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# 2 Continuous BIM-based assessment of embodied 3 environmental impacts throughout the design process 4

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13

## 14 **Abstract**

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

31

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

## 34 **1. Introduction**

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

42

43 The interest of Life cycle assessment (LCA) for the construction sector has been noted in several review papers  
44 [3–11]. LCA is widely recognized as a powerful tool to predict the environmental impacts of buildings during  
45 their life cycle [12,13]. LCA covers the entire life cycle of buildings from raw materials extraction and  
46 processing, manufacturing of building components, to use and end-of-life. The method as described in ISO  
47 14040 [14] consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact  
48 assessment (LCIA), and interpretation [14,15]. Usually, LCA studies of products are structured according to  
49 these four phases. For LCA of buildings, predefined datasets for the materials or components used in the  
50 building are used in most cases. As such, the LCI and LCIA are merged into one step and simplified [16].  
51 Basically, only a bill of quantities (BoQ) is needed that is multiplied with values of the respective datasets from  
52 the LCA database. Then, the results can be summed up under consideration of the reference service life of the  
53 individual components. Nevertheless, the LCA of buildings is a complex task because of the large amount of  
54 information required and time-consuming nature of the method [17]. Most time and effort is needed to establish  
55 the BoQ and find the correct datasets in the building material LCA database. As a result, the LCA of buildings is  
56 commonly conducted at the end of the design process, when the necessary information is available, but it is too  
57 late to affect the decision-making process [18]. This dilemma for LCA of buildings is closely related to the  
58 nature of the design process. On the one hand, early design choices are responsible for a significant amount of  
59 the total environmental impacts [19–21], but LCA cannot be fully applied because of the incompleteness of the  
60 data. On the other hand, LCA can no longer successfully be used as a decision-making tool in late design stages  
61 because making changes is too costly [22].

62

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

79

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

87

88 The paper is structured as follows. Section 2 presents a literature review, which is organized around the two  
89 different trends to conduct BIM-based LCA – either using simplified models in early design phases or very  
90 detailed approaches in late design phases. In section 3, the development of the framework for assessing  
91 embodied environmental impact continuously is described for the Swiss context. The building is structured into  
92 eleven elements according to the Swiss cost calculation standard. The design process is divided into five main

93 phases according to the Swiss practice. Here, the tendering and construction phase are also regarded as design  
94 phases, because decisions on materials are still taken in these phases and influence the environmental  
95 performance of the building. Furthermore, the LOD evolution of the building elements is assumed based on the  
96 typical Swiss architecture practice. The framework is tested by means of a case study of a multi-family house  
97 described in section 4. The results of applying the framework are described in section 5, before the main  
98 contributions and limitations are discussed in section 6. The paper concludes in section 7.

99

## 100 **2. Literature review**

101 Several studies have been conducted to enhance the dialogue between BIM and LCA for sustainable construction  
102 [25,30]. BIM is oriented to the modelling and communication of both graphic and non-graphic information to  
103 enable the extraction of quantities, cost estimations and material properties for buildings, facilities and  
104 infrastructures [31]. BIM allows different stakeholders to manage digital data of the building throughout its  
105 entire life cycle [32]. Recent studies have shown that BIM supports energy demand simulations and  
106 environmental impact assessments over the building's life cycle, which provides an effective method to consider  
107 scenarios to mitigate the emissions related to material processing and construction methods [33,34]. Two  
108 different trends can be observed to perform LCA of buildings based on BIM. The first trend concerns performing  
109 detailed LCA with refined processes and specific building performance simulation tools. The second trend  
110 involves simplified approaches for early design stages. The existing literature for both trends is reviewed and  
111 summarized in a list of BIM-based LCA studies in Table 1.

112

113 The use of BIM-based sustainable design tools has proven to be effective for the late stage of design and detailed  
114 BIM models [35,36]. Several studies employed BIM for automatic calculation of materials and components  
115 quantities and exported them to an Excel spreadsheet where operational and embodied emission are evaluated  
116 [37–39]. Peng [40] developed a BIM-based approach to obtain the building life cycle carbon emissions using  
117 Autodesk Revit to extract the bill of materials and Autodesk Ecotect to simulate the heating and cooling loads at  
118 the operational stage. Lee et al. [35] developed a green template using Revit as the BIM authoring software. The  
119 study provides a template that can be used for embodied environmental impact evaluation of a building. Other  
120 studies integrated various software to support an automated or semi-automated process. For example, Shadram  
121 and Mukkavaara [41] proposed a BIM-based framework to find the optimal design solution by solving the trade-  
122 off problems between the embodied and operational energy demands through the integration of a multi-objective  
123 optimization approach. The framework involves four main modules: (1) BIM module using the Autodesk Revit

124 software for the virtual representation of the building and Dynamo for the input-output data interface; (2) data  
125 repository module; (3) energy performance simulation; and (4) multi-objective optimization modules developed  
126 in Grasshopper. Shadram et al. [42] set up an integrated BIM-based framework to assess the embodied energy in  
127 the design development phase of the building's life cycle. The workflow integrates the Extract Transform Load  
128 (ETL) process to ensure the BIM-LCA interoperability. Marzouk et al. [43] proposed a BIM-based method that  
129 enables the estimation of six environmental indicators. The authors used Autodesk Revit to facilitate data  
130 retrieval from Microsoft Access and employed an application in C#.net to calculate the overall emissions using  
131 Athena Impact Estimator. Also, Abanda et al. [44] developed an algorithm that can be implemented in the BIM  
132 software to automatically calculate the embodied energy and GHG emissions of a building. Yang et al. [45]  
133 combined various software tools and data sources to enhance the data flow between BIM and LCA models.  
134 Autodesk Revit and Glondon BIM5D tools are used to create the BIM model, compute the inputs of on-site  
135 construction process, and simulate the energy consumption of building operation. Then, a detailed LCA model is  
136 built using a China's local LCA software tool.

137

138 In recent years, many scientific studies have acknowledged the great potential of analysis in early design stages  
139 to reduce the environmental impact of buildings. Nizam et al. [46] state that a BIM approach has the potential to  
140 generate a decision-support system in the early design phase, including the selection of building materials,  
141 spatial configuration, construction methods and building service systems. Recent studies present methods to  
142 calculate environmental impacts of different material options, dimensioning choices and design alternatives at  
143 the building conceptual stage [22,47–50]. For example, Basbagill et al. [48] propose a computational method  
144 combining BIM, LCA, energy simulation, and sensitivity analysis software to quickly evaluate the embodied  
145 impacts of thousands of building designs. Other studies focus on methods to enhance interoperability between  
146 BIM and LCA tools for early analysis. Kulahcioglu et al. [51] proposed a framework based on a prototype  
147 software for the environmental performance analysis of a 3D model. A BIM-LCA integration is enabled using  
148 the Industry Foundation Classes (IFC) as an open standard data model to develop a tool to support early design  
149 decisions making process. Bueno et al. [52] developed a routine for the BIM-LCA integration by combining,  
150 visual programming and a spreadsheet application to automatically obtain environmental profiles in the early  
151 design stages. Jrade and Jalaei [53] presented a methodology for the BIM-LCA integration with a database to  
152 simplify the process to evaluate the environmental impacts of buildings in the conceptual stage. The proposed  
153 approach involves the use of a material database stored in a BIM module linked to an LCA module, certification  
154 and cost module. Jalaei and Jrade [54] developed a plug-in to analyse the environmental impacts and embodied

155 energy of the building components linking BIM, LCA, energy performance analysis, and lighting simulation  
 156 with green building certification systems. Najjar et al. [55] employed Autodesk Revit to design a case study  
 157 building and used Green Building Studio and Tally to estimate the impact and give recommendations. Shafiq et  
 158 al. [56] employed Autodesk Revit and MS Excel to assess the embodied carbon footprint of a two-storey  
 159 building. The authors recommend that, other factors such as the cost of materials should be considered to create  
 160 a design that is both environmentally responsible and economically sustainable. An application to select  
 161 appropriate design alternatives using BIM for developing LCA and life cycle costing (LCC) was proposed by  
 162 Shin and Cho [57]. The authors developed an automatic framework to connect LCA with LCC methods in the  
 163 early phase of a construction project by manually entering data when it has been extracted using BIM software.

164

*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, Glodon BIM5D tools, eBALANCE, Designbuilder, Excel	300	X	

165

166 As can be seen in Table 1, the reviewed papers only refer to a single trend, without considering the entire design  
 167 process. Moreover, only few studies set a fixed LOD. Ajayi et al. [47] and Röck et al. [50] were based on a LOD  
 168 200 model to support early environmental analysis. LOD 300 was declared only in two cases to support detailed  
 169 analysis [35,45].

170

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

180

### 181 **3. Method**

182 The development of the framework is described for the Swiss context. The same approach can be followed to  
 183 define frameworks for other countries as well. The approach is based on the application of different levels of  
 184 detail of the embodied impact calculation depending on the available information, respectively LOD of the BIM.

185 As such, the method consist of three main steps (Fig. 1):

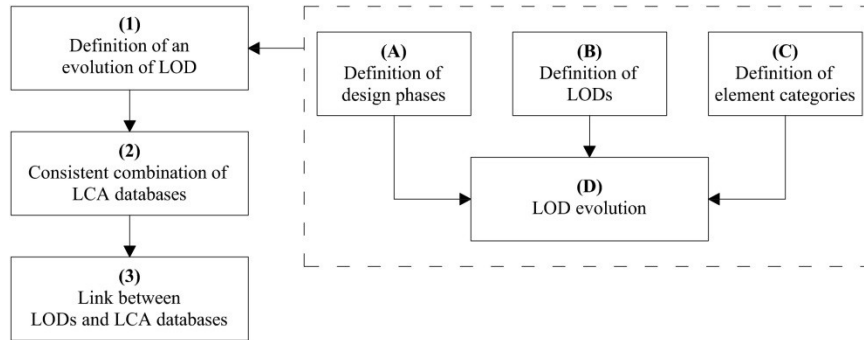
- 186 1. Definition of an evolution of LOD
- 187 2. Consistent combination of LCA databases
- 188 3. Link between LODs and LCA databases

189

190 **Definition of an evolution of LOD**

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

194



195

196

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

197 **A) Definition of design phases**

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

- 199 - Project Planning (PP)
  - 200 - Project (P)
  - 201 - Building Permit Application (BPA)
  - 202 - Tendering (T)
  - 203 - Construction (C)
- } Early design phase
- } Detailed design phase

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

212

## 213 **B) Definition of LODs**

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

222

## 223 **C) Definition of construction categories**

224 For the purpose of this study, the Swiss building element classification scheme for cost estimation e-BKP-H SN  
225 506 511 is used to define building elements. This structure divides a building into eleven *elements*:

- 226 1. Foundation / base slab
- 227 2. Exterior wall under ground
- 228 3. Exterior wall above ground
- 229 4. Windows
- 230 5. Interior wall
- 231 6. Partition wall
- 232 7. Column
- 233 8. Ceiling
- 234 9. Balcony
- 235 10. Roof
- 236 11. Technical equipment

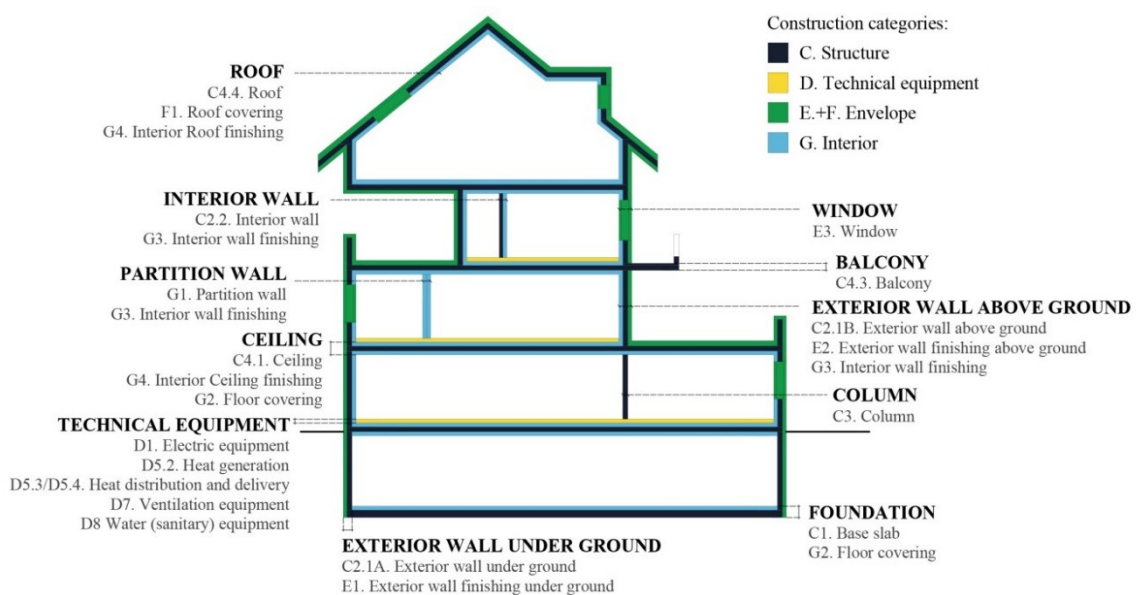
237 Each building *element* consists of several building *components*, which have different functions and belong to  
238 different *construction categories*. The classification system marks individual building components with an  
239 alphanumeric code. The alphabetic character can be matched with the construction categories. For example, the  
240 building element *exterior wall aboveground* is characterized by three different building components: *C2.1B*  
241 *exterior wall*, *E2 exterior wall finishing*, and *G3 interior wall finishing*, which belong to the construction

242 categories *structure (C)*, *envelope (E+F)*, and *interior (G)*. For this paper, four construction categories are  
 243 defined according to this scheme:

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

248

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



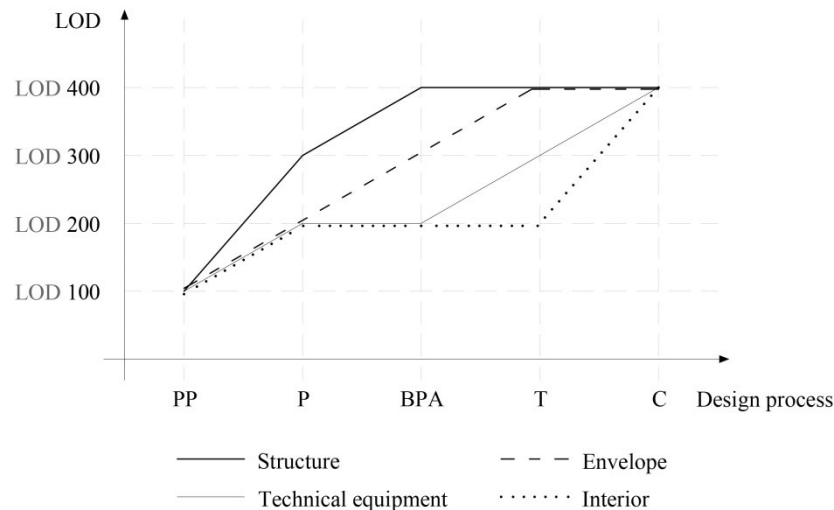
251

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

253

## 254 D) LOD evolution

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



261

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

264

### 265 Consistent combination of databases

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

279

### 280 Link between LOD and databases

281 In the third step, the LCA databases are linked according to the LOD. At the most detailed LOD 400 achieved in  
 282 the construction phase, the exact quantities of each material are known and the KBOB list can be used. At LOD  
 283 300, it is assumed that the type of component is known, but the exact quantities of each material layer of the

284 component might not have been specified yet, such as the thickness a rendering. Therefore, the predefined  
 285 components from the building component catalogue are used. At level 200, it is assumed that the type of  
 286 construction system is defined, for example an interior or an exterior insulation, but the exact material is not yet  
 287 defined. The insulation material could still be exchanged in the further design process, for example. Therefore,  
 288 average values of the building component catalogue are used. Next to the average value, the minimum and  
 289 maximum value are provided to show the range of possible solutions for this element. At LOD 100, the type of  
 290 element is still unknown. Therefore, the building component catalogue database is used by averaging the impact  
 291 values at the building element level. In other words, the LCA is performed by taking the average of each  
 292 building component and summing these components at the element level to have an average building element. In  
 293 addition, the minimum and maximum values are calculated to show the variability of all possible constructive  
 294 solutions.

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

300

*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

301

302 According to the proposed method, each design phase refers to a BIM where building components are modelled  
 303 at different LOD considering the construction categories to which they belong. Hence, since each LOD involves  
 304 the use of different database, the assessments of embodied impacts are based on mixing them in every design  
 305 phase. An example of the application of the proposed method related to the exterior wall above ground in the  
 306 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				
		Concrete	GWP					
		Reinforcement steel	GWP					
...	...	...	GWP	GWP				
E. Envelope	Exterior wall cladding	Wooden cladding	Pine wood	GWP	GWP	GWPaverage GWPmin GWPmax		GWPaverage GWPmin GWPmax
			Larch wood	GWP				
		...	...	GWP				
		plasterboard plastered, wooden substructure	Plaster	GWP				
...	...	...	Hard wood	GWP	GWP			
G. Finishing	Interior wall finishing	Gypsum finishing	Gypsum	GWP	GWP	GWPaverage GWPmin GWPmax	GWPaverage GWPmin GWPmax	
			Paint	GWP				
		...	...	GWP				
		Wooden finishing	Wood	GWP				
...	...	...	Paint	GWP	GWP			
...	...	...	...	GWP	GWP			
...	...	...	...	GWP	GWP			

307

308

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

309

#### 310 4. Application to a case study

311

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].

314



315

316

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

317

318

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.

323

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

Building element	Building component	m <sup>2</sup>	Material	KBOB ID	Amount per m <sup>2</sup> 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 <sup>2</sup>
			Double-glazing	05.001	0.90	m <sup>2</sup>
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
	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 <sup>2</sup>
			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*	Electric equipment for residential buildings	34.001	1.00	m <sup>2</sup>
	D5.2 Heat generation	*heated floor area (A <sub>E</sub> )	Heat generation (30 W/m <sup>2</sup> )	31.002	1.00	m <sup>2</sup>
	D5.3/D5.4 Heat distribution and delivery		Floor heating	31.024	1.00	m <sup>2</sup>
	D7 Ventilation equipment		Ventilation for kitchen and bathroom	32.003	1.00	m <sup>2</sup>

	D8 Water (sanitary) equipment		Sanitary equipment for residential buildings	33.003	1.00	m <sup>2</sup>
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325

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

334

## 335 5. Results

336 The results for the GWP of each building element for different planning phases are shown in Fig. 6. The results  
337 for the PP phase are provided for the entire building elements because they are modelled at LOD 100. The  
338 results for the later design stages are provided for the individual components and represent a mix of databases.  
339 The results for the average, minimum and maximum of the building elements and components at LOD 100, LOD  
340 200, and LOD 300 are provided in Table SII of the Supplementary Information (SI).

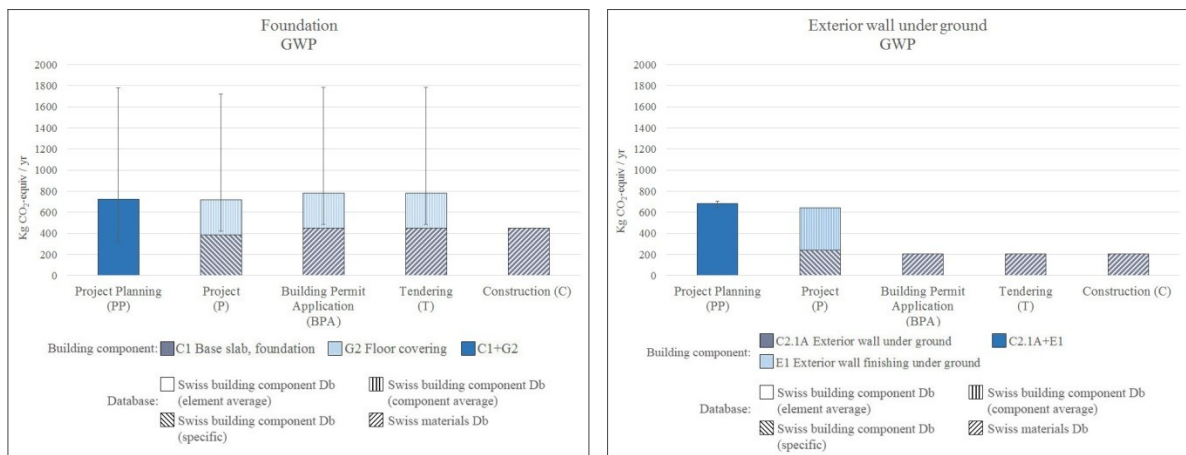
341 The building elements *Foundation* (Fig. 6a), *Exterior wall aboveground* (Fig. 6c), *Window* (Fig. 6d), *Interior*  
342 *wall* (Fig. 6e), *Partition wall* (Fig. 6f), *Roof* (Fig. 6i), and *Technical equipment* (Fig. 6j) show consistent results  
343 for embodied impacts during the design process.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

347 The results of the *Exterior wall underground* (Fig. 6b) do not show the same consistency during the design  
348 process. In the BPA phase, the component *E1 Exterior wall finishing underground* should be modelled at LOD  
349 300, but the case study building has no finishing (see Table 3). Therefore, the result of the BPA phase does not  
350 fall within the variability of the previous ones. In the early phases, the impact is overestimated compared to the  
351 final results. The same type of overestimation occurs for the *Ceiling* because building component *G4 Interior*  
352 *finishing* is not considered in the C phase (Fig. 6h). Furthermore, the assessment of building component *G2*  
353 *Floor covering* using the KBOB list in the C phase results in a much lower GWP than that in the T phase when  
354 the building component catalogue database is used, which causes a further overestimation of the impact in the

355 early design phases. Regarding the building element *Balcony*, the environmental impact in the PP phase is  
 356 significantly higher than those in the following phases because of a lack of data of the building component  
 357 catalogue. The database only provides concrete frame solutions, whereas the balcony of the case study building  
 358 is made of wood. To overcome the lack of data, the balcony is modelled using the wooden solution for the  
 359 component *C4.1 Ceiling*.

360 A detailed overview of the evolution of GWP during the design process for all building elements is provided in  
 361 Fig. S11 of the Supplementary Information (SI).

362

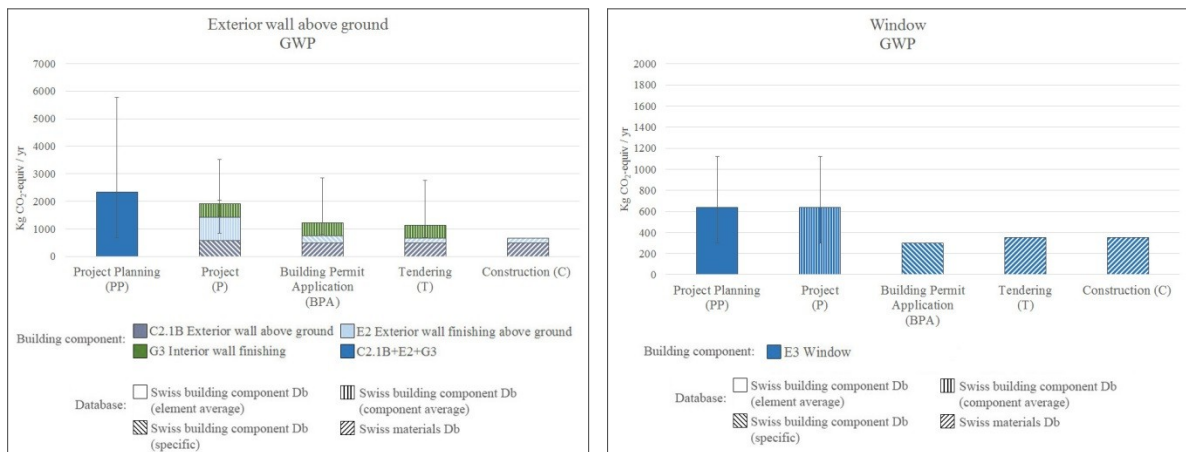


363

364

(a)

(b)

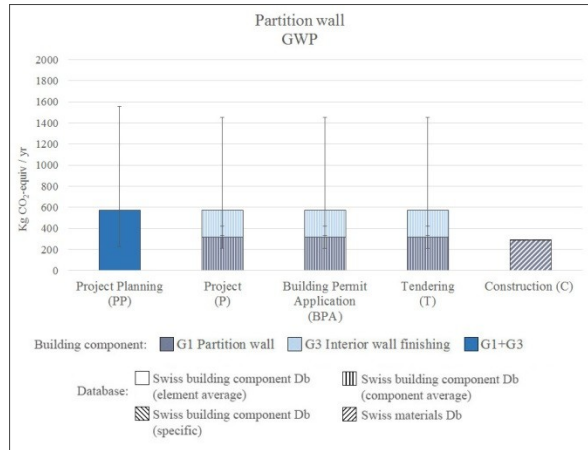
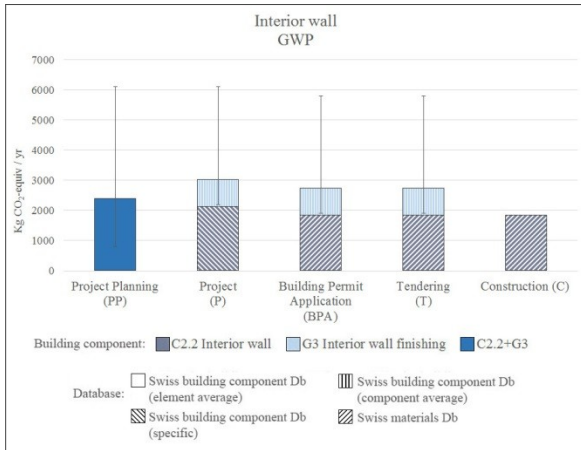


365

366

(c)

(d)

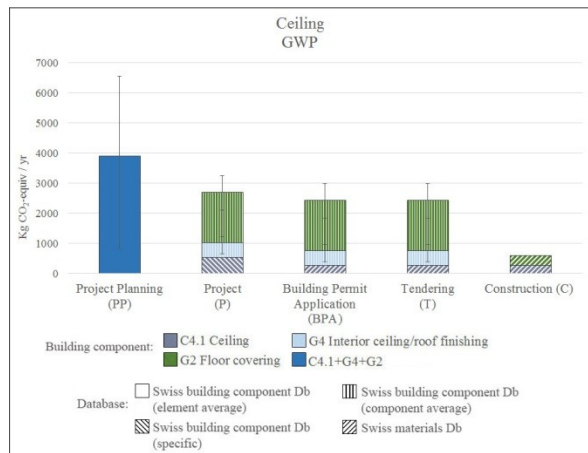
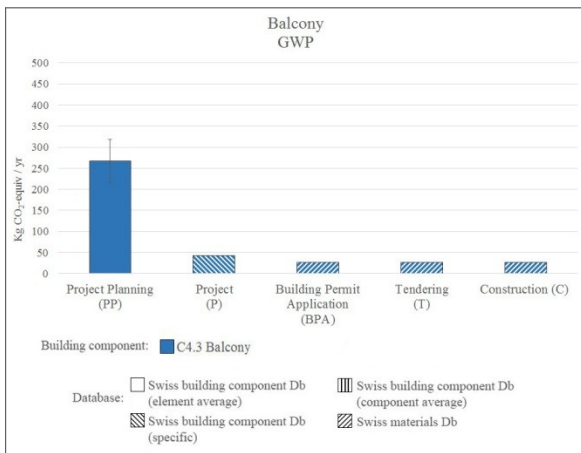


367

368

(e)

(f)

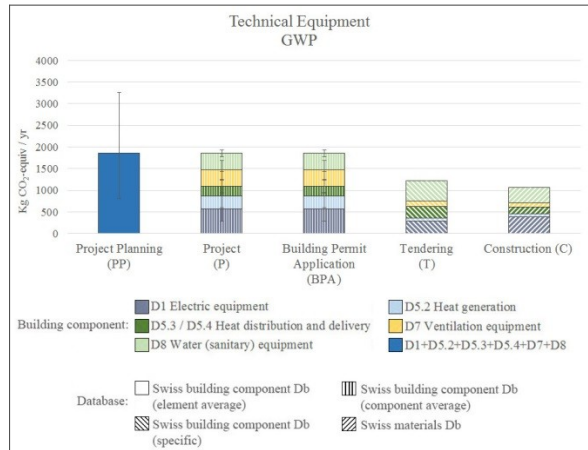
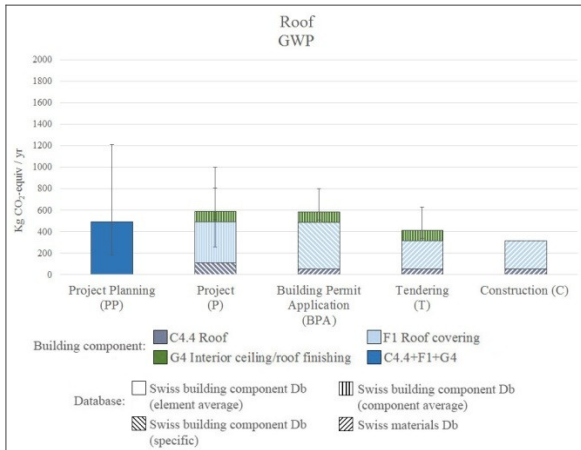


369

370

(g)

(h)



371

372

(i)

(j)

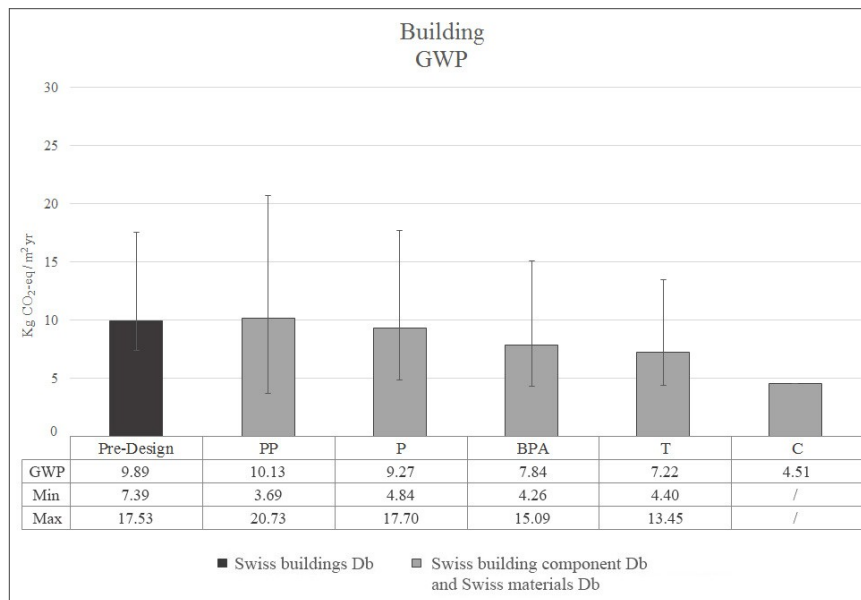
373 **Fig. 6.** Contribution to the GWP of building elements during the design process. The contribution of each building element  
 374 with the same scale is shown in the Supplementary Information (SI)

375

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

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

383



384

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

385

386

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

394

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

	Final energy demand kWh/(m <sup>2</sup> <sub>AE</sub> ·a)	KBOB ID	KBOB Name	GWP kg CO <sub>2</sub> -e/(m <sup>2</sup> <sub>AE</sub> ·a)
Heating	43.50	41.011	Wood chip boiler	0.48
Electricity	22.16	46.003	Photovoltaic on flat roof	1.80
<b>Sum</b>				<b>2.27</b>

395

## 396 6. Discussion

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

404 However, the results of a few individual building elements do not follow this general trend because of two main  
405 issues. First, the method considers all building components when modelling at LOD 100 or LOD 200, since it is  
406 unknown which ones will be part of the final solution. This approach can cause an overestimation in some cases  
407 because some components such as the interior finishing may be excluded at LOD 300 (Fig. 6b, h). To solve this  
408 issue, the option of not having a certain component such as a finishing can be added to the building component  
409 database. Thus, this aspect will be considered in the calculation of minimum values, and the variability at LOD  
410 100 and LOD 200 will increase. Second, the limited number of datasets in the databases affects the results, e.g.,  
411 in the case of the *balcony* (Fig. 6g). This issue can be solved by extending the building component database with  
412 more typical constructive solutions. Furthermore, because the method depends on the database, it is limited in  
413 terms of indicating the environmental potential of innovative constructive solutions that are not part of a  
414 catalogue of standard solutions. The catalogue covers the available solutions on the market. Thus, the proposed  
415 method is useful for mass construction but not the few ground-breaking solutions.

416

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

422 Furthermore, all possible solutions for building components have been combined to form building elements here.  
423 In some cases, this combination may result in an impractical solution, since not all combinations are technically  
424 feasible. In addition, all minimum values at the element level are summed up to indicate the minimum value of  
425 the building that might not be reachable in reality. Thus, the minimum values should be considered as the

426 indication of a potential and not a benchmark. However, the final result of the real case study is notably close to  
427 the minimum value in the PP phase (Fig. 7), which implies that it can be achieved in reality.

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

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

448

## 449 **7. Conclusion**

450 LCA is commonly difficult to apply during the entire building design process because the necessary data are  
451 only complete in the latest phases. However, the present study shows that it is possible to continuously assess the  
452 embodied environmental impacts in all phases of the building design process using BIM and mixing LCA  
453 databases with different level of detail. The suggested approach consists of structuring the building into  
454 functional elements and construction categories because they are typically modelled at different LODs in  
455 different planning stages. The novelty of the method is the consistent mixing of different LCA databases  
456 according to the LOD of the building elements at different design stages. By using different LCA databases that

457 match the LOD of the elements, the embodied impacts can be continuously assessed with the maximum level of  
458 detail of information available at the current design stage. Thus, the embodied impacts can be calculated even  
459 when information is missing, and the results are as accurate as possible at all times. Finally, the method enables  
460 the use of LCA for assessing embodied impacts as a decision-making tool to reach more sustainable solutions  
461 from the early to the detailed design phases. The present study is mainly based on the embodied impact of the  
462 building and the method was applied in the Swiss context using a single case study. To further improve the  
463 proposed framework, the operational impact should be included and additional case studies should be  
464 investigated in different national contexts.

465

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468

## 469 **References**

- 470 [1] IPCC, Climate Change 2014: Mitigation of Climate Change. Summary for Policymakers and Technical  
471 Summary, 2014. doi:10.1017/CBO9781107415416.005.
- 472 [2] G. Habert, D. Arribe, T. Dehove, L. Espinasse, R. Le Roy, Reducing environmental impact by increasing  
473 the strength of concrete: Quantification of the improvement to concrete bridges, *J. Clean. Prod.* 35  
474 (2012) 250–262. doi:10.1016/j.jclepro.2012.05.028.
- 475 [3] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: A review of recent  
476 developments based on LCA, *Constr. Build. Mater.* 23 (2009) 28–39.  
477 doi:10.1016/j.conbuildmat.2007.11.012.
- 478 [4] A. Singh, G. Berghorn, S. Joshi, M. Syal, M. Asce, Review of Life-Cycle Assessment Applications in  
479 Building Construction, *J. Archit. Eng.* 17 (2011) 15–23. doi:10.1061/(ASCE)AE.1943-5568.0000026.
- 480 [5] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: A review, *Renew.*  
481 *Sustain. Energy Rev.* 26 (2013) 379–388. doi:10.1016/j.rser.2013.05.001.
- 482 [6] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle  
483 energy analysis (LCEA) of buildings and the building sector: A review, *Renew. Sustain. Energy Rev.* 29  
484 (2014). doi:10.1016/j.rser.2013.08.037.
- 485 [7] H. Islam, M. Jollands, S. Setunge, Life cycle assessment and life cycle cost implication of residential  
486 buildings - A review, *Renew. Sustain. Energy Rev.* 42 (2015) 129–140. doi:10.1016/j.rser.2014.10.006.

- 487 [8] A.F. Abd Rashid, S. Yusoff, A review of life cycle assessment method for building industry, *Renew.*  
488 *Sustain. Energy Rev.* 45 (2015) 244–248. doi:10.1016/j.rser.2015.01.043.
- 489 [9] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Simplification in life cycle assessment of single-  
490 family houses: A review of recent developments, *Build. Environ.* 103 (2016) 215–227.  
491 doi:10.1016/j.buildenv.2016.04.014.
- 492 [10] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of  
493 buildings: A critical review, *Renew. Sustain. Energy Rev.* 67 (2017) 408–416.  
494 doi:10.1016/j.rser.2016.09.058.
- 495 [11] S. Geng, Y. Wang, J. Zuo, Z. Zhou, H. Du, G. Mao, Building life cycle assessment research: A review  
496 by bibliometric analysis, *Renew. Sustain. Energy Rev.* 76 (2017) 176–184.  
497 doi:10.1016/j.rser.2017.03.068.
- 498 [12] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA allocation procedure used as an incitative  
499 method for waste recycling: An application to mineral additions in concrete, *Resour. Conserv. Recycl.*  
500 54 (2010) 1231–1240. doi:10.1016/j.resconrec.2010.04.001.
- 501 [13] S. V. Russell-Smith, M.D. Lepech, R. Fruchter, Y.B. Meyer, Sustainable target value design: Integrating  
502 life cycle assessment and target value design to improve building energy and environmental  
503 performance, *J. Clean. Prod.* 88 (2015) 43–51. doi:10.1016/j.jclepro.2014.03.025.
- 504 [14] ISO 14040, Environmental management-Life Cycle Assessment-Principles and Framework, (2006).
- 505 [15] ISO 14044, Environmental management-Life Cycle Assessment-Requirements and guidelines, (2006).
- 506 [16] S. Lasvaux, J. Gantner, Towards a new generation of building LCA tools adapted to the building design  
507 process and to the user needs?, in: *Sustain. Build.*, Graz, 2013: pp. 406–417.
- 508 [17] I. Zabalza Bribián, A. Aranda Usón, S. Scarpellini, Life cycle assessment in buildings: State-of-the-art  
509 and simplified LCA methodology as a complement for building certification, *Build. Environ.* 44 (2009)  
510 2510–2520. doi:10.1016/j.buildenv.2009.05.001.
- 511 [18] J. Díaz, L.Á. Antón, Sustainable Construction Approach through Integration of LCA and BIM Tools,  
512 *Sixth Annu. Int. Conf. Comput. Civ. Build. Eng.* (2014) 455–462. doi:10.1061/9780784413616.053.
- 513 [19] S. Attia, E. Gratia, A. De Herde, J.L.M. Hensen, Simulation-based decision support tool for early stages  
514 of zero-energy building design, *Energy Build.* 49 (2012) 2–15. doi:10.1016/j.enbuild.2012.01.028.
- 515 [20] X. Shi, W. Yang, Performance-driven architectural design and optimization technique from a perspective  
516 of architects, *Autom. Constr.* 32 (2013) 125–135. doi:10.1016/j.autcon.2013.01.015.
- 517 [21] T. Häkkinen, M. Kuittinen, A. Ruuska, N. Jung, Reducing embodied carbon during the design process of

- 518 buildings, *J. Build. Eng.* 4 (2015) 1–13. doi:10.1016/j.jobe.2015.06.005.
- 519 [22] A. Hollberg, J. Ruth, LCA in architectural design—a parametric approach, *Int. J. Life Cycle Assess.* 21  
520 (2016) 943–960. doi:10.1007/s11367-016-1065-1.
- 521 [23] McGraw Hill Construction, *Green BIM: How Building Information Modeling is Contributing to Green*  
522 *Design and Construction*, 2010. doi:ISBN: 978-1-934926-26-0.
- 523 [24] S. Eleftheriadis, D. Mumovic, P. Greening, Life cycle energy efficiency in building structures: A review  
524 of current developments and future outlooks based on BIM capabilities, *Renew. Sustain. Energy Rev.* 67  
525 (2017) 811–825. doi:10.1016/j.rser.2016.09.028.
- 526 [25] J.K.W. Wong, J. Zhou, Enhancing environmental sustainability over building life cycles through green  
527 BIM: A review, *Autom. Constr.* 57 (2015) 156–165. doi:10.1016/j.autcon.2015.06.003.
- 528 [26] H. Chong, C. Lee, X. Wang, A mixed review of the adoption of Building Information Modelling (BIM)  
529 for sustainability, *J. Clean. Prod.* 142 (2017) 4114–4126. doi:10.1016/j.jclepro.2016.09.222.
- 530 [27] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Critical review of bim-based LCA method to  
531 buildings, *Energy Build.* 136 (2017) 110–120. doi:10.1016/j.enbuild.2016.12.009.
- 532 [28] AIA, Document E203™ – 2013 Building Information Modeling and Digital Data Exhibit, (2013) 1–7.
- 533 [29] AIA, Document G202™ – 2013 Project Building Information Modeling Protocol Form, (2013) 5.
- 534 [30] A. Kylili, P.A. Fokaides, J. Vaiciunas, L. Seduikyte, Integration of Building Information Modelling  
535 (BIM) and Life Cycle Assessment (LCA) for sustainable constructions, *J. Sustain. Archit. Civ. Eng.* 4  
536 (2015) 28–38. doi:http://dx.doi.org/10.5755/j01.sace.13.4.12862.
- 537 [31] F.K.T. Cheung, J. Rihan, J. Tah, D. Duce, E. Kurul, Early stage multi-level cost estimation for schematic  
538 BIM models, *Autom. Constr.* 27 (2012) 67–77. doi:10.1016/j.autcon.2012.05.008.
- 539 [32] B. Succar, Building information modelling framework: A research and delivery foundation for industry  
540 stakeholders, *Autom. Constr.* 18 (2009) 357–375. doi:10.1016/j.autcon.2008.10.003.
- 541 [33] J. Giesekam, J. Barrett, P. Taylor, A. Owen, The greenhouse gas emissions and mitigation options for  
542 materials used in UK construction, *Energy Build.* 78 (2014) 202–214.  
543 doi:10.1016/j.enbuild.2014.04.035.
- 544 [34] Y. Yuan, J. Yuan, The theory and framework of integration design of building consumption efficiency  
545 based on BIM, *Procedia Eng.* 15 (2011) 5323–5327. doi:10.1016/j.proeng.2011.08.987.
- 546 [35] S. Lee, S. Tae, S. Roh, T. Kim, Green template for life cycle assessment of buildings based on building  
547 information modeling: Focus on embodied environmental impact, *Sustain.* 7 (2015) 16498–16512.  
548 doi:10.3390/su71215830.

- 549 [36] I. Motawa, K. Carter, Sustainable BIM-based Evaluation of Buildings, *Procedia - Soc. Behav. Sci.* 74  
550 (2013) 419–428. doi:10.1016/j.sbspro.2013.03.015.
- 551 [37] L. Georges, M. Haase, A. Houlihan Wiberg, T. Kristjansdottir, B. Risholt, Life cycle emissions analysis  
552 of two nZEB concepts, *Build. Res. Inf.* 43 (2015) 82–93. doi:10.1080/09613218.2015.955755.
- 553 [38] A. Houlihan Wiberg, L. Georges, T.H. Dokka, M. Haase, B. Time, A.G. Lien, S. Mellegård, M. Maltha,  
554 A net zero emission concept analysis of a single-family house, *Energy Build.* 74 (2014) 101–110.  
555 doi:10.1016/j.enbuild.2014.01.037.
- 556 [39] C.R. Iddon, S.K. Firth, Embodied and operational energy for new-build housing: A case study of  
557 construction methods in the UK, *Energy Build.* 67 (2013) 479–488. doi:10.1016/j.enbuild.2013.08.041.
- 558 [40] C. Peng, Calculation of a building's life cycle carbon emissions based on Ecotect and building  
559 information modeling, *J. Clean. Prod.* 112 (2016) 453–465. doi:10.1016/j.jclepro.2015.08.078.
- 560 [41] F. Shadram, J. Mukkavaara, An integrated BIM-based framework for the optimization of the trade-off  
561 between embodied and operational energy, *Energy Build.* 158 (2018) 1189–1205.  
562 doi:10.1016/j.enbuild.2017.11.017.
- 563 [42] F. Shadram, T.D. Johansson, W. Lu, J. Schade, T. Olofsson, An integrated BIM-based framework for  
564 minimizing embodied energy during building design, *Energy Build.* 128 (2016) 592–604.  
565 doi:10.1016/j.enbuild.2016.07.007.
- 566 [43] M. Marzouk, E.M. Abdelkader, K. Al-Gahtani, Building information modeling-based model for  
567 calculating direct and indirect emissions in construction projects, *J. Clean. Prod.* 152 (2017) 351–363.  
568 doi:10.1016/j.jclepro.2017.03.138.
- 569 [44] F.H. Abanda, A.H. Oti, J.H.M. Tah, Integrating BIM and new rules of measurement for embodied  
570 energy and CO<sub>2</sub> assessment, *J. Build. Eng.* 12 (2017) 288–305. doi:10.1016/j.job.2017.06.017.
- 571 [45] X. Yang, M. Hu, J. Wu, B. Zhao, Building-information-modeling enabled life cycle assessment, a case  
572 study on carbon footprint accounting for a residential building in China, *J. Clean. Prod.* 183 (2018) 729–  
573 743. doi:10.1016/j.jclepro.2018.02.070.
- 574 [46] R.S. Nizam, C. Zhang, L. Tian, A BIM based tool for assessing embodied energy for buildings, *Energy  
575 Build.* 170 (2018) 1–14. doi:10.1016/j.enbuild.2018.03.067.
- 576 [47] S.O. Ajayi, L.O. Oyedele, B. Ceranic, M. Gallanagh, K.O. Kadiri, Life cycle environmental performance  
577 of material specification: a BIM-enhanced comparative assessment, *Int. J. Sustain. Build. Technol.  
578 Urban Dev.* 6 (2015) 14–24. doi:10.1080/2093761X.2015.1006708.
- 579 [48] J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage

- 580 building design for reduced embodied environmental impacts, *Build. Environ.* 60 (2013) 81–92.  
581 doi:10.1016/j.buildenv.2012.11.009.
- 582 [49] S. Eleftheriadis, P. Duffour, D. Mumovic, BIM-embedded life cycle carbon assessment of RC buildings  
583 using optimised structural design alternatives, *Energy Build.* 173 (2018) 587–600.  
584 doi:10.1016/j.enbuild.2018.05.042.
- 585 [50] M. Röck, A. Hollberg, G. Habert, A. Passer, LCA and BIM: Visualization of environmental potentials in  
586 building construction at early design stages, *Build. Environ.* (2018). doi:10.1016/j.buildenv.2018.05.006.
- 587 [51] T. Kulahcioglu, J. Dang, C. Toklu, A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole  
588 process of construction, *HVAC R Res.* 18 (2012) 283–293. doi:10.1080/10789669.2012.634264.
- 589 [52] C. Bueno, L.M. Pereira, M.M. Fabricio, Life cycle assessment and environmental-based choices at the  
590 early design stages : an application using building information modelling, *Archit. Eng. Des. Manag.* 0  
591 (2018) 1–15. doi:10.1080/17452007.2018.1458593.
- 592 [53] A. Jrade, F. Jalaei, Integrating building information modelling with sustainability to design building  
593 projects at the conceptual stage, *Build. Simul.* 6 (2013) 429–444. doi:10.1007/s12273-013-0120-0.
- 594 [54] F. Jalaei, A. Jrade, An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess  
595 Sustainable Building Projects, *J. Constr. Eng.* 2014 (2014) 1–21. doi:10.1155/2014/672896.
- 596 [55] M. Najjar, K. Figueiredo, M. Palumbo, A. Haddad, Integration of BIM and LCA : Evaluating the  
597 environmental impacts of building materials at an early stage of designing a typical office building, *J.*  
598 *Build. Eng.* 14 (2017) 115–126. doi:10.1016/j.jobe.2017.10.005.
- 599 [56] N. Shafiq, M.F. Nurrudin, S.S.S. Gardezi, A. Bin Kamaruzzaman, Carbon footprint assessment of a  
600 typical low rise office building in Malaysia using building information modelling (BIM), *Int. J. Sustain.*  
601 *Build. Technol. Urban Dev.* 6 (2015) 157–172. doi:10.1080/2093761X.2015.1057876.
- 602 [57] Y.S. Shin, K. Cho, BIM application to select appropriate design alternative with consideration of LCA  
603 and LCCA, *Math. Probl. Eng.* (2015) 1–15. doi:10.1155/2015/281640.
- 604 [58] A. Hollberg, J. Tschetwertak, S. Schneider, G. Habert, Design-Integrated LCA Using Early BIM, in: E.  
605 Benetto, K. Gericke, M. Guiton (Eds.), *Des. Sustain. Technol. Prod. Policies*, Springer International  
606 Publishing, 2018. doi:10.1007/978-3-319-66981-6.
- 607 [59] DIN, DIN 276-1: Kosten im Bauwesen, (2008) 1–26.
- 608 [60] KBOB Ökobilanzdaten im Baubereich, (n.d.).
- 609 [61] bauteilkatalog.ch, Bauteilkatalog, (n.d.).
- 610 [62] Swiss Eco-Factors 2013 according to the Ecological Scarcity Method, 2013, (n.d.).

- 611 [63] F. Wyss, R. Frischknecht, K. Pfäffli, V. John, Zielwert Gesamtumweltbelastung Gebäude -  
612 Machbarkeitsstudie, 2014.
- 613 [64] J. Hartwig, Ökobilanz WoodCube Hamburg, 2012.
- 614 [65] SIA, Graue Energie von Gebäuden, (2012).
- 615 [66] EN 15978, Sustainability of construction works - Assessment of environmental performance of buildings  
616 - Calculation method, (2011).
- 617 [67] R. Azari, N. Abbasabadi, Embodied energy of buildings: A review of data, methods, challenges, and  
618 research trends, *Energy Build.* 168 (2018) 225–235. doi:10.1016/j.enbuild.2018.03.003.
- 619 [68] E. Hoxha, G. Habert, S. Lasvaux, J. Chevalier, R. Le Roy, Influence of construction material  
620 uncertainties on residential building LCA reliability, *J. Clean. Prod.* 144 (2017) 33–47.  
621 doi:10.1016/j.jclepro.2016.12.068.
- 622