it is now possible to calculate the embodied impacts in all design stages while being consistent with the results from the completed project. The environmental impact in a certain design phase is always within the range of variability of the previous phase. Therefore, the method allows to estimate the final embodied environmental impact with increasing accuracy and by thatprovide information for decision-making throughout the whole design process.

Keywords: Life Cycle Assessment (LCA), Building Information Modelling (BIM), Embodied environmental impacts, Level of Development (LOD), Design Process, Sustainability

1. Introduction

The architecture, engineering and construction (AEC) sector is one of the major carbon emitters and energy consumers. Since 1970, energy-related greenhouse gas (GHG) emissions from the operation of buildings have more than doubled, accounting for 19% of the total emissions in 2010 [1]. Next to the operational environmental impact, the embodied GHG emissions related to the production, replacement and end-of-life of building components are responsible for a larger share of global GHG emissions. The manufacturing of building materials alone represents 5-10% of the global GHG emissions [2]. This highlights the importance of considering the entire life cycle of buildings.

The interest of Life cycle assessment (LCA) for the construction sector has been noted in several review papers [3–11]. LCA is widely recognized as a powerful tool to predict the environmental impacts of buildings during their life cycle [12,13]. LCA covers the entire life cycle of buildings from raw materials extraction and processing, manufacturing of building components, to use and end-of-life. The method as described in ISO 14040 [14] consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [14,15]. Usually, LCA studies of products are structured according to these four phases. For LCA of buildings, predefined datasets for the materials or components used in the building are used in most cases. As such, the LCI and LCIA are merged into one step and simplified [16]. Basically, only a bill of quantities (BoQ) is needed that is multiplied with values of the respective datasets from the LCA database. Then, the results can be summed up under consideration of the reference service life of the individual components. Nevertheless, the LCA of buildings is a complex task because of the large amount of information required and time-consuming nature of the method [17]. Most time and effort is needed to establish the BoQ and find the correct datasets in the building material LCA database. As a result, the LCA of buildings is commonly conducted at the end of the design process, when the necessary information is available, but it is too late to affect the decision-making process [18]. This dilemma for LCA of buildings is closely related to the nature of the design process. On the one hand, early design choices are responsible for a significant amount of the total environmental impacts [19–21], but LCA cannot be fully applied because of the incompleteness of the data. On the other hand, LCA can no longer successfully be used as a decision-making tool in late design stages because making changes is too costly [22].

Building Information Modelling (BIM) can facilitate establishing a BoQ and support project teams by providing immediate insight into how design decisions affect the building performance [23]. Hence, BIM is increasingly used to explore design solutions to improve the life cycle performance [24,25]. BIM-LCA integration is a powerful approach to perform LCA for buildings during the design process and the growing number of applications on BIM-based LCA is underlined in recent papers [24,26,27]. However, the existing studies present methods for conducting BIM-based LCA in a specific design phase. They usually either focus on an early concept phase or a very detailed design stage when all material information is known. The methods cannot be used as a design process-integrated decision tool, because they do not consider the entire building design process and the evolution of available information throughout the process. Moreover, most papers on BIM-based LCA methods do not declare the Level of Development (LOD) for the LCA [27]. The LOD defines the minimum content requirements for each element of the BIM at five progressively detailed level of completeness, from LOD 100 to LOD 500; see [28,29]. Thus, the LOD of each element represents the information content of the object, based on which LCA can be performed. The LOD of the elements undergo an evolution from low to high according to the needs of each design phases. However, not all elements undergo this evolution at the same time, as they are not defined simultaneously. Typically, structural elements are defined early in the design process, while materials for interior surfaces might even be changed after the construction of the building has started.

The goal of this paper is to provide a framework allowing to use LCA as a consistent decision-making support tool regarding the embodied environmental impacts of a building during all phases of the design process. The novel approach considers the available information in the BIM model as accurate as possible in every design phase. This is achieved by mixing LCA databases for building elements and materials with different levels of detail and matching them according to the individual LOD of the various BIM components. This approach has not been considered by any method described in the reviewed literature and allows to overcome the current problem of disconnection between building LCA tools for early and late design phases.

The paper is structured as follows. Section 2 presents a literature review, which is organized around the two different trends to conduct BIM-based LCA – either using simplified models in early design phases or very detailed approaches in late design phases. In section 3, the development of the framework for assessing embodied environmental impact continuously is described for the Swiss context. The building is structured into eleven elements according to the Swiss cost calculation standard. The design process is divided into five main phases according to the Swiss practice. Here, the tendering and construction phase are also regarded as design phases, because decisions on materials are still taken in these phases and influence the environmental performance of the building. Furthermore, the LOD evolution of the building elements is assumed based on the typical Swiss architecture practice. The framework is tested by means of a case study of a multi-family house described in section 4. The results of applying the framework are described in section 5, before the main contributions and limitations are discussed in section 6. The paper concludes in section 7.

2. Literature review

Several studies have been conducted to enhance the dialogue between BIM and LCA for sustainable construction [25,30]. BIM is oriented to the modelling and communication of both graphic and non-graphic information to enable the extraction of quantities, cost estimations and material properties for buildings, facilities and infrastructures [31]. BIM allows different stakeholders to manage digital data of the building throughout its entire life cycle [32]. Recent studies have shown that BIM supports energy demand simulations and environmental impact assessments over the building's life cycle, which provides an effective method to consider scenarios to mitigate the emissions related to material processing and construction methods [33,34]. Two different trends can be observed to perform LCA of buildings based on BIM. The first trend concerns performing detailed LCA with refined processes and specific building performance simulation tools. The second trend involves simplified approaches for early design stages. The existing literature for both trends is reviewed and summarized in a list of BIM-based LCA studies in Table 1.

The use of BIM-based sustainable design tools has proven to be effective for the late stage of design and detailed BIM models [35,36]. Several studies employed BIM for automatic calculation of materials and components quantities and exported them to an Excel spreadsheet where operational and embodied emission are evaluated [37–39]. Peng [40] developed a BIM-based approach to obtain the building life cycle carbon emissions using Autodesk Revit to extract the bill of materials and Autodesk Ecotect to simulate the heating and cooling loads at the operational stage. Lee et al. [35] developed a green template using Revit as the BIM authoring software. The study provides a template that can be used for embodied environmental impact evaluation of a building. Other studies integrated various software to support an automated or semi-automated process. For example, Shadram and Mukkavaara [41] proposed a BIM-based framework to find the optimal design solution by solving the trade-off problems between the embodied and operational energy demands through the integration of a multi-objective optimization approach. The framework involves four main modules: (1) BIM module using the Autodesk Revit software for the virtual representation of the building and Dynamo for the input-output data interface; (2) data repository module; (3) energy performance simulation; and (4) multi-objective optimization modules developed in Grasshopper. Shadram et al. [42] set up an integrated BIM-based framework to assess the embodied energy in the design development phase of the building's life cycle. The workflow integrates the Extract Transform Load (ETL) process to ensure the BIM-LCA interoperability. Marzouk et al. [43] proposed a BIM-based method that enables the estimation of six environmental indicators. The authors used Autodesk Revit to facilitate data retrieval from Microsoft Access and employed an application in C#.net to calculate the overall emissions using Athena Impact Estimator. Also, Abanda et al. [44] developed an algorithm that can be implemented in the BIM software to automatically calculate the embodied energy and GHG emissions of a building. Yang et al. [45] combined various software tools and data sources to enhance the data flow between BIM and LCA models. Autodesk Revit and Glondon BIM5D tools are used to create the BIM model, compute the inputs of on-site construction process, and simulate the energy consumption of building operation. Then, a detailed LCA model is built using a China's local LCA software tool.

In recent years, many scientific studies have acknowledged the great potential of analysis in early design stages to reduce the environmental impact of buildings. Nizam et al. [46] state that a BIM approach has the potential to generate a decision-support system in the early design phase, including the selection of building materials, spatial configuration, construction methods and building service systems. Recent studies present methods to calculate environmental impacts of different material options, dimensioning choices and design alternatives at the building conceptual stage [22,47–50]. For example, Basbagill et al. [48] propose a computational method combining BIM, LCA, energy simulation, and sensitivity analysis software to quickly evaluate the embodied impacts of thousands of building designs. Other studies focus on methods to enhance interoperability between BIM and LCA tools for early analysis. Kulahcioglu et al. [51] proposed a framework based on a prototype software for the environmental performance analysis of a 3D model. A BIM-LCA integration is enabled using the Industry Foundation Classes (IFC) as an open standard data model to develop a tool to support early design decisions making process. Bueno et al. [52] developed a routine for the BIM-LCA integration by combining, visual programming and a spreadsheet application to automatically obtain environmental profiles in the early design stages. Jrade and Jalaei [53] presented a methodology for the BIM-LCA integration with a database to simplify the process to evaluate the environmental impacts of buildings in the conceptual stage. The proposed approach involves the use of a material database stored in a BIM module linked to an LCA module, certification and cost module. Jalaei and Jrade [54] developed a plug-in to analyse the environmental impacts and embodied energy of the building components linking BIM, LCA, energy performance analysis, and lighting simulation with green building certification systems. Najjar et al. [55] employed Autodesk Revit to design a case study building and used Green Building Studio and Tally to estimate the impact and give recommendations. Shafiq et al. [56] employed Autodesk Revit and MS Excel to assess the embodied carbon footprint of a two-storey building. The authors recommend that, other factors such as the cost of materials should be considered to create a design that is both environmentally responsible and economically sustainable. An application to select appropriate design alternatives using BIM for developing LCA and life cycle costing (LCC) was proposed by Shin and Cho [57]. The authors developed an automatic framework to connect LCA with LCC methods in the early phase of a construction project by manually entering data when it has been extracted using BIM software.

***Table 1**. List of BIM-based LCA studies*

Reference	Year	Building type	Tools used	LOD	I	II
Abanda et al. [44]	2017	Single-ground floor house	Revit, Navisworks, Excel, Revit API	-	X	
Ajayi et al. [47]	2015	Two-storey primary school building	Revit, Green Building Studio, ATHENA Impact Estimator, Excel	200		X
Basbagill et al. [48]	2013	Residential building	Dprofiler, CostLab, eQUEST, SimaPro, ATHENA EcoCalculator, Excel	-		X
Bueno et al. [52]	2018	Single-family social housing	Revit, Dynamo, Excel	-		X
Eleftheriadis et al. [49]	2018	Multi-storey reinforced concrete buildings	-	-		X
Georges et al. [37]	2015	Two-storey single-family house and office building	Revit, Excel, SIMIEN, SimaPro 7.3	-	X	
Hollberg & Ruth [22]	2016	Multi-family house and single-family house	Grasshopper, Rhinoceros	-		X
Hollberg et al. [58]	2017	Residential neighbourhood	Grasshopper, Rhinoceros	-		X
Houlihan et al. [38]	2014	Single-family house	Revit, Excel, SIMIEN, SimaPro 7.3	-	X	
Iddon & Firth [39]	2013	Single-family house	BIM tool (N/S), Excel	-	X	
Jalaei & Jrade [54]	2014	Three-storey office building	Revit, Ecotect, IESVE, Excel, Athena Impact Estimator	-		X
Jrade & Jalaei [53]	2013	Six-storey apartment building	Revit, Athena Impact Estimator, Excel	-		X
Kulahcioglu et al. [51]	2012	-	Google SketchUp, IFC2SKP plug-in, Blender, GABI	-		X
Lee et al. [35]	2015	18-storey Korean apartment building	Revit, Korea LCI database	300	X	
Marzouk et al. [43]	2017	Three-floors building with isolated footings	Revit, Revit DB link (plug-in), Microsoft Access, Athena Impact Estimator, MS Excel, Microsoft visual studio 2010	-	X	
Najjar et al. [55]	2017	Multi-story office building	Revit, Tally, Green Building Studio	-		X
Nizam et al. [46]	2018	Cast-in-situ concrete frame structure	Revit, Revit API, External databases	-		X
Peng [40]	2016	Office building	Revit, Ecotect, Excel	-	X	
Röck et al. [50]	2018	Residential building	Revit, Dynamo, Excel	200		X
Shadram et al. [42]	2016	Semi-detached dwelling	Revit, Power Pivot, FME, Google Maps API	-	X	
Shadram et al. [41]	2018	Semi-detached low-energy dwelling	Revit, Dynamo, MySQL, Grasshopper, Slingshot plug-in, Archsim plug-in, Octopus plug-in	-	X	
Shafiq et al. [56]	2015	Two-storey office	Revit, Excel	-		X

		building				
Shin & Cho [57]	2015	11-storey office building	ArchiCAD, Excel	-		X
Yang et al. [45]	2018	Residential building	Revit, Glondon BIM5D tools, eBALANCE, Designbuilder, Excel	300	X	

As can be seen in Table 1, the reviewed papers only refer to a single trend, without considering the entire design process. Moreover, only few studies set a fixed LOD. Ajayi et al. [47] and Röck et al. [50] were based on a LOD 200 model to support early environmental analysis. LOD 300 was declared only in two cases to support detailed analysis [35,45].

The solutions described as first trend in this paper clearly provide benefits for performing detailed LCA. However, this approach requires a detailed BIM model and can only be applied in the advanced design stages. Furthermore, only the experts can use the method, and designers find it difficult to adopt it to improve the buildings environmental performance in early design stages. The simplified approaches described as second trend prove to be suitable for the early design stages. However, they do not make use of detailed information available in complex BIM in detailed design stages. The main problem is that these trends are not linked. To overcome these limitations, this paper proposes a framework linking both trends and by that performing continuous LCA calculation through the whole design process. The method currently only considers the embodied environmental impact of the building.

3. Method

The development of the framework is described for the Swiss context. The same approach can be followed to define frameworks for other countries as well. The approach is based on the application of different levels of detail of the embodied impact calculation depending on the available information, respectively LOD of the BIM. As such, the method consist of three main steps (Fig. 1):

1. Definition of an evolution of LOD
2. Consistent combination of LCA databases
3. Link between LODs and LCA databases

Definition of an evolution of LOD

To define the evolution of LOD throughout the design phases in the first step four parts are needed (Fig. 1): A) Definition of design phases, B) Definition of LODs, and C) Definition of element categories. These are matched according to the countries specific construction practice into D) LOD evolution.

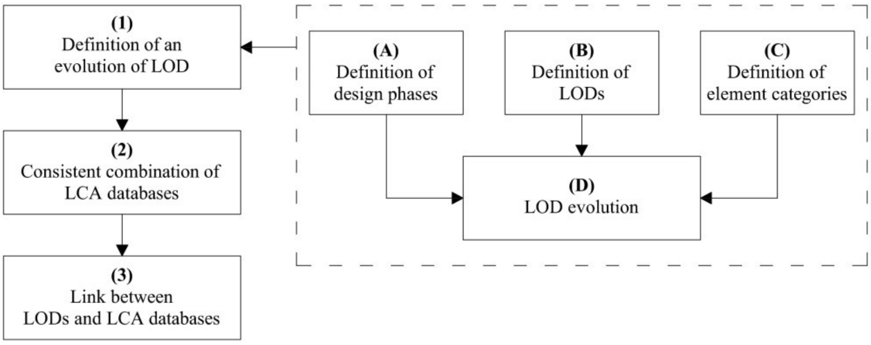


Fig. 1. *Schematic workflow of the proposed method*

A) Definition of design phases

For the present study, the design process is divided into five phases:

- Project Planning (PP)
- Project (P)

Early design phase

- Building Permit Application (BPA)
- Tendering (T)

Detailed design phase

- Construction (C)

The early design stages refer to the Project Planning (PP) and Project (P) phase. The core objectives are to undertake feasibility studies in the PP phase and to prepare the concept design in the P phase, including outlining proposals for structural design, building envelope, technical equipment, and interior. The detailed stages refer to the Building Permit Application (BPA) and Tendering (T) phase. They aim at elaborating design documentation for the building permit and procurement. While most design decisions should be taken before tendering, individual material properties are often specified afterwards in practice. The type of construction is usually known, but materials might be exchanged later. In addition, the Construction (C) stage is included as part of the design process.

B) Definition of LODs

In general, the LOD of BIM are described in five steps as LOD 100 to LOD 500. In practice, LOD 500 is rarely achieved during the design process because the modelling effort is immense and it refers to the as-built model. In some studies an intermediate LOD, for example 350, is described. Here, four steps from low information content (LOD 100) to high information content (LOD 400) are assumed. However, the LODs of different elements do not always evolve simultaneously, but depend on the aim of specific design phases. For example, the structure is typically defined with a higher detail in the early design stages because a structural calculation is needed, but the interior finishing is defined late. The type of paint may only be defined during the construction phase because the client has not decided before. Therefore, construction categories with a similar LOD evolution can be assumed.

C) Definition of construction categories

For the purpose of this study, the Swiss building element classification scheme for cost estimation e-BKP-H SN 506 511 is used to define building elements. This structure divides a building into eleven *elements*:

1. Foundation / base slab
2. Exterior wall under ground
3. Exterior wall above ground
4. Windows
5. Interior wall
6. Partition wall
7. Column
8. Ceiling
9. Balcony
10. Roof
11. Technical equipment

Each building *element* consists of several building *components*, which have different functions and belong to different *construction categories*. The classification system marks individual building components with an alphanumeric code. The alphabetic character can be matched with the construction categories. For example, the building element *exterior wall aboveground* is characterized by three different building components: *C2.1B exterior wall*, *E2 exterior wall finishing*, and *G3 interior wall finishing*, which belong to the construction categories *structure (C)*, *envelope (E+F)*, and *interior (G)*. For this paper, four construction categories are defined according to this scheme:

- Structure (all load-bearing parts)
- Envelope (façade and roof covering)
- Interior (non-load-bearing walls and interior finishing)
- Technical equipment

An overview of the building structure is provided in Fig. 2. Similar structuring approaches can be found in others countries as well, for example DIN 276 [59] in Germany.

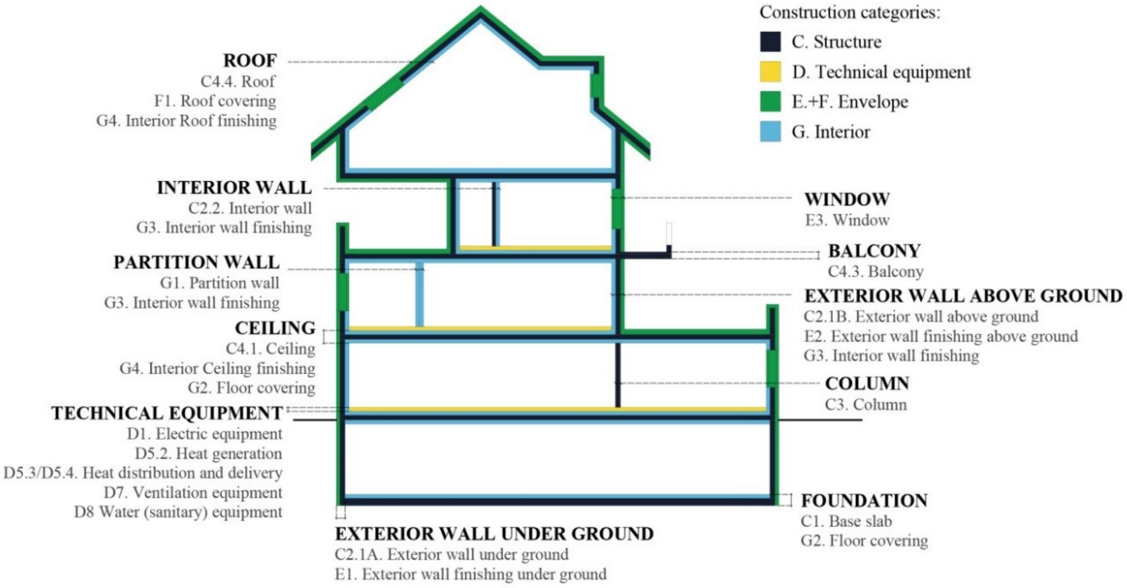


Fig. 2. *General description of the building, building element, building component and construction categories*

D) LOD evolution

For the purpose of this paper, it is assumed that all components belonging to one construction category are developed at the same LOD at a specific design phase. For example, in the Project Planning (PP) phase, all building components belonging to the construction category *structure* are modelled at LOD 100; in the Project (P) phase, they are modelled at LOD 300. In the following phases (Building Permit Application (BPA), Tendering (T), and Construction (C) phase), they are modelled at LOD 400. The evolution of LOD is shown in Fig. 3Errore: sorgente del riferimento non trovata.

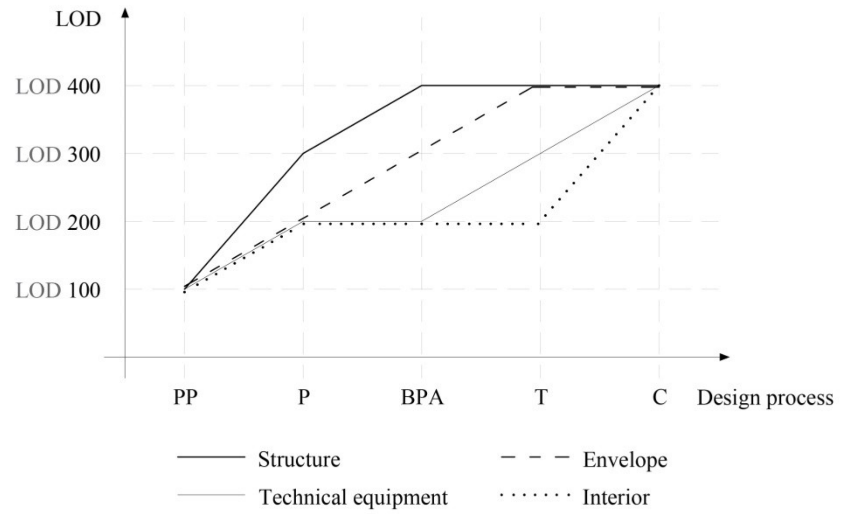


Fig. 3. *Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction.*

Consistent combination of databases

The second steps consists of combining LCA data for the embodied impact of building materials and components in a consistent way. In Switzerland, LCA data for the embodied impact of building materials are provided in a list called *KBOB Ökobilanzdaten im Baubereich* [60]. The values are provided per mass (for example metals) or per surface area (for example window panes). To facilitate the application of this data, a building component catalogue called *Bauteilkatalog* [61] has been established. The building component catalogue is structured according to the Swiss building classification system e-BKP-H SN 506 511. This database provides the embodied environmental impact of pre-defined typical Swiss constructive solutions for building components, for example an external insulation system containing the materials EPS insulation, reinforcement fabric, rendering and paint. The building component catalogue uses the materials provided in the KBOB list and both databases are based on the same background data of Ecoinvent 2.2. Therefore, they can be mixed. Both databases provide values for the indicators Global Warming Potential (GWP) and non-renewable Primary Energy (PEnr). In addition, a single-score indicator called *Umweltbelastungspunkte* is provided. This indicator is specifically calculated for Switzerland based on the method of ecological scarcity [62].

Link between LOD and databases

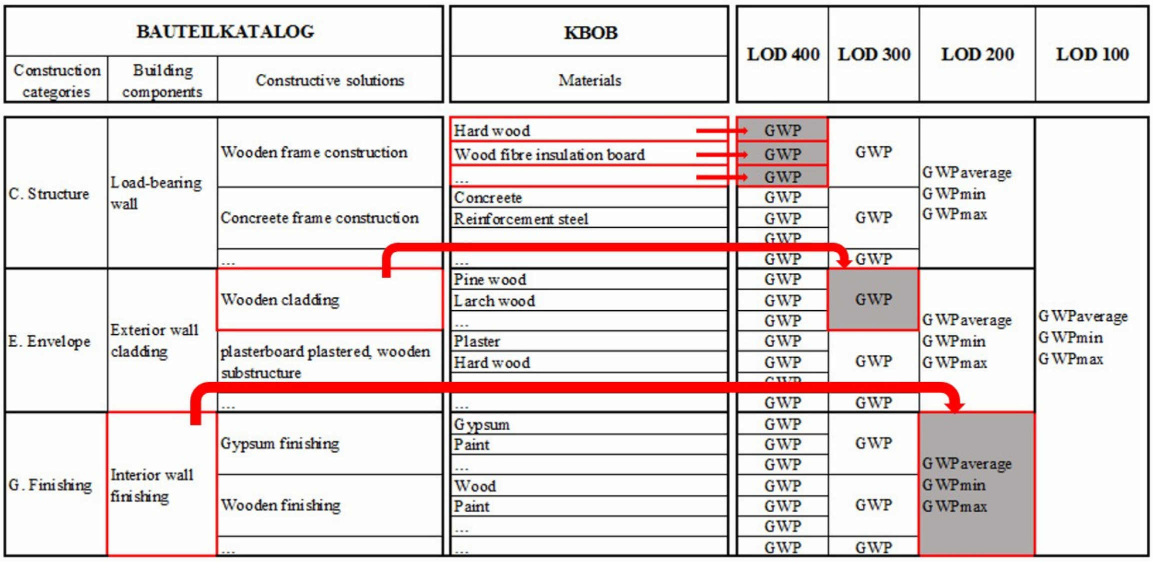
In the third step, the LCA databases are linked according to the LOD. At the most detailed LOD 400 achieved in the construction phase, the exact quantities of each material are known and the KBOB list can be used. At LOD 300, it is assumed that the type of component is known, but the exact quantities of each material layer of the component might not have been specified yet, such as the thickness a rendering. Therefore, the predefined components from the building component catalogue are used. At level 200, it is assumed that the type of construction system is defined, for example an interior or an exterior insulation, but the exact material is not yet defined. The insulation material could still be exchanged in the further design process, for example. Therefore, average values of the building component catalogue are used. Next to the average value, the minimum and maximum value are provided to show the range of possible solutions for this element. At LOD 100, the type of element is still unknown. Therefore, the building component catalogue database is used by averaging the impact values at the building element level. In other words, the LCA is performed by taking the average of each building component and summing these components at the element level to have an average building element. In addition, the minimum and maximum values are calculated to show the variability of all possible constructive solutions.

In the earliest planning stage, for example the strategic definition, before the design process is started, there is no BIM. Therefore, it is called pre-LOD. The environmental impact can be estimated using the average impact per of floor area for new buildings in Switzerland. In addition, the minimum and maximum values can be calculated based on the data from [63]. The matching of LOD with the databased is summarized in the LOD matrix in Table 2.

Table 2. *LCA database used for different LOD*

LOD Matrix		
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

According to the proposed method, each design phase refers to a BIM where building components are modelled at different LOD considering the construction categories to which they belong. Hence, since each LOD involves the use of different database, the assessments of embodied impacts are based on mixing them in every design phase. An example of the application of the proposed method related to the exterior wall above ground in the BPA phase is shown in Fig. 4.



BAUTEILKATALOG			KBOB	LOD 400	LOD 300	LOD 200	LOD 100
Construction categories	Building components	Constructive solutions	Materials				
C. Structure	Load-bearing wall	Wooden frame construction	Hard wood	GWP	GWP	GWPaverage GWPmin GWPmax	GWPaverage GWPmin GWPmax
			Wood fibre insulation board	GWP			
			...	GWP			
		Concreete frame construction	Concreete	GWP	GWP		
			Reinforcement steel	GWP			
				GWP			
		...	...	GWP	GWP		
E. Envelope	Exterior wall cladding	Wooden cladding	Pine wood	GWP	GWP	GWPaverage GWPmin GWPmax	
			Larch wood	GWP			
			...	GWP			
		plasterboard plastered, wooden substructure	Plaster	GWP	GWP		
			Hard wood	GWP			
				GWP			
		...	...	GWP	GWP		
G. Finishing	Interior wall finishing	Gypsum finishing	Gypsum	GWP	GWP	GWPaverage GWPmin GWPmax	
			Paint	GWP			
			...	GWP			
		Wooden finishing	Wood	GWP	GWP		
			Paint	GWP			
			...	GWP			
		...	...	GWP	GWP		

Fig. 4. Example of the proposed method for LCA of exterior wall above ground at the Building Permit Application phase

4. Application to a case study

The method is applied using a case study of a multi-family house. The building in the case study is based on a real building called WoodCube (Fig. 5). The five-story building measures approximately 15 m × 15 m and provides eight apartments. Some small modifications to the geometry were made to simplify it for the case study [22].

Fig. 5. Left: WoodCube; right: simplified 3D model of the building

All material properties are obtained from a published LCA report [64]. Length, area and volume of different materials and components are extracted from the 3D model in Rhinoceros to an Excel spreadsheet. Then the quantities are used to calculate the results for the embodied impacts according to the proposed method. The building elements and related building components are listed in Table 3. In addition, Table 3 provides the areas, quantities, and materials of the building components and the code relating to the material at LOD 400 using the KBOB list. The staircase and elevator are excluded from the analysis.

Table 3. *Bill of materials organized along Swiss e-BKP catalogue*

Building element	**Building component**	**m^2**	**Material**	**KBOB ID**	**Amount per m^2 of building component**	**Unit**
Foundation	C1 Base slab, foundation	228.00	Concrete C25/30	01.002	811.20	kg
			Reinforcement	06.003	54.95	kg
	G2 Floor covering	NONE				
Exterior wall underground	C2.1A Exterior wall underground	183.00	Concrete C25/30	01.002	463.54	kg
			Reinforcement	06.003	31.40	kg
	E1 Exterior wall finishing underground	NONE				
Exterior wall aboveground	C2.1B Exterior wall aboveground	723.50	Pinewood	07.010	114.48	kg
			Hardwood	07.008	9.24	kg
			Wood fibre insulation board	10.009	4.55	kg
			Pinewood	07.010	13.28	kg
			Hardwood	07.008	1.07	kg
	E2 Exterior wall finishing aboveground		Wood fibre insulation board	10.009	5.20	kg
			Pinewood	07.010	13.74	kg
			Hardwood	07.008	1.11	kg
			Larch wood	07.008	15.86	kg
	G3 Interior wall finishing	NONE				
Window	E3 Window	200.70	Wood frame	05.005	0.10	m^2
			Double-glazing	05.001	0.90	m^2
Interior wall	C2.2 Interior wall	1368.10	Concrete C25/30	01.002	556.25	kg
			Reinforcement	06.003	37.68	kg
	G3 Interior wall finishing	NONE				
Partition wall	G1 Partition wall	391.40	Gypsum fibre panel	03.007	20.00	kg
			Pinewood frame	07.010	3.86	kg
			Gypsum fibre panel	03.007	20.00	kg
	G3 Interior wall finishing		Clay plaster	04.004	4.80	kg
			Clay plaster	04.004	4.80	kg
Column	C3 Column	NONE				
Ceiling	C4.1 Ceiling	1140.00	Pinewood	07.010	107.61	kg
			Hardwood	07.008	8.68	kg
	G2 Floor covering		Parquet	11.019	1.00	m^2
			Wood fibre insulation board	10.009	2.60	kg
			Separating foil	09.006	0.80	kg
			Wood fibre insulation board	10.009	2.60	kg
			Wood fibre insulation board	10.009	3.90	kg
			Perlite	10.012	60.00	kg
			Separating foil	09.006	0.80	kg
	G4 Interior ceiling/roof finishing	NONE				
Balcony	C4.3 Balcony	90.00	Pinewood	07.010	113.27	kg
			Hardwood	07.008	5.6635	kg
			Sealing strip	09.004	0.40	kg
Roof	C4.4 Roof	228.00	Pinewood	07.010	107.61	kg
			Hardwood	07.008	8.68	kg
	F1 Roof covering		Plastic	09.007	0.09	kg
			Gravel	03.012	80.00	kg
			Moisture barrier	09.002	0.28	kg
			Phenolic resin foam	10.003	5.00	kg
	G4 Interior ceiling/roof finishing	NONE				
Technical equipment	D1 Electric equipment	912.00* *heated floor area (A_E)	Electric equipment for residential buildings	34.001	1.00	m^2
	D5.2 Heat generation		Heat generation (30 W/m^2)	31.002	1.00	m^2
	D5.3/D5.4 Heat distribution and delivery		Floor heating	31.024	1.00	m^2
	D7 Ventilation equipment		Ventilation for kitchen and bathroom	32.003	1.00	m^2

	D8 Water (sanitary) equipment		Sanitary equipment for residential buildings	33.003	1.00	m^2

The functional unit of the performed LCA is the entire building with a reference study period of 60 years according to SIA 2032:2012 [65]. Regarding the system boundaries, the LCA is performed focusing on the embodied impact including production, replacement and end-of-life of building materials and elements without considering the transportation to the construction site, operational energy use, and operational water use. Described as life cycle modules according to EN 15978 [66], these phases correspond to A1-A3, B4, C3 and C4. The replacement of building components and material are evaluated according to the reference service life (RSL) of SIA 2032:2012. The results are calculated for the environmental indicator GWP in kg CO_2-equivilant. The results are provided per year and per m^2 of heated floor area.

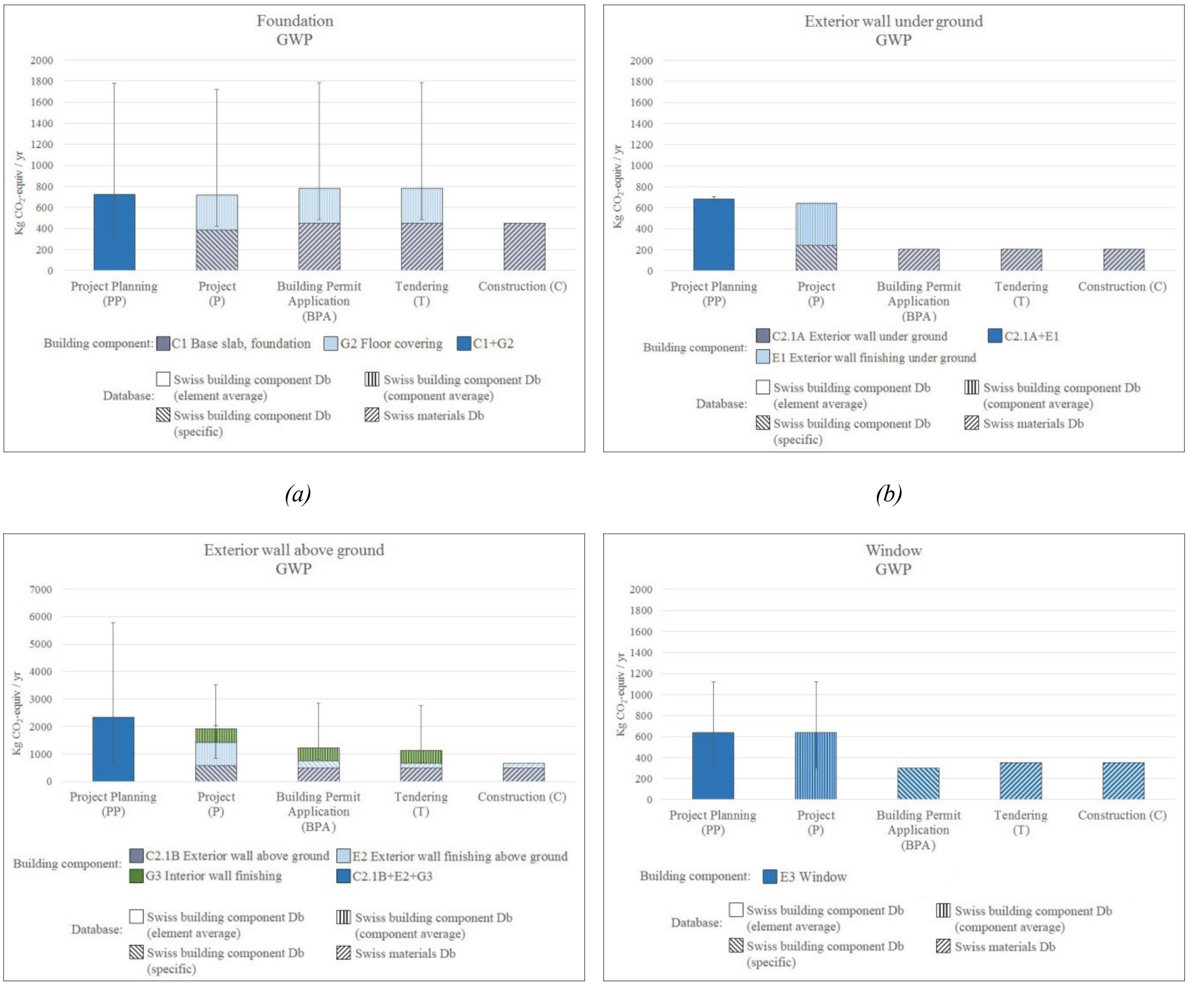
5. Results

The results for the GWP of each building element for different planning phases are shown in Fig. 6. The results for the PP phase are provided for the entire building elements because they are modelled at LOD 100. The results for the later design stages are provided for the individual components and represent a mix of databases. The results for the average, minimum and maximum of the building elements and components at LOD 100, LOD 200, and LOD 300 are provided in Table SI1 of the Supplementary Information (SI).

The building elements *Foundation* (Fig. 6a), *Exterior wall aboveground* (Fig. 6c), *Window* (Fig. 6d), *Interior wall* (Fig. 6e), *Partition wall* (Fig. 6f), *Roof* (Fig. 6i), and *Technical equipment* (Fig. 6j) show consistent results for embodied impacts during the design process. The use of increasingly refined data reduces the range of variability from the PP phase to the C phase. The GWP at one specific phase is always within the variability of the previous phase. This outcome allows to predict the final environmental impact of the C phase from the early phases of the building process.

The results of the *Exterior wall underground* (Fig. 6b) do not show the same consistency during the design process. In the BPA phase, the component *E1 Exterior wall finishing underground* should be modelled at LOD 300, but the case study building has no finishing (see Table 3). Therefore, the result of the BPA phase does not fall within the variability of the previous ones. In the early phases, the impact is overestimated compared to the final results. The same type of overestimation occurs for the *Ceiling* because building component *G4 Interior finishing* is not considered in the C phase (Fig. 6h). Furthermore, the assessment of building component *G2 Floor covering* using the KBOB list in the C phase results in a much lower GWP than that in the T phase when the building component catalogue database is used, which causes a further overestimation of the impact in the early design phases. Regarding the building element *Balcony*, the environmental impact in the PP phase is significantly higher than those in the following phases because of a lack of data of the building component catalogue. The database only provides concrete frame solutions, whereas the balcony of the case study building is made of wood. To overcome the lack of data, the balcony is modelled using the wooden solution for the component *C4.1 Ceiling*.

A detailed overview of the evolution of GWP during the design process for all building elements is provided in Fig. SI1 of the Supplementary Information (SI).



(a) *(b)*

(c) *(d)*

(e) *(f)*

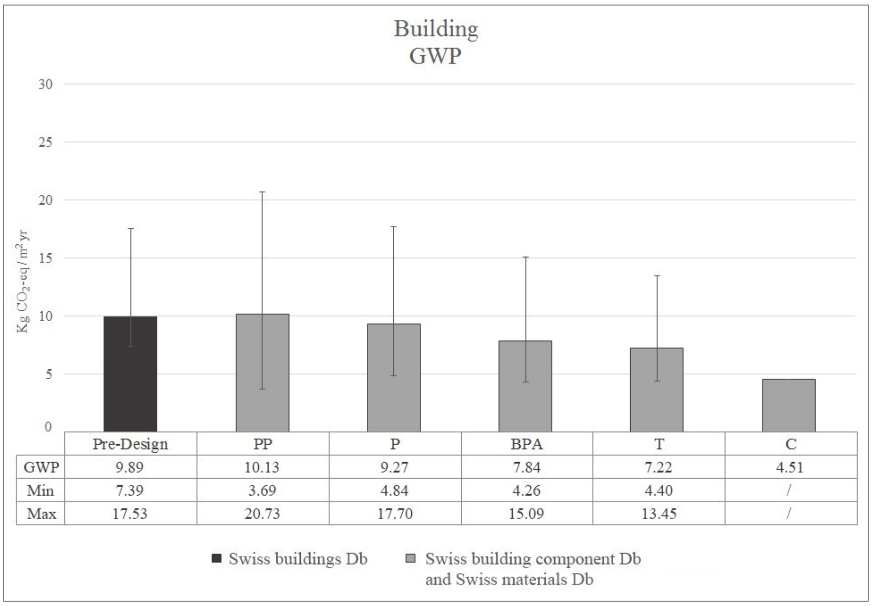
(g) *(h)*

(i) *(j)*

Fig. 6. *Contribution to the GWP of building elements during the design process. The contribution of each building element with the same scale is shown in the Supplementary Information (SI)*

By aggregating the results of all building elements and performing the analysis at the building level, the results show a general coherence throughout the design process (Fig. 7). From the PP phase to the C phase, the GWP in each design phase is within the variability of all previous phases.

In the Pre-Design phase, the results are based on the Pre-LOD. The use of the Swiss buildings database in the Pre-Design phase leads to a consistent variability until the BPA phase. The results in the T and C phases do not fall within the variability of the Pre-Design phase. The Swiss buildings database provides LCA results based on only fifteen residential buildings, which results in a limited range of variability.



	Pre-Design	PP	P	BPA	T	C
GWP	9.89	10.13	9.27	7.84	7.22	4.51
Min	7.39	3.69	4.84	4.26	4.40	/
Max	17.53	20.73	17.70	15.09	13.45	/

Fig. 7. *Evolution of calculated GWP of the building during the design process*

The operational impact is not the focus of this paper. To provide a relation of the share of embodied to operational impact it was calculated nevertheless. According to the data of the report on the building [64], the building has a final energy demand for heating and hot water of 43.5 kWh/(m^2_{AE}·a). The electricity demand (including auxiliary energy, ventilation, lighting and equipment) is 22.2 kWh/(m^2_{AE}·a). The heating is provided though a wood chip boiler and the photovoltaic modules on the roof produce the required electricity. The annual electricity demand can be fully covered by the building itself. Excess energy fed into the grid as well as hourly variations are not considered. The results for the operational impacts are provided in Table 4.

Table 4. *Results for the operational impact of the building case study*

	Final energy demand kWh/(m^2_{AE}·a)	**KBOB ID**	**KBOB Name**	**GWP kg CO_2-e/(m^2_{AE}·a)**
Heating	43.50	41.011	Wood chip boiler	0.48
Electricity	22.16	46.003	Photovoltaic on flat roof	1.80
Sum				**2.27**

6. Discussion

The application of the proposed method in a case study shows that it is possible to continuously assess the embodied impacts throughout the building design process. Fig. 6 shows that the variability decreases from the early design phases to the final ones for most building elements because more refined data are used at higher LODs. As a result, the GWP in a certain design stage is within the variability of the previous one. The main contribution of the research is to predict the GWP during the entire design process. Thus, the method helps to provide reliable information for decision-making during the entire design process, beginning with the first building concept.

However, the results of a few individual building elements do not follow this general trend because of two main issues. First, the method considers all building components when modelling at LOD 100 or LOD 200, since it is unknown which ones will be part of the final solution. This approach can cause an overestimation in some cases because some components such as the interior finishing may be excluded at LOD 300 (Fig. 6b, h). To solve this issue, the option of not having a certain component such as a finishing can be added to the building component database. Thus, this aspect will be considered in the calculation of minimum values, and the variability at LOD 100 and LOD 200 will increase. Second, the limited number of datasets in the databases affects the results, e.g., in the case of the *balcony* (Fig. 6g). This issue can be solved by extending the building component database with more typical constructive solutions. Furthermore, because the method depends on the database, it is limited in terms of indicating the environmental potential of innovative constructive solutions that are not part of a catalogue of standard solutions. The catalogue covers the available solutions on the market. Thus, the proposed method is useful for mass construction but not the few ground-breaking solutions.

When adding the results of all building elements to calculate the embodied impacts of the entire building, the inconsistencies of the individual elements are not visible. The results for the entire building in a certain design phase comply with the forecast from the variability range in the previous stages, as shown in Fig. 7. Only the variability of the Pre-Design stage does not match the GWP of the last two design phases because of the limited number of buildings in the database. This issue can be solved by extending the database.

Furthermore, all possible solutions for building components have been combined to form building elements here. In some cases, this combination may result in an impractical solution, since not all combinations are technically feasible. In addition, all minimum values at the element level are summed up to indicate the minimum value of the building that might not be reachable in reality. Thus, the minimum values should be considered as the indication of a potential and not a benchmark. However, the final result of the real case study is notably close to the minimum value in the PP phase (Fig. 7), which implies that it can be achieved in reality.

The proposed framework should be evolved in the future. First, the method currently only includes the embodied impact of the building. Depending on the building, the environmental impact that results from the use phase can be a major part of the overall life cycle impact. However, for this specific case study building, the operational impact is only about 50% of the embodied impact. As such, it is only responsible for one third of the environmental impact during the life cycle of 60 years. This confirms the findings of recent publications stating that the embodied impact of very energy efficient residential buildings often exceeds the impact from the use phase [67]. In addition, a recent publication shows that the embodied and operational impacts of residential buildings in France are not correlated [68]. This is due to the fact that the drivers for the embodied impact are mainly the structural elements. Currently, the insulation typically does not contribute very much to the embodied energy. To ensure that the solutions form the component catalogue comply with current regulations, all components that form the envelope have a u-value of approximately 0.2. This means that the final operational energy demand is not affected regardless of the specific solution. For commercial buildings of other types the relation between embodied and operational impact might be very different. In the future, the method can be extended to include the operational impact.

Second, the method was applied on a single case study using Swiss databases and standards. In the proposed case study, the results for GWP decrease as the design process advances because the specific building selected for the case study is composed of materials with a low impact compared to the average solutions. To confirm the validity of the proposed method, it should be applied on further real case studies in the future. The method can be applied using any databases based on identical background data to allow for mixing. In the future, the use of the method in other national contexts should be investigated.

7. Conclusion

LCA is commonly difficult to apply during the entire building design process because the necessary data are only complete in the latest phases. However, the present study shows that it is possible to continuously assess the embodied environmental impacts in all phases of the building design process using BIM and mixing LCA databases with different level of detail. The suggested approach consists of structuring the building into functional elements and construction categories because they are typically modelled at different LODs in different planning stages. The novelty of the method is the consistent mixing of different LCA databases according to the LOD of the building elements at different design stages. By using different LCA databases that match the LOD of the elements, the embodied impacts can be continuously assessed with the maximum level of detail of information available at the current design stage. Thus, the embodied impacts can be calculated even when information is missing, and the results are as accurate as possible at all times. Finally, the method enables the use of LCA for assessing embodied impacts as a decision-making tool to reach more sustainable solutions from the early to the detailed design phases. The present study is mainly based on the embodied impact of the building and the method was applied in the Swiss context using a single case study. To further improve the proposed framework, the operational impact should be included and additional case studies should be investigated in different national contexts.

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