Peer-reviewed version available at *Sustainability* **2020**, *12*, 3748; doi:10.3390/su12093748

Article

Integrated BIM-Based LCA for the Entire Building Process Using an Existing Structure for Cost Estimation

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Abstract: The building sector has a big potential to reduce the material resource demand needed for building construction and therefore, greenhouse gas (GHG) emissions. Digitalisation can help to make use of this potential and improve sustainability throughout the entire building's life cycle. One way to address this potential is through the integration of Life-Cycle Assessment (LCA) into the building process by employing Building Information Modelling (BIM). BIM can reduce the effort needed to carry out an LCA and therefore facilitate the integration into the building process. A review of current industry practice and scientific literature shows two main approaches to address BIM-LCA integration. Either the LCA is performed in a simplified way at the beginning of the building process using unprecise techniques, or it is done at the very end when all the needed information is available, but it is too late for decision-making. One reason for this is the lack of methods, workflows and tools to implement BIM-LCA integration over the whole building development. Therefore, the main objective of this study is to establish an integrated BIM-LCA method for the entire building process using an existing structure for cost estimation. The established workflow is implemented in a tool and used in a case study in Switzerland to test the developed approach. The results of this study show that LCA can be performed continuously in each building phase over the entire building process using existing BIM modelling techniques. The main benefit of this approach is that the re-work caused by the need for re-entering data and the usage of many different software tools that characterise most of the current LCA practices is minimised. Furthermore, decision-making, both at the element and building levels, is supported.

Keywords: Building Information Modelling (BIM); Life-Cycle Assessment (LCA); Building process; Level of Development (LOD); Embodied environmental impacts; Greenhouse Gas emissions (GHG); LCA databases; LCA values; LCA benchmarks; cost estimation structure doi:10.20944/preprints202003.0012.v1

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1. Introduction

The Architecture, Engineering, Construction and Operations (AECO) industry has a high impact on the environment and is responsible for more than one-third of global GHG emissions (UN Environment and IEA, 2018). Due to the implementation of energy efficiency regulations in most industrialised building practices in the last years, the operational energy demand and associated GHG emissions of new buildings have been reduced (UN Environment and IEA, 2018). In consequence, the share of GHG emissions due to the manufacturing, replacement and disposal of building materials gained importance (IRP, 2018). The significance of accounting for these embodied environmental impacts is highlighted by the recent report of the World Green Building Council (*World Green Building Council*, 2020).

Life Cycle Assessment (LCA) is a methodology to assess environmental issues holistically throughout the building process. It covers the entire life cycle of buildings from raw materials extraction and processing, manufacturing of building components, through the building's use and end-of-life. According to Russell-Smith and Lepech (2012), LCA can predict the environmental impact of buildings during their life-cycle and support sustainable decisions. LCA is widely used for environmental evaluation in industrial manufacturing practices involving standardised processes (Braet, 2011). However, when applied in the AECO industry, LCA becomes more challenging, since more complex processes are involved (Ortiz et al., 2009). Researchers have been looking at different options on how to simplify LCA for buildings. Within the last years, there has been increased interest in using Building Information Modeling (BIM) as a basis for establishing the inventory of materials needed for the LCA (Meex et al., 2018; Röck et al., 2019; Verdaguer et al., 2017).

BIM is a 3D model-based process and technology by which a structured multi-layered organisation of information obtained by different stakeholders can be gathered and a multidisciplinary collaboration amongst them could be achieved (Eadie et al., 2013). Building Information Models are progressively being applied throughout the life-cycle of buildings, serving various applications, expanding from the design, construction and maintenance processes.

To perform LCA, the collection of data about materials and information regarding their production and transportation is required. The process of re-entering the data about materials in environmental assessment software is time-consuming and typically not done by the specialists involved in the creation of the BIM model (Sharma et al., 2011). A computational workflow is required for an efficient, dynamic life-cycle approach that can link BIM software with LCA tools. The integration of BIM and LCA has the potential to automate this approach by using material specifications and material quantity take-off that are already included in the BIM model. The definition of data sources from the BIM-based environment eliminates the need for manual re-entry of LCA-related data (Bueno and Fabricio, 2016b). Therefore, the BIM-LCA integration can help to accelerate the overall environmental assessment process (Russell-Smith and Lepech, 2012) (Figure 1).

Figure 1: Life-Cycle Assessment (LCA) and Building Information Modeling (BIM)

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BIM-LCA integration provides a powerful approach to perform LCA more efficiently and in an automated way (Soust-Verdaguer et al., 2017). Different methods try to simplify LCA so that its applicability is enhanced. However, the entire building process is currently not evaluated in terms of environmental LCA. Existing studies present methods for BIM-based LCA with application in a specific phase (Cavalliere et al., 2018). Still, the current practice does not implement such approaches. It either focuses on an early conceptual phase, relying on simplified methods for applying LCA and resulting in not precise outcomes, or on a very late detailed phase, when accurate information about the building is available, but it is too late for design changes to be performed. Moreover, existing methods use LCA databases that do not distinguish between different building phases. Most BIM-based LCA studies do not declare the Level of Development (LOD) (Soust-Verdaguer et al., 2017). There is an inconsistency between the structure of BIM models and the that of LCA databases. BIM models and LCA databases are currently not aligned to a standard code structure for the LCA to be parameterised in a simple and reliable way (Cavalliere et al., 2018).

For the foregoing reasons, the main objective of this paper is to develop an integrated BIM-LCA workflow for the entire building process using an existing structure for cost estimation. By using this structure, the novel approach aims at minimising the need for re-entering data and the usage of many different software tools. It should provide a methodology for Swiss companies to perform LCA continuously over the whole building process without additional effort. The building phases part of the building process in Switzerland (SIA), and their related Levels of Development (LOD) are reviewed so that the needed information required to perform LCA is identified. Existing LCA databases in Switzerland that can provide the needed data are examined. Current techniques used to structure BIM models according to common code structures are analysed. Based on that, a new process-structured LCA database is formulated, and a new digital BIM-based tool is developed. The presented workflow and the corresponding tool are tested by means of a case study.

2. State of the art

2.1 Building phases in Switzerland (SIA) and Level of Development (LOD)

The Swiss National Organization of Engineers and Architects (SIA - Schweizerischer Ingenieur- und Architektenverein), distinguishes six building phases – strategic briefing, preliminary studies, project, invitation to tender, construction and facility management.

Every BIM software creates a different data structure (Bueno and Fabricio, 2016a). Röck et al. (2019) point out that the quality of a BIM depends on its Level of Development (LOD). The authors highlight that the LOD depends on two other factors, namely Level of Geometry (LOG) and Level of Information (LOI). For the environmental impact to be better understood, both the geometrical and the data structure of the BIM should be examined (Bueno and Fabricio, 2016a). In general, the LOD concept proposes for the building process to start with generic, yet representative elements, that are being refined continuously throughout the design decision-making process (Meex et al., 2018).

Curschellas et al. (2018) from Bauen Digital Schweiz (BDCH) and buildingSMART Switzerland (bSCH) (part of BuildingSMART International) develop definitions for LOD, LOG, and LOI in the context of the country. Maier et al. (2018) develop a BIM Workbook (for BDCH and bSCH). In their study, the authors associate the Swiss building phases defined by SIA to LOD (SIA, 2014). Each different LOD is related to an existing building phase.

2.2 LCA databases in Switzerland

LCA databases are composed according to various building elements. Area-based LCA databases use the surface area of building components (m^2) and the floor area (m^2) to calculate the environmental impact. They allow the first estimation of LCA parameters at the beginning of the building process. An example of such a database, mainly used in the Swiss context, is the SIA2040 (SIA-Effizienzpfad Energie (SIA-Energy-efficiency path)) (SIA, 2017). The SIA2040 provides estimation and prediction of LCA parameters during building phases 1 and 2 (strategic briefing and

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preliminary studies) in the areas of design, operation, and mobility. Through a calculation based on SIA2040, a preliminary analysis can be done, and the potential LCA evaluated.

Component-based LCA databases provide information regarding LCA parameters for different building components (m^2). An example from Switzerland is the Bauteilkatalog (Bauteilkatalog, 2016). The database combines building component data from BFE (Bundesamt für Energie)[1] / Hollinger Consult GmbH [2] and LCA data from KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren)[3] / eco-bau[4] / IPB (Interessengemeinschaft privater professioneller Bauherren)[5]. In this way, the building components are evaluated according to LCA parameters per m^2 for their more straightforward implementation and decision-making basis provision.

Material-based LCA databases provide information regarding the environmental impact of different building materials. A Swiss material-based LCA database example is the KBOB / eco-bau / IPB database. The information regarding LCA provided by the database is based on volume (m^3) or mass (kg) of building materials.

2.3 Cost-planning structure in Switzerland (eBKP-H)

An existing cost-planning structure for buildings (eBKP-H – Baukostenplan Hochbau (Cost-plan Buildings)) developed by crb[6] (crb, 2012) is examined for this study. eBKP-H is a structure used by most Swiss construction companies for cost-planning. The developer crb proposes a system that covers the building process up to building phase 5 (construction) (crb, 2017). Different eBKP-H groups are associated with different building phases and LOD throughout the entire building process. As the building process evolves, more detailed information is provided for the eBKP-H groups (Figure 2).

[1] BFE (Bundesamt für Energie) – Swiss Federal Office of Energy. The Federal Office of Energy is a federal agency of the Swiss Confederation. It is responsible for national energy supply and use. The Office is part of the Federal Department of the Environment, Transport, Energy and Communications (DETEC). Source: https://www.bfe.admin.ch/

[2] Hollinger Consult GmbH – a consulting company working in the area of sustainability. Source: https://www.holligerconsult.ch/

[3] KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) - Coordination conference of the building and real estate organs of public builders. The KBOB was founded in 1968 as a coordinating body of the federal building authorities, namely for questions of submission, the inflation compensation on construction works and the architect and engineer fees. Source: https://www.kbob.admin.ch/

[4] eco-bau - The eco-bau association was founded in 2005 to promote sustainable building environment. Members of the association are public builders of the federal government, cantons and cities as well as organizations such as KBOB, crb and educational institutions. Source: https://www.eco-bau.ch/

[5] IPB (Interessengemeinschaft privater professioneller Bauherren) - Interest group of private professional builders. The association represents the interests of private professional builders, service providers, trade associations, authorities and other organizations. Source: http://www.ipb-online.ch/

[6] crb - competence center for standards in the construction and real estate industry in Switzerland. Together with professional and partner organizations, work equipment is developed and provided in the form of catalogs, web applications and data for software programs. Source: http://crb.ch.

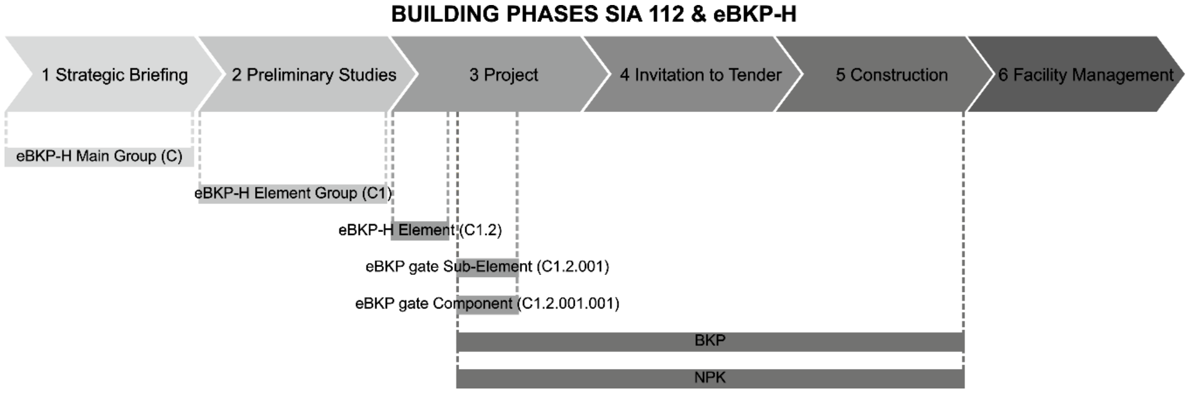

Figure 2: Cost-planning system over the building process (eBKP-H, BKP, and NPK) developed by crb (crb, 2017)

3. Methodology

In developing an integrated BIM-LCA workflow for the whole building process, the following methodology is used. It consists of four main steps. First, the relationship between the building phases in Switzerland (SIA) and the Level of Development (LOD) is identified. Second, the relationship between LCA databases and the cost-planning structure in Switzerland (eBKP-H) is determined. Third, based on the relation between the building phases, the LOD, the LCA databases and the cost-planning structure, a new, process-structured LCA database for building components is developed. Fourth, the newly developed LCA database is connected to a BIM model employing a dynamic tool. The tool is applied in a case study building to validate the applicability throughout the building process.

3.1 Relationship between building phases in Switzerland (SIA) and Level of Development (LOD)

The building phases are related to the LOD throughout the entire building process. The building phases and the related LOD are mapped on top of each other while pointing out their relation to the LOG and LOI. As the process evolves, building components and materials part of it are better defined. The building process is divided into two parts. From building phases 1 to 3, a simplified component-based approach is considered, while from building phases 4 to 6, a detailed material-based approach is proposed (Figure 3).

3.2 Relationship between LCA databases and cost-planning structure in Switzerland (eBKP-H)

The LCA databases used for the evaluation of the building are the Bauteilkatalog and the KBOB database. The Bauteilkatalog provides information regarding the simplified component-based approach, while the KBOB database serves for the evaluation of the detailed material-based approach. For the assessment of the simplified component-based approach, the cost-planning structure provided by eBKP-H is used and mapped with LCA data for different building elements and sub-elements. The cost-planning structure is used as a base for the evaluation of the detailed material-based approach as well, mapping the eBKP-H building elements structure with the KBOB material one.

eBKP-H provides a methodology that is acknowledged for BIM model creation and elements identification through a code-base system for cost estimation. The structure of the BIM model reviewed during the case study analysis is composed according to it. Each building element part of the BIM model is associated with a code for its identification. In that way, information derived from LCA databases can be associated with the code system provided by the cost-planning structure (Figure 3).

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3.3 New process-structured LCA database

The identified relationship between the building phases (SIA) and the Level of Development (LOD) is associated with the recognised relationship between LCA databases and the cost-planning structure (eBKP-H). Through the identification, the building phases and LOD are related to the LCA databases and the cost-planning structure. A new process-structured LCA database is composed following the identification (Table 1). LCA values and LCA benchmarks are provided by the database. The database is later incorporated in automated workflow and dynamic tool for LCA so that the implementation of BIM-LCA calculation and integration is achieved.

For the evaluation of the simplified approach, building components with different LOD are taken into account. Since in building phase 3 there is enough information regarding the concept of the building itself, it is assessed with specific values of building sub-elements. In building phase 2, most commonly used building sub-elements are taken into account and grouped according to the Element or Element Material groups. These groups are evaluated with an average value, based on the Sub-Elements that are composing them. Similar logic is applied for the evaluation of building phase 1 – building Element Groups are evaluated with an average value from building phase 2. For the detailed material-based approach, information regarding the building materials is assessed. In building phase 4 data about the materials As-Planned is used, while in building phase 5 information about the As-Built materials. In building phase 6, the materials are evaluated based on their Reference Service Life (RSL). In that way, the whole building process is evaluated, providing a method for LCA that is applied continuously over the entire building process (Figure 3).

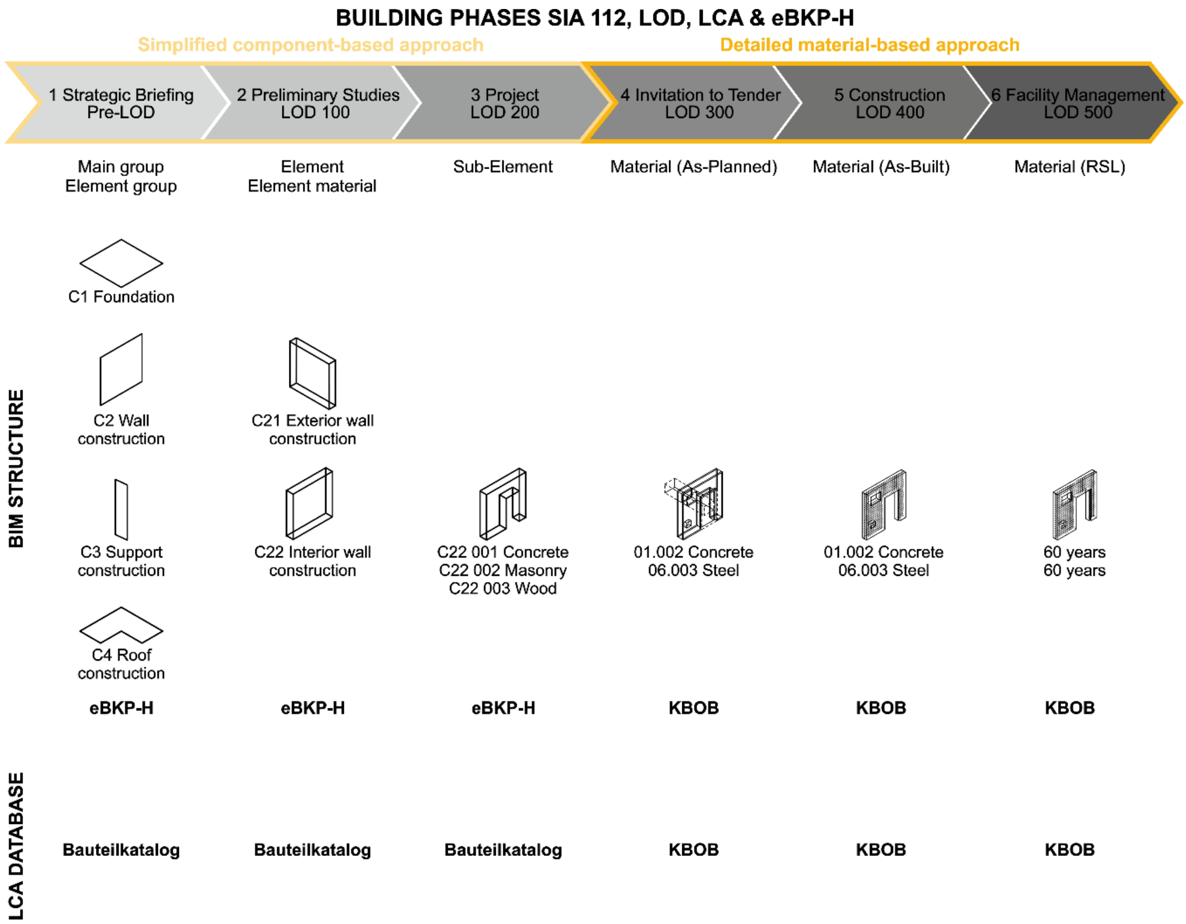

Figure 3: Relationship between building phases in Switzerland (SIA), Level of Development (LOD), LCA databases and cost-planning structure in Switzerland (eBKP-H)

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3.4 Developing a link between the new process-structured LCA database and BIM – dynamic tool for LCA

A dynamic tool for LCA is developed to link the new process-structured LCA database and BIM. The tool is created in the parametric program Dynamo and connected to the BIM program Revit. A case study analysis is used as a research approach for the development of the link. The aim behind the implementation of the new process-oriented LCA database into a dynamic tool is to provide an automated method for a BIM-based LCA calculation, leading to a BIM-LCA integration.

Through the creation of the tool, a dynamic workflow is developed (Figure 4). The workflow uses the existing code-structure part of the BIM and links it to LCA values from the new process-structured LCA database. In that sense, the tool builds upon the existing methodology for BIM creation by adding additional value in the sense of LCA evaluation opportunities.

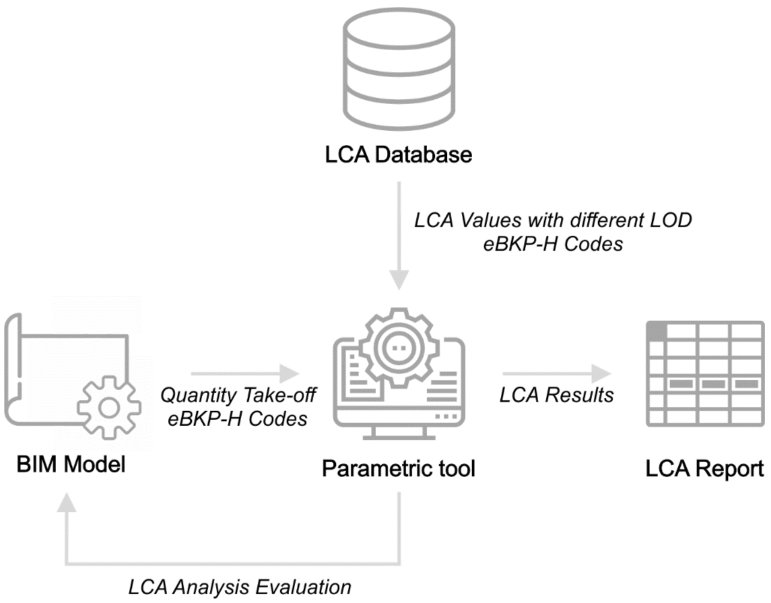

Figure 4: Developing a link between the new process-structured LCA database and BIM – dynamic workflow

Three steps are followed for the development of the link: LCA parameters creation, calculation and check, and LCA Report. Through the LCA parameters creation, LCA parameters are calculated, checked and filtered for their evaluation and visualisation. The results are then exported in the form of an LCA Report.

Step 1: LCA parameters creation

The first step is related to the creation of LCA parameters in Revit. The reason behind is to provide a basis for the evaluation of building components, part of the BIM geometry. Native BIM libraries do not contain information regarding specific LCA parameters and lack a basis for the provision of environmental evaluation. The LCA parameters creation enables the possibility for assessment of building geometries.

Parameters related to grey energy[7], GHG[8] and UBP[9] are created and incorporated in the BIM. Once the parameters are created, they are assigned to different Revit element categories (e.g., walls,

[7] Grey energy - Grey energy is defined as the non-renewable primary energy associated with a manufacturing and disposal of a product (SIA 2032).

[8] GHG (greenhouse gas) – The global warming potential of the greenhouse gases are provided in CO_2-equivilant calculated based on the IPCC 2013 method.

[9] UBP – a point system that quantifies the environmental impact using a single score based on the method of ecological scarcity.

floors, roofs). The values are extracted from the new process-structured LCA database. The database provides information regarding LCA values and LCA benchmarks for both the calculation and evaluation of building components. The automated creation of project parameters in Revit eliminates the need for manual parameters input.

Step 2: Calculation and check

The second step is related to the calculation of LCA values (Bauteilkatalog, 2016) and check of LCA benchmarks (Hollberg et al., 2019; SIA, 2019) at both the element and building levels (MINERGIE, 2014).

The calculation is done through a mapping of eBKP-H codes part of the new process-structured LCA database to eBKP-H codes assigned to building components. The quantities of building components are derived from the BIM model. LCA values with different LOI can be extracted from the LCA database according to the building phase and the LOD. After extraction LCA values are multiplied with the respective building element quantities from the BIM model. The results are then filled in the LCA parameters created during the first step and compared to the LCA benchmarks. Subsequently, the calculation and check at the element level, the same is accomplished at the building level. The calculated LCA values for all building components are gathered and associated with the Energy Reference Area (ERA) (MINERGIE, 2014) of the building, providing a decision metric on a building level. The building elements` surfaces (for an indication on element level) and lines (for an indication on building level) are coloured in three colours: red (above), orange (at), and green (below) following the LCA benchmarks (Figure 5). As such, the second step provides a decision-making metric through visualisation on both element and building levels for overall optimisation of the evaluated building.

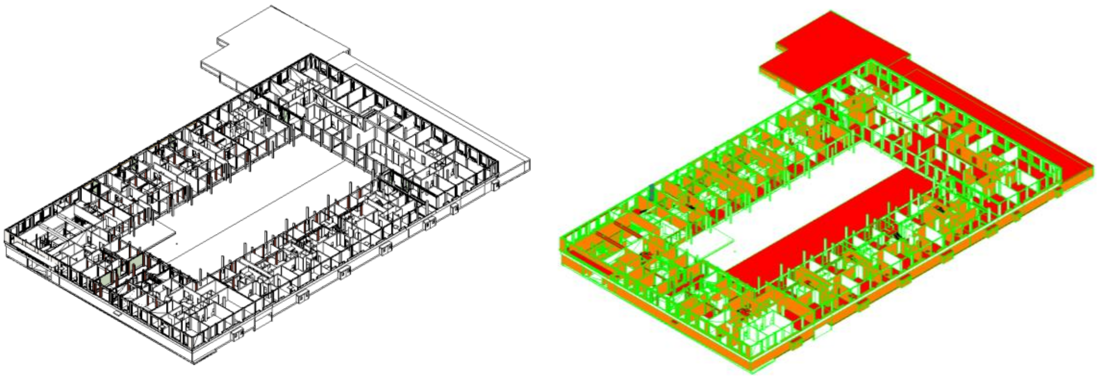

Figure 5: Dynamic tool for LCA – Step 2: Calculation and check

Step 3: Report

With the implementation of the third step, an LCA report is created. The values for all the LCA parameters are collected and summed up according to the different element groups. Finally, the information is extracted and input in an Excel sheet, while creating a table and graphs with the respective values on the respective LOD.

3.5 Case study description and dynamic tool for LCA test and calibration

The case study is provided by the Swiss construction company Implenia. Implenia is a leading construction and construction services firm in Switzerland. It also has strong positions in the German, French, Austrian, Swedish and Norwegian infrastructure markets, as well as significant building construction and civil engineering operations in Germany and Austria[10].

Source: (MINERGIE, 2014).

[10] More information can be found at www.implenia.com.

The case study itself is a mixed-use new building called Krokodil (Figure 6). The building is located in the Lokstadt district, in Winterthur, Switzerland. The project has started in 2016 and is expected to be completed in 2020. The gross floor area of the building is 31 559 m². The building is composed of eight floors above ground level and two floors below. The general planner and the total entrepreneur of the project is Implenia. One of the main strategic goals of the project design is the achievement of the sustainability targets set by the 2000-Watt Society[11].

The case study analysis helps for the derivation of the results. For that purpose, two floors of the building are extracted for their prompt evaluation. In that sense, the results provided by the assessment do not resemble the environmental impact of the whole building. The dynamic tool for LCA developed is tested on the case study and calibrated according to the results.

Figure 6: Case study – mixed-use new building Krokodil, Lokstadt, Winterthur, Switzerland (Source: Implenia)

4. Results

4.1 Process-structured LCA database

Through the developed relationship between the building phases in Switzerland (SIA), the Level of Development (LOD), the LCA databases and the cost-planning structure in Switzerland (eBKP-H), a new process-structured LCA database is created (Table 1: New process-structured LCA database). The database is structured according to different building phases (SIA, 2014) and their related LOD (Curschellas et al., 2018). The building phases mapped with LOD are then related to the existing code-based structure for cost-planning (eBKP-H) (crb, 2012). Data from existing LCA databases regarding building elements is used to provide LCA values (Bauteilkatalog, 2016) and LCA benchmarks (SIA, 2019). This data is then related to the other eBKP-H groups.

[11] 2000-Watt Society is a program created by The City of Zurich that defines target values for 2050 year of 3500 Watts and 2 tons of CO_2-eq per person. The program sets goals related to consumption, settlement, buildings, energy supply and mobility for reaching these target values (City of Zurich, 2011).

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Pre-LOD		LOD100		LOD200								
1 Strategic Briefing		2 Preliminary Studies		3 Project								
					LCA Values				LCA Benchmarks			
eBKP-H					Bauteilkatalog				SIA2032/ETH Zurich			
Main group	Element group	Element	Element material	Sub-Element	Unit	Grey Enegry (SIA 2032) (MJ)	GHG (kg CO2-eq)	UBP 06 (Pt.)	Unit	Grey Enegry (SIA 2032) (MJ)	GHG (kg CO2-eq)	RFL
C	C2				m2.year	12.19	1.24	1541.81	m2.year	12.60	1.16	48.00
		C21			m2.year	13.36	1.33	1682.42	m2.year	8.94	0.78	45.75
			C21 Element concrete		m2.year	16.90	1.47	1529.50	m2.year	12.83	1.35	47.25
				C2.1A 029 Concrete wall up to K32, 20 cm, B 90kg/m3	m2.year	11.99	1.32	1879.00	m2.year	14.20	1.42	51.00
				C2.1A 030 Concrete wall over K32, 25 cm, W 85kg/m3	m2.year	14.23	1.59	2242.00	m2.year	14.20	1.42	51.00
				C2.1A 031 Concrete wall above K32, 25 cm, waterproof, B 110 kg/m3	m2.year	15.63	1.67	2495.00	m2.year	14.20	1.42	51.00
				C2.1B 029 Concrete wall up to K32, 20 cm, B 90kg/m3	m2.year	15.13	0.78	1731	m2.year	12.00	1.30	45.00
				C2.1B 030 Concrete wall over K32, 25 cm, W 85kg/m3	m2.year	31.29	3.02	2381	m2.year	12.00	1.30	45.00
				C2.1B 035 Concrete wall up to K32, crude, 20 cm, B 90 kg/m3	m2.year	20.72	2.10	1499.00	m2.year	12.00	1.30	45.00
				C2.1B 036 Concrete wall over K32, crude, 20 cm, B 105 kg/m3	m2.year	11.99	1.30	1879.00	m2.year	12.00	1.30	45.00
				C2.1B 037 Concrete wall above K32, crude, 25 cm, B 105 kg/m3	m2.year	14.23	1.6	2242.00	m2.year	12.00	1.30	45.00
			C21 Element masonry		m2.year	8.78	0.93	1171.75	m2.year	8.00	0.70	45.00
				C2.1B 038 Brick BN, raw, bearing, 15 cm	m2.year	11.05	1.20	1781.00	m2.year	8.00	0.70	45.00
				C2.1B 040 Brick KS, raw, bearing, 15 cm	m2.year	11.73	1.30	1902.00	m2.year	8.00	0.70	45.00
				C2.1B 060 Aerated concrete 36.5 cm	m2.year	6.83	0.60	475.00	m2.year	8.00	0.70	45.00
				C2.1B 061 Single brick work, high hole brick 42.5 cm	m2.year	5.50	0.60	529.00	m2.year	8.00	0.70	45.00
			C21 Element wood		m2.year	14.41	1.60	2346.00	m2.year	6.00	0.30	45.00
				C2.1B 058 Wooden frame construction	m2.year	14.41	1.60	2346.00	m2.year	6.00	0.30	45.00
		C22			m2.year	11.01	1.15	1401.21	m2.year	11.00	0.90	45.00

Table 1: New process-structured LCA database

4.2 Dynamic tool for LCA

The developed link between the new process-structured LCA database and BIM results in a dynamic tool for LCA. The tool is generated in the software program Dynamo and applied on the case study building. On Figure 7, results derived after running the Dynamo scripts on BIM models from building phases 22, 31, and 32 with different LOD are shown. The results provide information regarding grey energy (MJ/a) in different building elements and building elements groups. The application of the tool helps to distinguish the amount of various environmental parameters in the different building phases.

On the BIM from building phase 22 calculations regarding Main Group and Element Group (Pre-LOD), and Element and Element Material (LOD100) are performed. Changing the Level of Development from Pre-LOD to LOD100, different Elements are distinguished from the different Element Groups, providing more precise information regarding each Element. In LOD100, the impact of varying Element materials is highlighted. Results regarding Element Material Concrete (LOD100) and Element Material Wood (LOD100) are compared to Element (LOD100).

The dynamo scripts are run from building phases 31 and 32 giving results regarding Sub-Element Materials (LOD200). For that purpose, specific wooden building components with low LCA values from the LCA database are chosen. Comparing the results between building phase 31 and 32, the grey energy is increasing.

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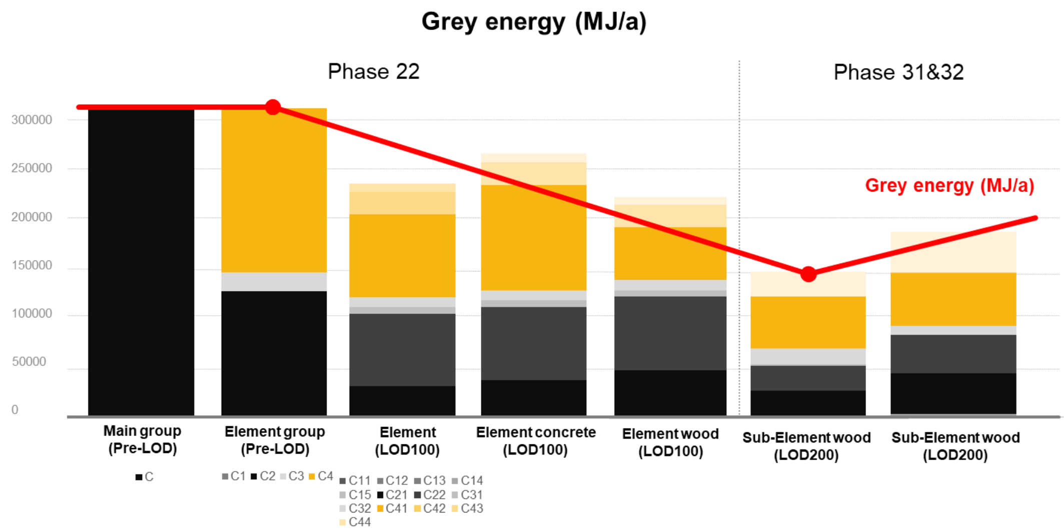

Figure 7: Test and calibration of dynamic tool for LCA

5. Discussion

5.1 Limitations

5.1.1 Information Modelling

Incompleteness of BIM Models

There are limitations related to the incompleteness of BIM models. These limitations can also be associated with the incompleteness of the IFC files used for their creation. Furthermore, the incompleteness of BIM models can be caused by issues related to the application of IFC models to different BIM software programs. Two general trends are identified in relation to these limitations. The first one is related to missing building elements (e.g. HVAC elements) and building sub-elements (e.g. finishing plaster within a wall element). The second one is regarding missing parts of the BIM geometry as well as information assigned to it (e.g. different parameters or eBKP-H codes). These limitations lead to an incomplete BIM model and incomplete Bill of Quantities (BOQ).

BIM models' LOD

Some building elements (structural elements) are defined before others (claddings). These issues lead to variability between the LOD of different components. Another critical point in that sense is that even if structural elements are defined, the materials they are identified with still do not represent the same LOD as the BIM model. For example, composite walls composed of concrete and steel are modelled with only concrete as a material. That means that if such elements are evaluated in terms of grey energy and other LCA parameters based on their material content, such evaluations will not represent the actual LCA values. Therefore, it can be concluded that the usage of some materials in BIM is slightly related to a group of materials rather to a particular single one.

BIM Models' modelling methodology

The concept behind the dynamic tool for LCA and the related workflow developed in this study are strongly associated with the modelling structure used in BIM models. The main idea adopted from this methodology is that different building elements in the BIM model are distinguished according to the Swiss cost-planning structure for buildings developed by crb (eBKP-H). These element codes are later mapped to an LCA database structured according to the same code system. That means that if the BIM methodology does not incorporate such a code system, this mapping would not be possible unless such codes are assigned manually in the BIM model before its LCA evaluation. The limitation can be prevented if eBKP-H codes are mapped to the model-specific BIM structure in advance. In the case study, the LOD of the codes assigned in the BIM model is LOD100.

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For that reason, the codes from this LOD are used for the evaluation of LCA in LOD200 as well. That leads to the fact that different Sub-Elements levels could not be identified in different elements level. For example, all interior walls are considered to be from the same type, since they all have the same code assigned. In that sense, a higher level of LOD code differentiation would lead to more detailed results and better decision-making metrics.

5.1.2 LCA Databases

New process-structured LCA database

Using average values for Elements and associating them with Element Groups implies that different Elements are equally distributed in different Element Groups. For example, Element Group C2 Walls is composed of Elements C21 Exterior Walls and C22 Interior Walls. Taking the average value of these two Elements would mean that the Element Group C2 Walls is composed of 50% interior and 50% exterior walls, which is not precise. Still, for an early estimation when there are not sufficient details about the further development of the building project, such simplification can be taken into account for LCA estimation. Hollberg et al. (2019) use benchmarks based on the market share of different building materials within Switzerland to provide more realistic values. These could be integrated into the database in the future.

Existing LCA databases

The main issue with LCA databases is that they do not declare LOD, leading to the possibility of imprecise application time, as well as inaccurate LCA results. Another problem is that LCA databases are inconsistent in terms of variability of proposed building components and materials used in them. For example, most databases focus mainly on traditional building components and neglect the usage of more sustainable and bio-based materials. There is also variability in the units used in the databases. Regarding BIM-LCA integration, the biggest challenge associated with LCA databases is their structure and its difference when compared to the BIM modelling structure.

5.2 Future potential

5.2.1 Information Modelling

BIM model structure

There is a need for a common modelling structure to be recognised and adopted by different specialists when they are developing various building projects. This structure should be associated with different LOD and their related LOI and LOG. A common BIM structure used for different project needs will provide a more straightforward implementation and easier evaluation for the building elements it is applied to. For that reason, researchers and specialists working in different disciplines of the building industry should find a common ground for standardisation of common building components, elements, and sub-elements.

The method of using an existing cost-planning BIM structure for LCA evaluation gives construction companies an incentive to implement LCA without additional efforts. Moreover, through the implementation of this automated method, the manual input of data is limited and hence, the potential of errors, caused by the human factor, minimised. Another associated benefit is the capacity to provide decision-making support while implementing LCA values and LCA benchmarks, related to the different building phases and their associated LODs at both the element and building levels.

The method applied in this research strongly relies on the information provided and the structure implemented in the case study developed by the Swiss construction company Implenia. Case studies from other construction companies of the same scale should be reviewed so that different approaches are compared. In addition, case studies from different planning companies, e.g., architectural offices, should be considered as well. The method is also strongly dependent on the existing databases and cost-planning structure in Switzerland. Nevertheless, the method can be adapted to other national contexts using databases and structures from other countries.

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openBIM

There is a future potential for improvement of the approach, applied in this study, by adopting the following trends:

- Trend 1: Incorporating LCA parameters in the methodology for the BIM model creation (Figure 8);
- Trend 2: Using IFC files for LCA evaluation (Figure 9).

For the first trend, LCA parameters should be part of the methodology during the project creation (Figure 8). If LCA parameters exist in the model from its very beginning that would allow different specialists involved in the building process to evaluate such parameters in their desired software environment. In that way, the need to import the LCA database in a later phase of the building process would be eliminated. There are several ways in which that can be accomplished. One way is for the LCA database to be incorporated in the form of an openBIM file (IFC). Another is to integrate LCA databases in the form of closedBIM files (Revit, ArchiCAD). Data storage methods (XML, SQL) can also be used for the provision of LCA values. Trend 1 can be associated with the provision of decision-making metrics while modelling the project.

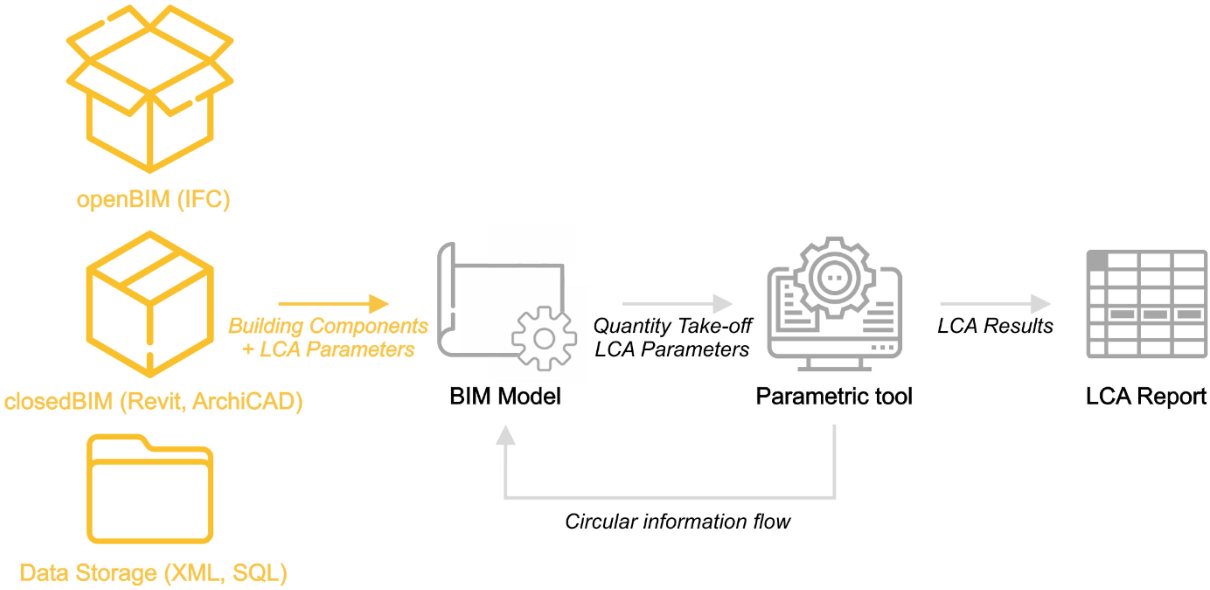

Figure 8: Trend 1: Incorporating LCA parameters in the methodology for the BIM model creation

For the second trend, IFC files could be used for LCA evaluation (Figure 9). That would allow for the BIM model to be created in a desired BIM software program and then exchanged in the form of IFC file. Several criteria are identified related to that approach (Santos, Costa, Silvestre, and Pyl, 2019):

- BIM library requirements, a BIM guideline and a Model View Definition (MVD);
- An IFC file model checker to ensure that the IFC file contains all the relevant information;
- An IFC Viewer Plugin or a newly developed software tool that performs the LCA Evaluation.

For the creation of an IFC-based tool for LCA evaluation, a specific IFC viewer software program is required. This fact comes to imply again that an approach for BIM-LCA integration is associated with the exchange of information between different software programs. The trend can be pointed out as an approach providing consultation on the project regarding the usage of materials in it, rather than improving it by changes on the form, since the project's geometry cannot be remodelled.

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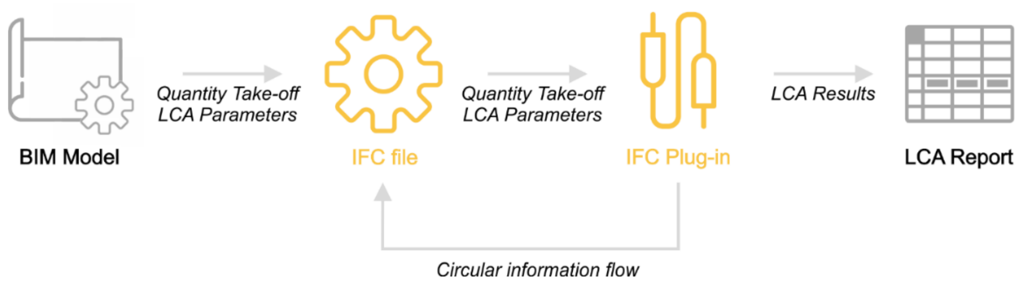

Figure 9: Trend 2: Using IFC files for LCA evaluation

5.2.2 LCA databases

Future potential can be identified with further development of LCA databases. Existing LCA databases can be restructured so that different building phases and LOD levels are distinguished. The databases should adopt a standard generalised code structure that is related to different LOD levels for their more straightforward implementation in BIM. LCA values should be incorporated into existing building components and libraries, BIM families, pre-fabricated elements, technical equipment. At the same time, LCA parameters should be distinguished using a standardised LCA dictionary, which provides keywords associated with LCA so that a common understanding is achieved.

The new process-structured LCA database relies on information from databases, which consist of only traditional components and materials. In that sense the proposed method is useful for mass construction, but not for innovative construction solutions. Development of databases for bio-based materials, as well as recycled and innovative materials, should be considered for their easier implementation in buildings and for large companies to have a higher motivation to use them.

5.2.3 Dynamic tool for LCA and new process-structured LCA database

Since the dynamic tool for LCA and the new process-structured LCA database are developed until building phase 3, project (SIA), there is a future potential for their development in building phases 4 to 6, adopting a detailed material-based approach for LCA. There is also a potential for the development of a tool with a specific approach for building phase 1, strategic briefing, since, in that phase, there is usually no BIM model. This tool can be developed using the software program Grasshopper in combination with modelling software tools like Rhino or ArchiCAD, which are typically associated with providing decision-making metrics during conceptual design phases.

The proposed dynamic tool and workflow for LCA evaluation account only for embodied energy. An operational energy impact is not considered. However, the same logic can be applied for the future development of a tool and workflow for evaluation of operational energy. Nevertheless, it is essential to highlight, that in newly developed energy-efficient buildings, the impact of embodied energy often exceeds the one from operational energy (Azari and Abbasabadi, 2018). In that sense, the dynamic tool and the related workflow developed in this study provide an instrument to account for the contribution of a type of energy in buildings, which has a higher overall impact.

5.2.4 Decision-making

The newly composed LCA database (错误!未找到引用源。) provides a code-base that is commonly used for BIM modelling in Switzerland, meaning there is no need for data re-entry and restructuring. The eBKP-H structure is used for the evaluation of different Green Building Standards as well (SIA, 2019; MINERGIE, 2014). Once the LOD is better defined, there is a base for better decision-making (错误!未找到引用源。).

The results derived after running the dynamic tool for LCA provide only concrete numbers, based on the quantities of the building elements and the building's gross floor area. Still, there might exist other indicators that can be taken into account. For example, if a building element's LCA values are above the associated LCA benchmarks, this element can still be better positioned when related to

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the whole building than two elements with LCA values at the LCA benchmarks. This issue is partly addressed by the provision of decision-making metrics at the building level, taking into account all building elements and associating them with the whole building. However, there exist other possibilities to provide more sophisticated decision-making metrics, for example, by implementing artificial intelligence opportunities and machine learning. In that sense, artificial intelligence opportunities and machine learning can be pointed out as a way to address decision-making metrics during the building process in the future.

There is future potential in developing similar tools by adopting similar workflows for different purposes, for example, to evaluate operational energy or Life-Cycle Costing (LCC). The scripts can be optimised, and their computation done on a cloud source so that the time for their evaluation is reduced. Machine learning metrics are another general approach that can be used for future improvement of the method, for example, for smart mapping of components, elements, sub-elements, and materials.

6. Conclusion

The current study proposes a methodology for companies in Switzerland to perform LCA continuously in each building phase over the entire building process. The method provides decision-making support at both the element and building levels at every building phase and their associated Levels of Development (LOD). For its implementation, to prevent the re-entering of data, an existing cost-planning code structure (eBKP-H) applied in BIM for cost estimation is used. In that way, the methodology proposed in this study provides LCA results using an existing BIM structure while giving an incentive for construction companies to apply LCA methods in a simplified way.

For the development of the methodology, a new process-structured LCA database is created. The database is structured according to the building phases that are part of the building process in Switzerland (SIA), their associated LOD, LCA databases and the cost-planning structure for cost estimation in Switzerland (eBKP-H). By these means, the database provides information about embodied environmental impacts for each building phase and its associated LOD, accounting for the environmental evaluation of the entire building process. Information about both LCA values and LCA benchmarks is provided, giving an incentive for decision-making metrics on both element and building levels, while implementing visualisation criteria. Through the implementation of the database, the existing cost-planning BIM code structure (eBKP-H) is used, leading to the prevention of the re-entering of LCA data into the BIM model. Therefore, mistakes associated with the human factor are prevented and time is saved.

The database is linked to BIM using a newly created dynamic tool for LCA. The tool connects the BIM model and the LCA database, calculates LCA values, and returns the results in the BIM model. After the results become part of the BIM, they are compared to the LCA benchmarks part of the LCA database. In that way, decision-making support through colour differentiation is achieved, based on the benchmarks for different building elements on the element and building levels. The application of the dynamic tool for LCA provides optimisation for the evaluation of materials used in buildings in a simplified way.

BIM integration in different parts of the building process is a powerful approach through which various areas of it can be optimised. Methodologies, similar to the one developed in this study, can be generated to improve specific areas of specialists' daily work. These methodologies can be applied in different case studies providing a proof of concept with different purposes. Information regarding different use cases can be formed according to LOD and an algorithm for their implementation in BIM provided. This information should be simplified and standardised for its easier assessment. Accordingly, simplification and standardisation of the building process through its digitalisation have the potential to improve its overall sustainability.

Supplementary Materials: The following are available online at https://www.youtube.com/watch?v=tPTFwZB-irU, Video: BIM and LCA: Dynamic BIM-based LCA with different LOD.

Author Contributions: conceptualisation, AN; methodology, AN, MB and AH; software, AN; validation, AN; formal analysis, AN; investigation, AN; resources, AN; data curation, AN; writing—original draft preparation, AN; writing—review and editing, AN, MB and AH; visualisation, AN; supervision, AN, MB, AH, GH and DH; project administration, MB and DH.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank Alar Jost for identifying the need and the given opportunity for collaboration between ETH Zurich and Implenia on BIM-LCA related topics.

Conflicts of Interest: The authors declare no conflict of interest.

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