Using systematic building decomposition for implementing LCA

The results of a comparative analysis as part of IEA EBC Annex 72

Soust-Verdaguer, Bernardette; Potrč, Tajda Obrech; Alaux, Nicolas; Hoxha, Endrit; Saade, Marcella Ruschi Mendes; Röck, Martin; Garcia-Martinez, Antonio; Llatas, Carmen; Gómez de Cózar, , Juan Carlos; Passer, Alexander

Published in:
Journal of Cleaner Production

DOI (link to publication from Publisher):
10.1016/j.jclepro.2022.135422

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Journal of Cleaner Production 384 (2023) 135422

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Using systematic building decomposition for implementing LCA: The results of a comparative analysis as part of IEA EBC Annex 72

B. Soust-Verdaguer [a,b], T. Potrč Obrecht [b,c], N. Alaux [b], E. Hoxha [b,e], M.R.M. Saade [b], M. Röck [b,d], A. Garcia-Martinez [a], C. Llatas [a], J.C. Gómez de Cózar [a], A. Passer [b,*]

[a] Universidad de Sevilla, Instituto de Arquitectura y Ciencias de la Construcción, Spain
[b] Graz University of Technology Working Group Sustainable Construction, Austria
[c] Slovenian National Building and Civil Engineering Institute, Slovenia
[d] KU Leuven, Design and Engineering of Construction and Architecture, Belgium
[e] Department of the Built Environment, Aalborg University, Denmark

ARTICLE INFO

Handling Editor: Zhen Leng

ABSTRACT

The building Life Cycle Assessment (LCA) applied to buildings requires collecting and organizing large quantities of data over all building life cycles. To overcome specific difficulties related to the system boundaries definition and life cycle inventory stages, the literature recognizes that systematic building decomposition methods (SBDM) can be used to classify building components, elements and materials, as well as to increase the reliability and transparency of LCA results, particularly for embodied carbon and other environmental impacts. In this paper developed in the context of the research project IEA EBC Annex 72, the authors aim to provide a basis for understanding how different SBDMs decompose a building and classify its parts. This study analyses the implications of using different SBDM along the steps of an LCA study. Such as to support transparent and comprehensible (de)composition of the life cycle inventory (LCI), definition of service lives for different building parts or clear and comparable communication of assessment results and environmental hotspots particularly when using digital tools to conduct LCA. The study analyses 12 national SBDMs used in participating countries of IEA EBC Annex 72. To showcase the implications of SBDMs in building LCA practice, an office building was used as a common case study for applying the different SBDM approaches. Differences were identified among the decomposition levels and the consequences of these differences on the LCI organization. Thus, some of the main contributions to this study are the investigation of different SBDM approaches for improving the design workflows, by discussing BIM model definitions and the recommendation to use hierarchically based methods to allow the building elements and materials decomposition.

1. Introduction

The Life Cycle Assessment (LCA) methodology calculates the potential environmental impacts caused by a product, such as a building. The method described in ISO-14040 (ISO, 2006a), ISO-14044 (ISO, 2006b) and particularly in EN-15978 (EN, 2011) can be applied to define the scope of the study, life cycle stages to be considered within the system boundary and determine the calculation procedure of environmental impacts. The standard recognizes the use of a structure to systematically organize the mass and energy flows in the LCA application at the building scale. In the Annex A.1, it proposes using an example of different decomposition levels from building to material level. However, specific guidelines on how to structure the building information or how to conduct the systematic building decomposition (i.e., how to decompose the building into systems and building components) are not specifically defined.

The use of a systematic building decomposition method (SBDM) can provide a comprehensible and standardized information structure of the building, generally based on national standards or guidelines, to support for the preparation of data for LCA, its application to buildings and identify the different levels of hierarchy (e.g., building, element, material) (Soust-Verdaguer et al., 2020). These methods for reporting the life cycle embodied impacts of a building are also highlighted in European initiatives such as the sustainability assessment framework Level(s)

* Corresponding author. Graz University of Technology, Working Group Sustainable Construction, Austria.
E-mail address: alexander.passer@tugraz.at (A. Passer).

https://doi.org/10.1016/j.jclepro.2022.135422
Received 4 August 2022; Received in revised form 20 November 2022; Accepted 26 November 2022
Available online 7 December 2022

(Dodd et al., 2017). A hierarchical systematic building decomposition can facilitate the process of revising assessed components (Shipra Singh Ahluwalia, 2008). These levels of hierarchy for the building information can generally be composed by a first group that identifies the systems (such as Façade, Structure, Installations) or group of elements that compose the building, a second or third level composed by elements (such as columns, beams, etc.) and components, and subsequent levels composed by sub-elements, materials, products, manufacturer types, among other classifications (EN, 2011; Hoxha, 2015).

The use of a systematic structure to decompose the building is needed for several purposes. For example, to simplify the processes of data gathering and its organization (EN, 2011). The concept of classification applied to buildings is a means to describe construction entities in a standardized way (Afsari and Eastman, 2016). Thus, a classification system is consistent support for conducting systematic decomposition of the building parts. It is used to provide a reliable description of the building, to organize and relate the different parts and also as a common reference to name the different systems, elements and components, among others (Röck et al., 2018). The organization of the building information is addressed in the ISO 12006-2 standard (ISO, 2012), which defines a framework for construction sector classification systems and identifies a set of recommended classification tables (ISO, 2012).

Various classification systems for the building decomposition to conduct an LCA are proposed (Röck et al., 2018; Naneva et al., 2020; Shipra Singh Ahluwalia, 2008; Soust-Verdaguer et al., 2020). Soust-Verdaguer et al. recognize differences in the national and regional methods of decomposing and classifying building sections and its components. In the context of the IEA EBC Annex 72 (IEA EBC, 2017) project, various classification systems applied in different countries to the building decomposition when conducting LCA were identified. Thus, one detected challenge derived from the diversity in the organization and classification criteria included in the SBDM. Major differences are observed in the way the relations and classification criteria are to be defined. Another detected challenge is the lack of comparison and analysis of the criteria structure. The data structure for the building decomposition can influence the number of building elements, components, materials, etc. included in the life cycle inventory (LCI), or the service life definition (Hoxha, 2015). Hence, the different ways of decomposition are also factors of influence on the results. Palumbo et al. (2022) compared two LCA methods for achieving sustainability certification frameworks (DGNB and Level(s)) and demonstrated that these differences in the building system boundaries could influence the LCA results. A third detected challenge is a lack of comparison and comprehensive analysis of the SBDM to conduct the LCA.

A special focus is given to the systematic decomposition of buildings and classification systems in building information modelling (BIM), since the use of digital tools for designing and constructing buildings has changed rapidly over the past few decades (Volk et al., 2014). The extensive use of BIM tools for supporting design and construction is recognized to have modified "the way we deal with information in the construction sector, transferring information contained in traditional documentation to ICT-handled data objects with attached information representing the construction complexes and entities, the spaces, and the elements" (International Construction Information Society, 2017). This integration can provide, among others, a common language, a structure for building decomposition, and ways of managing information more uniformly (Röck et al., 2018) and transparently. The study by Cavalliere et al. (2019) demonstrates the potential of using a hierarchical systematic decomposition of the building based on the Swiss code eBKP-H (CRB Schweizerische; SIA Schweizerischer, 2012) for the construction works classification system. It related different data granularity to conduct the LCA at different design steps in BIM, using the Bauteilkatalog (*Bauteilkatalog*, n.d.) and KBOB (*KBOB (Koordinationskonferenz Der Bau- Und Liegenschaftsorgane Der Öffentlichen Bauherren)*, n.d.) to conduct the LCA at different levels (including construction categories, building component, constructive solution, material levels). Despite this, the question arises of what happens in other countries? Is the SBDM aligned with the BIM-LCA workflow? For example, what is the level of integration of the classification systems in the BIM workflow? Moreover, are the SBDM to conduct LCA aligned with the different level of development (Forum, 2021) and design stages in BIM? A recent review by Obrecht et al. (2020)) showed that besides many existing potentials and other open challenges, thus far, no study has focused on investigating the potential of different SBDM approaches for improving LCA and BIM workflows. Thus, the specific study of the SBDM integration in the BIM-LCA workflow has not been addressed before in the literature. In this context, integrating of data structures focused on the description, organization, classification and identification of objects in digital tools as BIM is a challenge.

The current paper provides a basis for understanding the different approaches to conducting systematic building decomposition in LCA. It emphasizes the classification and decomposition criteria that each method proposes and investigates the consequences of using different approaches to conduct LCA. Thus, the main goals of the paper are:

- To provide a basis for understanding how each national SBDM decomposes and classifies the building parts based on the ISO 12006–2 (ISO, 2012) standard for organizing information about construction works.
- To analyse the implications of using different SBDM in the aspects of LCA, such as the LCI completeness, communication of results and service life definition, and in the BIM-LCA workflow.

To that end, the paper presents the comparison of twelve national SBDM that are taken to perform a systematic building decomposition from the viewpoint of building LCA information management. Section 2 of this paper presents the research methodology and basis for collecting and analysing the different SBDM. A reference building (be2226) (Spirinckx et al., 2019) is used to illustrate the main differences and similarities among the national approaches, sizing the main detected challenges: the LCI completeness and information of the building organization, the references service life definition of the building parts and objects (Frischknecht et al., 2019; Spirinckx et al., 2018). Its implications in the BIM-LCA workflow are then presented in Section 3. Finally, based on these findings, Section 4 includes recommendations for using SBDM to improve the completeness of the building description, the transparency and the comparability of LCA results, while also allowing the integration of the LCA application into BIM.

2. Methods

2.1. Overall methodology

The procedure followed is a comparative analysis of the national SBDM for conducting LCA, which were provided by 12 of the IEA EBC Annex 72 participant countries: Austria, Belgium, Brazil, Canada, Czech Republic, France, Germany, Netherlands, New Zealand, Spain, Switzerland and UK. The analysis aimed at addressing the main detected challenges regarding SBDM and was organized following main steps (Fig. 1):

a) **An internal survey (within the IEA EBC Annex 72)** was performed to collect the national SBDM used to conduct building LCA in the 12 different countries. This step includes compiling the available standards, guidelines and information tables provided by the respecting countries.
b) **An analysis of the provided SBDM** was carried out, after organizing the data received in a similar format to facilitate the comparisons. The focus was set on the different levels of decomposition and classification of the building parts used, following the ISO 12006 (ISO, 2012) principles and definitions for organizing of information about

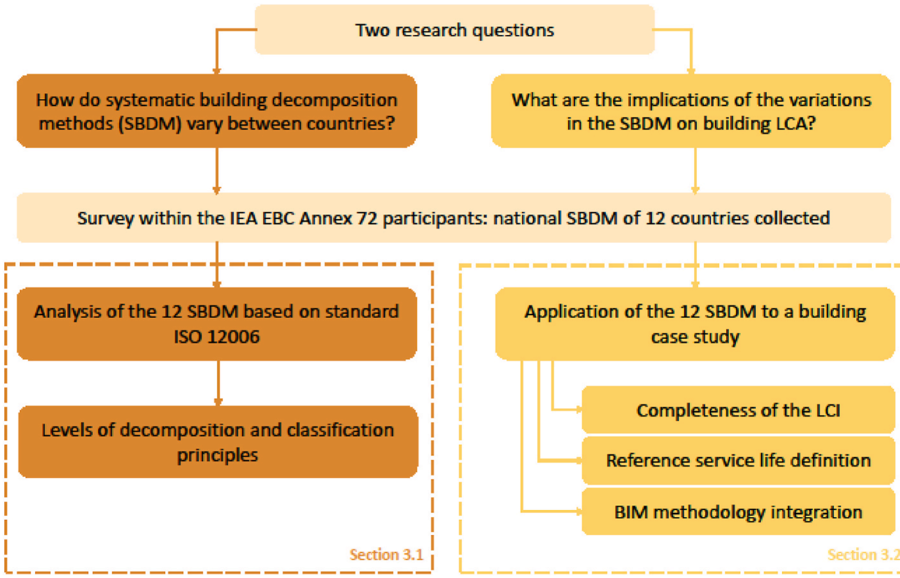

Fig. 1. Overview of the methodology and structure followed in this paper.

construction works. The overview of this analysis is presented in section 3.1.

c) **An application of the collected SBDM to a building LCA case study** was additionally performed. The office building "be2226" (Frischknecht et al., 2019) is used to illustrate the implications of using different SBDM on LCA-related data, such as the LCI, the communication of results and reference service life definition. Results are available in section 3.2. The implications of integrating these SBDM into BIM for LCA purposes are also addressed. Soust-Verdaguer et al. (2020) developed part of this work.

2.2. The framework used for the analysis of the SBDM

The ISO standard 12 006–2 provides a general framework to define the main organization criteria and principles (ISO, 2012), which can be used as a basis for developing the national SBDM. In order to detect the possible differences and analyse the organization criteria of each SBDM, the vertical levels and horizontal subdivisions were identified (see Fig. 2), based on the ISO 12006 principles of composition and classification (ISO, 2012):

- **Vertical levels** (composition principle according to ISO 12006–2): These usually follow a hierarchical structure starting with a first general level of decomposition, including the major groups' recognition, a second level including the element and component level, a third and fourth level including the product and material identification. For example, considering the structure, a first vertical level of decomposition can include columns, slabs and beams, among others.
- **Horizontal subdivisions** (classification principle according to ISO 12006–2): The horizontal subdivision generally refers to different classes and sub-classes of systems, by focusing on function, materiality, etc. For example, the first horizontal level of subdivision of a building can include the foundations, the interior walls, the envelope, the internal finishes, etc.

2.3. Case study analysis

The reference building (see Fig. 3) is referred to as the "be2226" and is an office building located in Lustenau (Austria). It was previously used as a reference building to compare national LCA methods in the IEA EBC Annex 72 ST 1 Activity 1.2 and reported in Frischknecht et al. (2019) (see Fig. 4).

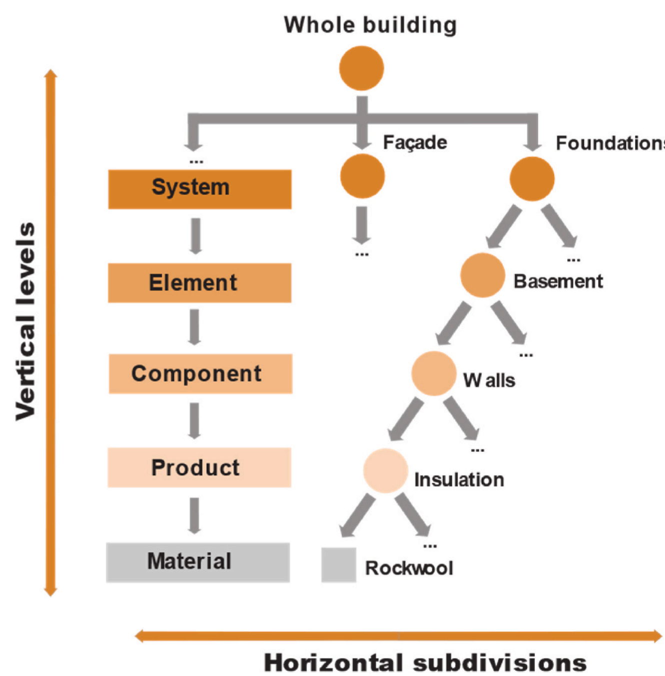

Fig. 2. Vertical levels of decomposition and horizontal subdivisions for buildings: principle and exemplary application adapted from ISO 12006–2.

The five-story building has an energy reference area of 2421 m^2. The building is a massive construction that consists of a pre-stressed and prefabricated concrete ceiling with overlay concrete. The façade is composed of two layers of hollow perforated bricks, covered on both sides with lime plaster (Frischknecht et al., 2019).

The present comparison started by using the same template information developed by (Frischknecht et al., 2019) to apply different national classification systems for the building decomposition and organize the building information. The template includes the building element types, including foundation, external walls, floor structure, roof structure, stairs, flooring, roofing, windows, doors and building services (see Table A1 Supplementary data). It was organized by a hierarchical structure that provides an element classification (including piles, slabs, etc.), a sub-element classification (including concrete for the

Fig. 3. View of the reference building (Source: exterior view Building 2226 Norbert Prommer).

foundation, etc.), and a material classification (including concrete in situ, reinforcing steel, etc.), which leads to three vertical levels of decomposition. The information in the template does not reach specific manufacturers for the materials; this information is thus not included in the structures for building decomposition of the reference building, which is a limitation of the present study.

The structure is organized according to the material quantity take-off that was automatically extracted from the BIM model of the building.

3. Results and discussion

3.1. Overview of state of play in annex countries

In the context of the IEA EBC Annex 72 participant countries, different national SBDMs are used to organize the information of the buildings when conducting the LCA. A summary of the collected contributions is presented in Table 1, including:

- Name of the country: Refers to the Annex participant country.
- Name of the standard or guideline: If it exists, this refers to the name of the code, standards, guideline or regulation of the SBDM.
- Main purpose: refers to the main purpose for which the SBDM was developed.

The SBDM used for building decomposition is generally composed of tables based on national standards for building construction cost estimations (e.g., UK, Germany, Switzerland). In several cases, they are based on national standards for the organizing of building parts or elements (e.g., Belgium). Other countries (e.g., France, Czech Republic) proposed specific structures for applying of LCA.

The overview of the collected data about the national SBDM is presented in Table A1, in the **Supplementary data section**. It provides evidence of the heterogeneity of the SBDM analyzed, which could be due to the differences in the classification of building elements, the criteria to organize the building elements (levels of decomposition and horizontal subdivision), and the naming codes.

3.1.1. Analysis and implications regarding the ISO standards aspects

Based on an in-depth review of the SBDM, it was identified that most of them (such as Austria, Belgium, Germany, Netherlands, New Zealand, Switzerland, Spain and UK) integrate at least three or four vertical levels of decomposition (from the complete building level to the element or material level): a first level integrates the general classification of the

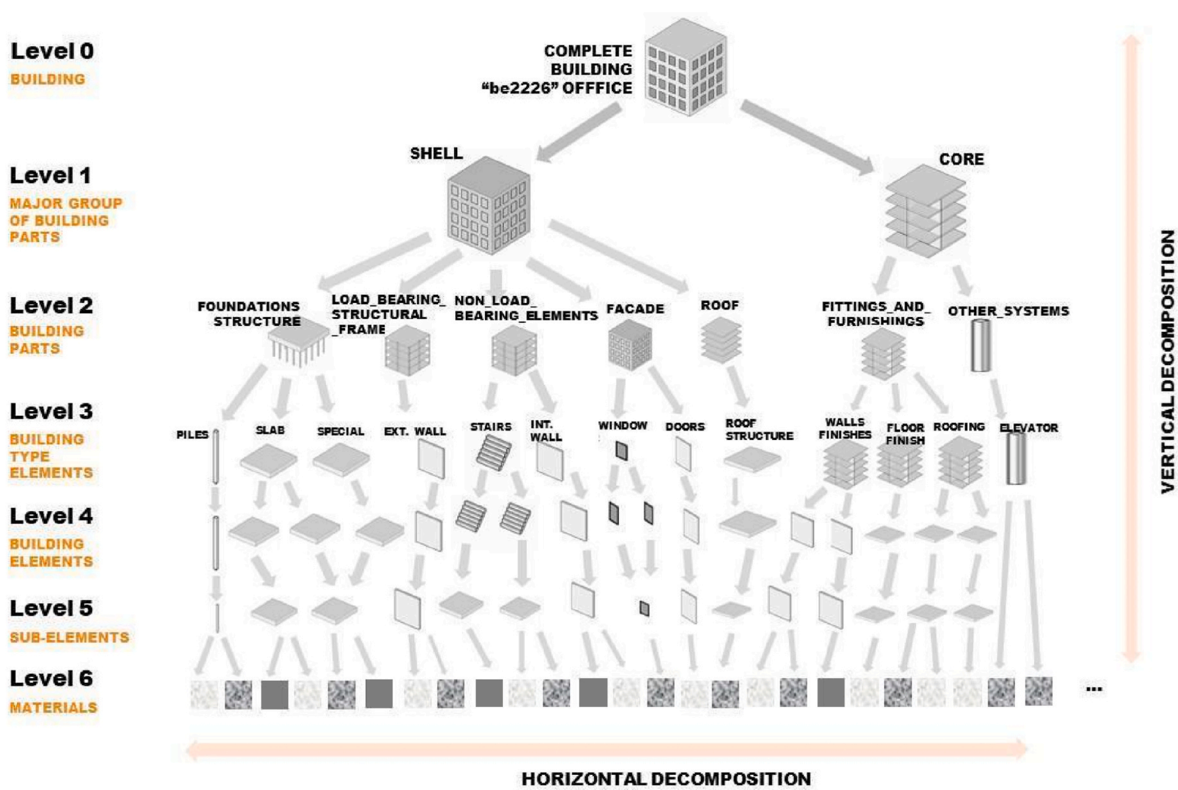

Fig. 4. Scheme for reference building decomposition using the Austrian standard (source: Soust-Verdaguer et al. (2020) prepared by authors based on ÖNORM B1801 (ÖNORM, 2015)).

Table 1
National SBDM used to organize LCA information.

Country	Standard or guideline based on	Main purpose
Austria	ÖNORM, ÖNORM B1801, 2015	Building construction cost estimation and LCA data structure.
Belgium	BB/SfB plus (De Troyer, 2008)	Classification and coding system, building construction cost estimation and LCA data structure.
Brazil	ABNT NBR 15575 (NBR 15575-1, 2013)	Building performance (also suitable for construction cost estimation and LCA data structure)
Canada	UNIFORMAT II Elemental Classification (E1557-97) (Charette and Marshall, 1999)	Building specifications, cost estimating, cost analysis and (also LCA data structure)
Czech Republic	Not specified – ad-hoc table	LCA data structure
France	EQUER (EQUER) model (Polster et al., 1996)	LCA data structure and energy demand calculation
Germany	DIN 276 (DIN, 2008) DIN 18960 (Siemon et al., 2021)	Building construction, cost estimation, (also LCA data structure).
The Netherlands	NL/SfB	Building construction, cost and LCA data structure
New Zealand	Uniclass 2015 (CPIc, 2015)	Building construction, cost estimation and LCA data structure.
Spain	CTE (CTE, 2006) (Spanish Building Technical Code) and BBCA (Andalusian Government, 2017)	Building construction, cost estimation, (also LCA data structure).
Switzerland	SN 506 511 (CRB Schweizerische, 2012)	Building construction, cost estimation and LCA data structure.
UK	SFCA (BCIS, 2012)	Building construction, cost estimation and LCA data structure.

building systems, a second level is composed of a group of elements classification, a third level is composed of an elemental classification and a fourth level integrates a material or product classification. None of the tables provide detailed specifications for the more detailed vertical levels of decomposition (such as material typology or manufacture levels), introduced by Hoxha (2015) as the highest levels of specification to describe the building parts when conducting LCA. Several exceptions to this include the Spanish (Andalusian Government, 2017), Belgian (De Troyer, 2008), Canadian (Charette and Marshall, 1999), French (Centre Efficacité énergétique des Systèmes de Mines ParisTech, n.d.), and Swiss (CRB Schweizerische; SIA Schweizerischer, 2012) data structures that include several specifications about the organization of the sub-element or/and the material level. For example, Switzerland uses the KBOB (*KBOB. Okobilanzdaten Im Baubereich*, n.d.) list of materials for defining the material level. The Spanish data structure (Andalusian Government, 2017), (developed for the cost estimation dataset and to organize the cost estimation database) provides a complete description of the systems and processes that comprise the building construction, including a description of the elements, sub-element, materials, products, machinery and labor, according to the regional technical characteristics (more detailed information is included in the Supplementary data section). This approach can provide a complete dataset and increase transparency when conducting the detailed modelling of construction (A5), replacement (B4) or deconstruction modules (C1), since it allows organizing the specific information about the building parts (e.g., energy consumption for installation of the items).

When exanimating the vertical subdivisions, Table A1 (Supplementary data) shows the differences in the organization of the elements (groups) and the number of elements considered, which also affect the subsequent sub-elements, components, products and materials. For example, considering the building decomposition at vertical level 1 (first classification criteria), it was detected that national regulations do not consider the same number of building groups elements and their subsequent elements/sub-elements/materials and products. In this vein, the results also show that some of the analyzed examples combine an element classification (relating to the elements that compose the building) with a classification of the systems that compose the building (relating to the systems that compose the building) (see Fig. 3 method). It means that some countries firstly perform a classification into systems and then a classification of building elements (e.g., Spain (Andalusian Government, 2017) firstly recognizes the “Finishing system” and then the elements (such as the external wall, ceiling, etc.) that include the finishing). The Uniclass 2015 (CPIc, 2015) standard is the unique standard for the classification system that explicitly provides a set of classification tables focused on different purposes (systems, elements, among others). The element decomposition generally allows the identification of the most relevant elements of which the building is composed, such as the structure, exterior walls, partitions, etc. It can also help track an item from the element level to the material level (e.g., alkyd paint (material level) _paint layer (sub-element) _exterior wall 2 (element level)). In contrast, system decomposition can help to group the main systems that compose the building by their function. This approach, however, limits the traceability of the materials to the element level. For example, once material is quantified and grouped in the system that it comes from (e.g., wall paint to finishing system), it is not possible to track from which building elements it comes (e.g., interior wall, exterior wall). For example, the finishing material for the walls (e.g., lime plaster interior) can be grouped without specifying which type of wall it belongs to (interior or exterior).

However, major differences have been detected in the horizontal sub-divisions (see Table A1 in Supplementary data). Despite the heterogeneity in the number of the horizontal sub-divisions (from 9 to 32 at the vertical level 2), the results show (see Table A1 in Supplementary data) that several elements have been generally considered. These are foundations, façade, roofs, floors and partitions (related items coloured in orange in Table A1 in Supplementary data). Hence, the main differences are related to their conception, organization and the number of type-of relations considered. For example, the Uniformat standard (Charette and Marshall, 1999) (Canada) defines three element types in the group of foundations (“Standard Foundations”, “Special Foundations”, “Slab on Grade”), while the German standard (DIN, 2008) defines eight types (”321 Soil improvement”, “322 Shallow foundations”, “323 Deep foundations”, “324 Subfloors and base slabs”, “325 Floorings”, “326 Waterproofing of structure”, “327 Drainage”, and “329 Foundations, other items”).

3.2. Case study application

To better illustrate and analyse the implication of using a SBDM when conducting a building LCA, a case study is used to compare the LCA aspects. The obtained results confirm the detected tendencies in the classification and decomposition criteria (Section 3.1), and provide evidence of the potential implication of these differences in the LCA application (Supplementary data Table A1).

3.2.1. Implications of the SBDM regarding aspects of LCA

The results show that the major differences were detected at the first horizontal level, and thus affecting the decomposition for the rest of the building. For example, the Austrian standard can be used to consider two major groups (Core and Shell) (Fig. 2), while the Swiss and Spanish codes respectively take into account four categories (Structure, Technical equipment, Envelope, Interior) or five systems (Structure;

Envelope; Partitions; Finishing; Air conditioning and installations). Most SBDMs integrate at least six vertical levels of decomposition in the results context (from the whole building level (level 0) to the material level (level 6). For the case study ("be2226" reference building), the maximum number of materials extracted from the template inventory was 73, which corresponds to the decomposition of 24 building specific-elements (included in the BIM model) into 54 sub-elements, and finally into 73 materials (Soust-Verdaguer et al., 2020).

In the vertical subdivisions, as shown in Soust-Verdaguer et al. (2020), the results demonstrate that from vertical levels 1–3 the building data structure depends on the SBDM, which influences the number of elements and the sub-elements considered in the system boundaries definition and also the LCI. The decomposition at the subsequent levels (levels 4–6, sub-element and material level), was a consequence of that level and these were not carefully described in the SBDM. Thus, one of the consequences of using one or other SBDM is differences in the number of tagged materials or elements included in the LCA application. For example, Table A2 shows that the number of tagged materials for Austria was 67 and for France it was 47. This means that the way elements, sub-elements and materials are organized can affect the number of recognized building materials, and the possibility of tracking material, elements and building systems.

3.2.2. Implications of the SBDM to terms of the service life definition

The service life definition of the building systems, group of elements, elements, components, products and material is a relevant aspect of conducting building LCA. The structure of the building decomposition plays an important role there, because it can affect the LCA results. For example, the level of decomposition used to define the reference service life of a wall can be an overall value for the building element (with the same value for all the layers such as external and internal finishes, insulations, etc.) or different values depending on the sub-elements included in the wall, and derivated to a different renovation number depending on the material. Table A3 in the supplementary data section summarizes the results obtained for the service life consideration included in the IEA EBC Annex 72 ST 1 Activity 1.2. The activity comprised a basic template building decomposition structure, in which each country declared the years of service life assumed to conduct the LCA of the reference building "be2226". This template aims to summarise the information included in the different national SBDM for defining the number of renovations for the items along the building life cycle, using a simplified information structure focused on the items that have been included since the construction stage. Most countries considered a similar number of years and data granularity to define their service life of systems and elements. Canada, however, has defined a service life of 60 years to all the building elements and sub-elements (independent of their function) included in the template, except for the roof cladding. The **building services system** was one of the most heterogeneous, either because of the neglect of this system (in the LCA system boundaries definition) or because of the differences in the years of service life (ranging from 15 to 50 years). In the **finishes system,** differences have been detected in the data granularity of the service life definition. Countries such as Belgium or the Netherlands, included a higher level of decomposition in this, which defines a different service life depending on the material. In conclusion, the obtained results provide evidence that the service life definition in the LCA national methods is mainly based on the function of the building systems and elements, however the material consideration and decomposition of those systems and elements is hardly considered. For example, the service life of the structure is defined independently of the material.

3.2.3. Implications for design phases in digital design tools (BIM)

The results of the overview (section 3.1) and the case study confirm (section 3.2) that the organization of the building elements/objects differed, especially in their hierarchy (Soust-Verdaguer et al., 2020). For example, the French table used for building decomposition defines that the elements of the "Exterior walls" contain the finishing materials (e.g., "B Envelope"→ "B1 Exterior walls"→"B12 Finishes") in the "Envelope" system. Nevertheless, the Austrian standard considered the internal wall finishes as part of a separate group under the name "Wall and ceiling finishes" (e.g., "Core (fittings, furnishings and services)"→ "Fittings_and_furnishings" → "Wall and ceiling finishes"). Similar differences were also detected in the organization of other systems and elements. Thus, no matter which standards or guidelines are considered most appropriate, the results indicate that the decomposition or disaggregation level of the building elements needs to mirror the way in which they are organized in the model, especially when considering the different design phase in BIM and their hierarchical organization (Soust-Verdaguer et al., 2020). This approach can reduce efforts to identify hotspots and develop strategies to reduce impacts along the design steps. If this approach is combined with the system decomposition approach (see Fig. 3 method), it can provide more guarantees (improving the traceability and transparency) when organizing the LCI and communicating of the results in LCA.

In current practice, the systematic building decomposition in the context of digital design tools is supported by classification systems, which allow (among other features) the insertion of naming codes/tags and list elements in the BIM model. Two of the most widely used BIM softwares - Autodesk Revit (2021) and ArchiCad (GRAPHISOFT, 2017) - allow the integration of many classification systems in the BIM model in an easy and user-friendly way (included in the default configuration of the software or by a downloadable add-in or packaged). Autodesk Revit (2021), for example, integrates *Autodesk Classification Manager for Revit* (Autodesk Revit, n.d.) an add-in that allows integrating UniFormat (Charette and Marshall, 1999), MasterFormat, OmniClass (International Organization for Standardization (ISO) et al., n.d.), Uniclass, or a custom database classification system to the BIM model. For example, Archicad (GRAPHISOFT, 2017), integrates a 'BIM Content' that can be imported from its web page. An automatic workflow between the classification system and the BIM model can reduce the effort when integrating LCA in the BIM workflow.

Table 2 introduces the list of existing classification systems integrated in BIM and shows if the Annex participant country uses the standard for implementing LCA. The results show that the most popular classification systems (e.g., Master Format, Uniformat) are included in the automatic workflow of the most used BIM commercial software. The reason for this may be because some BIM software has adapted its capabilities to the national requirements (e.g., Revit to the United States of America). Table 2 also shows that the integration of the classification system into the BIM automatic workflow is still scarce in the context of the Annex participant countries.

In addition, during the modelling process in BIM, in building decomposition, the granularity of the data structure can increase, as well as the number of vertical decomposition levels. This means that the higher the number of vertical levels, the greater the number of building elements, building sub-elements, products and materials that are identified. However, modelling tools do not always allow for managing objects/materials/components/products at the same level of decomposition as structures for building decomposition (International Construction Information Society, 2017). Thus, considering the design steps defined in the IEA EBC Annex (IEA EBC, 2017), two milestones are identified for carrying out the systematic building decomposition for the LCA application (see Table 6): **the early design steps and the detailed steps.**

The element level (at early design steps) can include a general classification of the building elements in terms of their main function in the building (Table 6). At detailed steps, the number of building elements can be higher than at the early stage because other secondary elements (e.g., sealing and joining elements) are integrated in the model and in the LCA inventory. The sub-element decomposition refers to the specific function of a portion of the building element e.g., vapour barrier membrane and the material decomposition refers to the specific material

Table 2
Integration of classification systems (tables) in BIM. Source based on: Classification system and their use in Autodesk (Autodesk Revit, n.d.) and BIM content for ArchiCAD (GRAPHISOFT, 2017).

Revit		
Classification system	Country of origin	Annex participant in practice
UniFormat	US	Canada
MasterFormat	US	–
OmniClass	US	–
Uniclass	UK	–
a custom database classification system	–	–
ArchiCAD		
2010 CSI UniFormat	US	–
BB/SfB	BE	Belgium
BIM7AA	DK	–
BIMTypeCode	SE	–
CAWS	UK	–
CCS	DK	–
CCTB	BE	–
EcoQuestor	NL	–
Funktionskoder Regionservice -CD001_001_004	SE	–
GuBIMclass	ES	–
MasterFormat	US	–
NATSPEC	AU	–
NBS Create	UK	
NL/SfB	NL	NL
NS 3451 – Beygningsdelstabell	NO	–
OmniClass	US	–
ÖNORM B 6241-2	AT	–
RICS NRM 1	UK	UK
RICS NRM 3	UK	–
Rumsfunktion - CD002_001_001	SE	–
Rumsfunktionskoder	SE	–
SFG20	UK	–
SINAPI	BZ	–
STABU-Element	NL	–
TALO 2000 Building Component Classification	FI	–
TALO 2000 Hankenimikkeistö	FI	–
Uniclass 2	UK	–
Uniclass 2015	UK	New Zealand
UniFormat	US	Canada
VMSW	BE	–

of the sub-element (e.g., polyethylene plastic sheet). Hence, at the sub-element and material level the decomposition can include (at least) the main sub-elements and materials that compose the elements and could be a consequence of the element decomposition. The "elemental" or "component-oriented" approach is considered a suitable method to calculate the total costs of building works (International Construction Information Society, 2018) and the sustainable assessment (Lützkendorf, 2019). The following Table 7 introduces an overview of these aspects in the context of the Annex participants.

The obtained results confirm that the criteria to perform the element decomposition of the building are heterogeneous. Considering that the elemental classification (needed at the early design stages), is the decomposition of the building parts into items such as pillars, beams, roof, floor, external walls, windows, doors, balconies, etc., some data structures combine different levels of disaggregation. For example, the Austrian structure combines a group of elements such as "Foundations substructure" and "Load-bearing structural frame" at level 2, where it contains the element "External walls" (level 3), while the German structure includes a group of elements referred to as "External walls" as well as "Foundations" at level 2. Also, the decomposition regarding the number of elements considered can be different, for example the German structure includes 9 categories for decomposing the "external walls" group (331 Load-bearing external walls, 332 Non-load-bearing external walls, 333 External columns, 334 External doors and windows, 335 Cladding units, 336 Internal linings (of external walls), 337 Prefabricated façade units, 338 Solar protection, 339 External walls, other items), while the Dutch structure includes a group of elements designated "External walls" at level 2 and 3 includes a type-of classification of that element into "Cavity walls", "System walls", "Curtain wall", "Façade". This fact provides evidence that the rules for identifying the element decomposition and the definition of the vertical level are diverse. Table 7 uses two different colours to identify the elemental classification level: orange is used to indicate the cases that fit the criteria mentioned above and pale orange is used for indicating the cases that combines element and system or group of elements decomposition. Similar difficulties are detected after reading the sub-elemental and material decomposition (needed at the detailed design stages). In such a case the dark grey indicates the SBDM that mostly conduct a sub-elemental and material decomposition at the same level of decomposition, and the light grey indicate the cases that combines element, sub-element, and material decomposition.

Table 7 provides evidence of the differences in the granularity of the building decomposition structures (element or product/material decomposition) used by the Annex country participants to conduct early or detailed LCA. These differences can affect the data structure for the building decomposition in organizing not only the LCI, but also the data set of databases and other data sources needed for implementing the LCA. Moreover, in terms of the evolution of the building definition through the design stages, several standards that combine the decomposition into *the system* and *elements* approaches do not always integrate a hierarchical approach in the building elemental decomposition of all the building elements. What this means is for example, that the "Internal walls finishing" are not included in the internal walls category, they are grouped in another category instead with the designation "Finishing" (e.g., Austrian standard).

A possible path to a solution there could be the defining of a common element decomposition structure (adapted to the different national standards and guidelines and BIM workflow), to identify those minimum elements that should be defined at the early design step and those

Table 6
Correlation between the BIM model definition, the design stages, and the environmental databases and environmental information about the building.

	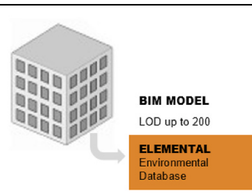	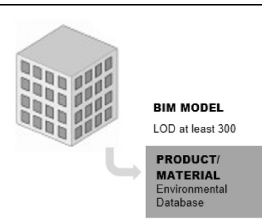
Design step	Early	Detailed
Overall LOD (BIM Forum (2021) of the BIM objects	up to 200	mor than 300
Information definition requirements	Element definition (Lower modelling precision, use of generic objects).	Product/material definition (Higher element modelling precision and product/material definition).

Table 7
Differences on vertical and horizontal level definition and the correlation with the design stages. (Source: Prepared by the authors based on national standards and guidelines for building decomposition to conduct LCA).

Number of V-levels	Country code											
	AT	BE	BZ	CA	CH	CZ	DE	ES	FR	NL	NZ	UK
1												
2			○ (orange)			○ (orange)			○ (orange)			
3	● (orange)	● (orange)		● (orange)	● (orange)		○ (orange)	● (orange)	○ (grey)	○ (orange)	○ (orange)	○ (orange)
4		● (grey)		● (grey)	● (grey)			● (grey)				
5												

References: Number of Vertical Levels of decomposition
● (orange) element decomposition in the early design stage
○ (orange) combination of element and system decomposition in the early design stage
● (grey) sub-element and material decomposition in the detailed design stage
○ (grey) combination of element and sub-element and material decomposition in the detailed design stage

elements and systems that should be defined at detailed design steps. For the early design step, the IFC (Industry Foundation Classes) Building Element classes could represent a possible list of building elements (buildingSMART, 2020).

4. Conclusions and recommendations

The implementation of building LCA requires a transparent and reliable data structure to organize the building parts. This allows among other things the preparation of the LCI, as well as defining the building system boundaries. A standardized structure for organizing and grouping the building parts potentially affects the ability to verify the LCI completeness. What this means is that the more detailed and hierarchically organized the LCI is, the easier it will be to identify the building parts, the elements, the sub-elements and the materials. Given the diversity in the SBDM for decomposing building parts, this paper presented the implication of using different methods and how this can affect the LCA procedure, the compilation and the completeness of the information provided about the building.

The overview of the existing SBDM used for LCA implementation shows two tendencies. The first of these provides a decomposition based on the recognition of the main systems (system approach) and the second is more focused on the classification of the building elements (element approach) based on their function. These two approaches are needed and provide a valid structure for the building decomposition. Most of the standards and guidelines that support the national SBDM are based on a combination of both, except for the Uniclass 2015 standard (CPIc, 2015), which explicitly provides one table for the systems and another for the element classification. Regarding the implementation of LCA in BIM, and the integration of systematic building decomposition into BIM methodology, on the one hand, the element approach can be more compatible with the BIM workflow than the system approach, because it allows tracking and identifying the hierarchical decomposition of the building included elements, sub-elements and materials and products.

On the other hand, the system approach allows a global overview of the systems but has only limited capability to track and identify specific elements, sub-elements, and building materials. In sum, the two approaches are complementary regarding the scale and complexity of the building, the design stage that is implemented in the LCA and the scope of the study. Moreover, the authors conclude that (at least now) it cannot be possible in the short term, to define one harmonized information structure to the systematic building decomposition for implementing the LCA due to the great heterogeneity and the strong connection of these structures with national or regional datasets and databases (e.g., environmental impacts databases) for implementing the LCA (e.g., KBOB). However, the possibility of defining a common reference or harmonized standard should be addressed in the long term.

The study also provides evidence of the building decomposition hierarchy structure limits, which come up to material level, and thus became necessary when introducing the circularity principles in the construction sector for the integration of information about material flows (e.g. raw materials, manufacturing process, etc.). The approach can be relevant for the concepts of "material passport" (BAMB. Materials Passports, 2019) and "building and material inventories" (Leibniz Institute of Ecological Urban and Regional Development & Karlsruhe Institute of Technology, 2020), and especially to support decisions related to the replacement of components and the deconstruction of existing buildings (Lützkendorf, 2019) (potential of reuse, recycling). This fact also provides evidence that further developments should be pursued for the further improvement in comparability and transparency when conducting LCA, especially at the detailed design steps. Also, further harmonization could be introduced relating to the building definition at different design stages and also the building decomposition. The building life cycle inventory covers not only the components and materials that compose the building during the construction stage, but also their renovation and other types of item required throughout its life cycle. The SBDM can help to support and provide a systematic data structure to include the elements, components and materials generally focused not only on the construction stage, but also in the use and end of life stage.

The application of consistent and comparable SBDM approaches can substantially enhance the comparability of LCA studies at the level of individual buildings as well as when assessing building stocks at scale (Röck et al., 2020). Thus, future research can focus on development of correspondence tables for mapping different building part definitions, as well as LCI data and LCA results of studies using different SBDM to support improved comparability and harmonization of building LCA in the future.

General recommendations for the use of SBDM to conduct LCA are presented below:

- To use, whenever possible, a classification system **based on hierarchical grouping principles** and on the ISO 12006–2 (ISO, 2012), which allows to identify the main systems and elements that compose the building, improves transparency on LCA application and support during the design steps.

- To promote the **compatibility** of structures for systematic building decomposition with environmental, economic datasets and databases, that enables to improve the interoperability of data during the design steps of buildings.
- To pay special attention when comparing LCA results from different countries, where the use of the same standard and guidelines for building decomposition should be implemented to provide a fair case study comparison.
- To develop, wherever possible, the service life definition conducting a systematic building decomposition addressing the material level, and preferably not only based on the function of the building systems and elements.
- In the context of the BIM-LCA workflow, to promote the development of packages or add-ins to encourage the integration of the most frequently used classification systems and SBDM for LCA application.

CRediT authorship contribution statement

B. Soust-Verdaguer: Data curation, Investigation, Writing – original draft, Conceptualization, Methodology, Visualization. **T. Potrč Obrecht:** Data curation, Investigation, Conceptualization, Methodology, Visualization. **N. Alaux:** Data curation, Investigation, Conceptualization, Methodology, Visualization. **E. Hoxha:** Data curation, Investigation. **M.R.M. Saade:** Data curation, Investigation. **M. Röck:** Data curation, Investigation. **A. Garcia-Martinez:** Data curation, Investigation. **C. Llatas:** Data curation, Investigation. **J.C. Gómez de Cózar:** Data curation, Investigation. **A. Passer:** Data curation, Investigation, Conceptualization, Methodology, Visualization, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The presented research results are part of ongoing research activities in the IEA EBC Annex 72: Assessing Life Cycle-Related Environmental Impacts Caused by Buildings. A final series of guidelines and reports summarising research outputs will be published by the end of 2022. The authors thank the IEA EBC Annex 72 experts who provided useful input that has enriched this research. The authors would like to thank all the participants of the IEA EBC Annex 72 project for their fruitful collaboration. The authors appreciate the contributions to survey answers by D. Trigaux (EnergyVille/VITO and KU Leuven), K. Allacker (KU Leuven), C. Ouellet-Plamondon (Université du Québec), B. Peuportier (MINES ParisTech), Erik Alsema (W/E Consultants), Dave Dowdell and B Berg (BRANZ), R. Frischknecht and L. Ramseier (treeze Ltd.), A. Hollberg (Chalmers University of Technology and ETH Zurich) and G. Habert (ETH Zurich), W. Debacker (EnergyVille/VITO); J. Veselka, M. Volf, P. Hajek, A. Lupíšek, Z. Malik (Czech Technical University), S. Lasvaux (University of Applied Sciences of Western Switzerland), F. Pomponi (Edinburgh Napier University), L. Wastiel (BBRI-CSTC-WTCB), V. Gomes, O. Zara, A. Gusson Baiocchi and L. Pulgrossi (University of Campinas), M. Gomes (Federal University of Espirito Santo), A. Moncaster (Open University) R. di Bari, R. Horn and K. Lenz (Fraunhofer IBP), M. Balouktsi, T. Lützkendorf (Karlsruhe University).

The Spanish authors thank the Spanish Ministry of the Economy and the ERDF A way of making Europe, for supporting the research project Grant BIA2017-84830-R and the Junta de Andalucía and the ERDF A way of making Europe, for supporting the research project Grant P20_00541. B.S–V appreciate the support from the University of Seville and the VI Plan Propio de Investigación (VIPPIT-2021-I.3) that supported her research visit at the Graz University of Technology financially.

The Austrian contributions were supported financially by the Austrian Ministry for Transport, Innovation and Technology (BMVIT), IEA Research Cooperation via the Austrian Research Promotion Agency (FFG) Grant #864142. M.Röck received funding through a DOC Fellowship of the Austrian Academy of Sciences (OeAW) [2019/1].

The authors thank Baumschlager Eberle Architekten for providing the case study and Norbert Prommer for providing the picture for Fig. 3.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135422.

References

Afsari, K., Eastman, C.M., 2016. A comparison of construction classification systems used for classifying building product models. 52nd ASC Annual International Conference. https://doi.org/10.13140/RG.2.2.20388.27529.

Andalusian Government, 2017. BCCA. Base de Costes de la Construcción de Andalucía. https://www.juntadeandalucia.es/.

2012 BCIS, 2012. Elemental standard form of cost analysis, 2012. Bcis.

Autodesk Revit. (n.d.). Classification Systems and Their Use in Autodesk Revit.

BAMB, 2019. Materials Passports.

Bauteilkatalog. n.d. www.bauteilkatalog.ch.

buildingSMART, 2020. buildingSMART. https://www.buildingsmart.org/.

Cavalliere, C., Habert, G., Dell'Osso, G.R., Hollberg, A., 2019. Continuous BIM-based assessment of embodied environmental impacts throughout the design process. J. Clean. Prod. 211, 941–952. https://doi.org/10.1016/j.jclepro.2018.11.247.

Charette, R.P., Marshall, H.E., 1999. UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis. U.S. Department Os Commerce.

CPIc, 2015. Uniclass2. http://www.cpic.org.uk/uniclass/.

CTE, 2006. Spanish Building Technical Code. In Real Decreto 314/2006 de 17 de marzo Vol. BOE 74, 11816–11831. CTE-DB-SE.

De Troyer, F., 2008. BB/SfB-plus.

DIN, 2008. DIN 276-1: Kosten im Bauwesen - Teil 1: Hochbau. In: Deutsche Norm.

Dodd, N., Cordella, M., Traverso, M., Donatello, S., 2017. Level(s)-A common EU framework of core sustainability indicators for office and residential buildings Part 3: How to make performance assessments using Level(s) (Draft Beta v1.0). In: Report EUR 28898 EN. https://doi.org/10.2760/95143.

EN, 2011. EN 15978:2011 - Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method. International Standard, November.

BIM Forum, 2021. *Level of Development (LOD) Specification Part I & Commentary*.

Frischknecht, R., Birgisdottir, H., Chae, C.-U.U., Lützkendorf, T., Passer, A., Alsema, E., Balouktsi, M., Berg, B., Dowdell, D., Garcia Martinez, A., Habert, G., Hollberg, A., König, H., Lasvaux, S., Llatas, C., Nygaard Rasmussen, F., Peuportier, B., Ramseier, L., Röck, M., Yang, W., 2019. Comparison of the environmental assessment of an identical office building with national methods. IOP Conf. Ser. Earth Environ. Sci. 323 (1) https://doi.org/10.1088/1755-1315/323/1/012037.

GRAPHISOFT, 2017. Archicad 19. http://www.graphisoft.es/.

Hoxha, E.. Amélioration de la fiabilité des évaluations environnementales des bâtiments. https://hal.archives-ouvertes.fr/tel-01214629/.

IEA EBC, 2017. IEA EBC ANNEX 72. http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-72/.

International Construction Information Society, 2017. Classification, identification, and BIM. http://www.icis.org/publications/papers/.

International Construction Information Society, 2018b. Cost Estimating and BIM. http://www.icis.org/publications/papers/.

International Organization for Standardization (ISO), (ICIS), & Society, I. C. I. (n.d.). OmniClass Construction Classification System. Retrieved March 30, 2019, from http://www.omniclass.org/.

ISO, 2006a. ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework, vol. 3.

ISO, 2006b. ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements and Guidelines. ISO.

ISO, 2012. ISO 12006-2 : 2015 - Building Construction - Organization of Information about Construction Works - Part 2 : Framework for Classification of Information. Iso.

KBOB. Okobilanzdaten im Baubereich. (n.d.).

BOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren). (n.d.). www.kbob.admin.ch.

Leibniz Institute of Ecological Urban and Regional Development, Karlsruhe Institute of Technology, 2020. Mapping the anthropogenic stock IV: development of a building passport and building inventory concept for the regional recording of materials with the aim of optimising recycling. https://www.ifeu.de/en/project/kartal-iv/.
Lützkendorf, T., 2019. Application of "Element"-method in sustainability assessment. Central Europe towards Sustainable Building 2019 (CESB19) 1–8.
Naneva, A., Bonanomi, M., Habert, G., Hollberg, A., Hall, D., 2020. Integrated BIM-based LCA for the Entire building process using an existing structure for cost estimation in the Swiss context. Sustainability 12 (9). https://doi.org/10.3390/su12093748.
NBR 15575–1, 2013. Edificações habitacionais — Desempenho Parte 1: Requisitos gerais, Associação Brasileira de Normas Técnicas, 01.080.10; 13.220.99.
Obrecht, T.P., Röck, M., Hoxha, E., Passer, A., 2020. BIM and LCA integration: a systematic literature review. Sustainability (Switzerland) 12 (14). https://doi.org/10.3390/su12145534.
ÖNORM, 2015. ÖNORM B1801.
Palumbo, E., Soust-Verdaguer, B., Llatas, C., Traverso, M., 2022. Implications of the building system boundary definition to conduct an LCA. A case study comparison of two frameworks for assessing building sustainability: DGNB and Level(s). E3S Web of Conferences 349, 04015. https://doi.org/10.1051/E3SCONF/202234904015.
Polster, B., Peuportier, B., Blanc Sommereux, I., Diaz Pedregal, P., Gobin, C., Durand, E., 1996. Evaluation of the environmental quality of buildings towards a more environmentally conscious design. Sol. Energy 57 (3), 219–230. https://doi.org/10.1016/S0038-092X(96)00071-0.
Revit, A., 2021. Autodesk Revit. *Architecture, 1*, about Revit Architecture. http://usa.autodesk.com/adsk/servlet/pc/index?id=17801984&siteID=123112&s_tnt=31959:0:0.
Röck, M., Hollberg, A., Habert, G., Passer, A., 2018. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. Build. Environ. 140 (May), 153–161. https://doi.org/10.1016/j.buildenv.2018.05.006.
Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – the hidden challenge for effective climate change mitigation. Appl. Energy 258, 114107. https://doi.org/10.1016/j.apenergy.2019.114107.
Schweizerische, C.R.B., Schweizerischer, S.I.A., 2012. Standards für das Bauwesen eBKP-H SN 506 511 Baukostenplan Hochbau.
Siemon, K.D., Speckhals, R., Siemon, A., 2021. DIN 18960 – Nutzungskosten im Hochbau. In: Baukostenplanung und -steuerung. https://doi.org/10.1007/978-3-658-28460-2_15.
Singh Ahluwalia, Shipra, 2008. A Framework for Efficient Condition Assessment of the Building Infrastructure.
Soust-Verdaguer, B., García-Martínez, A., Llatas, C., Gómez de Cózar, J.C., Allacker, K., Trigaux, D., Alsema, E., Berg, B., Dowdell, D., Debacker, W., Frischknecht, R., Ramseier, L., Veselka, J., Volf, M., Hajek, P., Lupíšek, A., Malik, Z., Habert, G., Hollberg, A., et al., 2020. Implications of using systematic decomposition structures to organize building LCA information: a comparative analysis of national standards and guidelines- IEA EBC ANNEX 72. In: IOP Proceedings Earth and Environmental Science Journal 588, p. 022008, 2020.
Spirinckx, C., Thuring, M., Damen, L., Allacker, K., Mirabella, N., Ramon, D., Passer, A., Röck, M., 2018. Study and Related Guidance Documents on the Application of the PEF Method to a New Office Building.
Spirinckx, C., Thuring, M., Damen, L., Allacker, K., Ramon, D., Mirabella, N., Röck, M., Passer, A., 2019. Testing of PEF method to assess the environmental footprint of buildings - results of PEF4Buildings project. IOP Conf. Ser. Earth Environ. Sci. https://doi.org/10.1088/1755-1315/297/1/012033.
Volk, R., Stengel, J., Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - literature review and future needs. Autom. ConStruct. 38, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023.