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How to conduct consistent environmental, economic, and social assessment during the building design process. A BIM-based Life Cycle Sustainability Assessment method

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ABSTRACT

The built environment is significantly responsible for the current climate crisis, thus developing more sustainable projects is becoming an urgent objective. One widely recognized method that supports achieving this objective is the Life Cycle Sustainability Assessment (LCSA), which enables a holistic, quantitative evaluation of building sustainability, including environmental, economic, and social dimensions. The integration of this method in digital design tools such as Building Information Modelling (BIM) facilitates its use during the building design stages. However, data granularity is not the same in every design stage, and consequently data consistency cannot be assured. Hence, the margin of unexpected variation of the results shall be avoided and robust results from the early design stages should be obtained. During the early stage, the level of details is generally limited to the element definition, while during the detailed stages, the volume of information regarding the building increased. This paper aims to fill in the informational gaps during the early design stage and align those results with a detailed data structure developed for cost estimation during the detailed stages. Thus, based on a case study analysis, we can demonstrate the consistency of the method by determining the variation of material quantities and comparing the LCSA inventory indicators during the early and detailed stages. This method can estimate more than 60% of the LCSA inventory indicators during the early design stage and the total results during detailed design stage.

1. Introduction

The current challenges of decarbonization and resource depletion are relevant to implementing the reduction of environmental impact measures throughout the built environment [1]. The building and construction sector plays a significant role, as it has been shown to account for almost 40% of energy and process-related carbon dioxide emissions [2]. To reduce and mitigate these environmental burdens, the Life Cycle Assessment (LCA) is one of the most widely used methods to calculate the impacts of building

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projects [3]. However, reducing the environmental impacts of the built environment goes beyond the traditional unidimensional approaches. The Life Cycle Sustainability Assessment (LCSA) provides a more comprehensive approach to the LCA technique, by adding economic and social to the environmental dimension. Thus, the method is defined as the sum of the LCA (environmental), economic LCC (Life Cycle Costing), and social S-LCA (social life cycle assessment) [4]. As described in Ref. [5], the ISO 14040 [6] is the methodological framework for the LCSA implementation. Nevertheless, there is still no standardization for the specific integration of the three LCA-based techniques [7]. The ISO 14040 [6] includes four main phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation. Hence, when implementing the LCI in LCSA, the exchanges between unit processes, organizations of the system and the external environment are compiled [5]. Thus, it is recommended to achieve consistency in the data collected at the unit process and organizational level, considering the simultaneous implementation of the three techniques [5].

1.1. LCSA application at building design stages

The LCSA application during different building design stages, specifically integrated on a digital tool workflow, has been proposed to be implemented in the Spanish context [7]. The LCSA is proposed to be aligned with the most relevant design milestones that exist in Spain: the Basic Project (BP) (early design) and the execution project (EP) (detailed stage). The methodological approach [7] and case study validation [8] to implement a Triple Bottom Line sustainability assessment tool based on integrating the LCSA in Building Information Modelling (BIM) provide evidence of the potential of applying an “element method” during the early design stages (BP) and help the designer with decision-making during the detailed design stage (EP). The element method is focused on the IFC4 (Industry Foundation Classes) scheme [9] to enrich the environmental, economic, and social data included in the BIM model. Considering the IFC structure, the approach enriches the dynamic properties of the IfcElement class and consequently the IfcBuildingElement by using the dynamic properties (Property Set) (see Fig. 1). The IfcBuildingElement scheme is based on a building element classification that “comprises all elements that are primarily part of the construction of a building”, such as walls, beams and doors which are all physically existent and modeled components [9].

The acronyms included in Fig. 1 are defined in the IFC scheme and represent the different classes that the structure includes. Fig. 1 includes an example of the IFC classes involved in the method that proposed the IFC scheme enrichment to conduct the LCSA in BIM [8]. A detailed explanation about the acronym’s definition is included in Ref. [9].

The list of building elements includes the following Ifc classes: IfcBuildingElementProxy, IfcCovering, IfcBeam, IfcColumn, IfcCurtainWall, IfcDoor, IfcMember, IfcRailing, IfcRamp, IfcRampFlight, IfcWall, IfcSlab, IfcStairFlight, IfcWindow, IfcStair, IfcRoof, IfcPile, IfcFooting, IfcShadingDevice and IfcPlate. This “element method” is a simplified strategy frequently used for cost estimations in building design [10]. In theoretical studies, the “element method” is also considered by the literature as an appropriated approach to implement sustainability [11] and cost assessment [12] during the early design stages. The “element method” is based on subdividing the building into parts (so-called elements) and considering these parts as units to quantify (for example, economic costs) [11]. The method relates the building element quantities, measured in standard units such as m2 or m3 or units, with systematic information about the cost considering materials, labor and machinery used in the construction work process. To obtain the final results the cost unit values and building element quantities are multiplied. A systematic building decomposition or data structure is generally used during detailed design stages to organize the LCI [13]. For the Spanish context, classification systems and a systematic data structure to organize the data that compose the building in a detailed manner can be the BCCA (in Spanish “Base de Costes de la Construcción de Andalucía”, or, in English “Andalusian Construction Cost Base”) [14]. The classification system was conceived of to develop cost estimation during the detailed building design stages (Execution Project (EP). In this vein, this data structure is also used for LCA, as in Ref. [15]. Moreover, the strategy can be verified in some of the existing Spanish commercial tools for LCA and cost estimations during

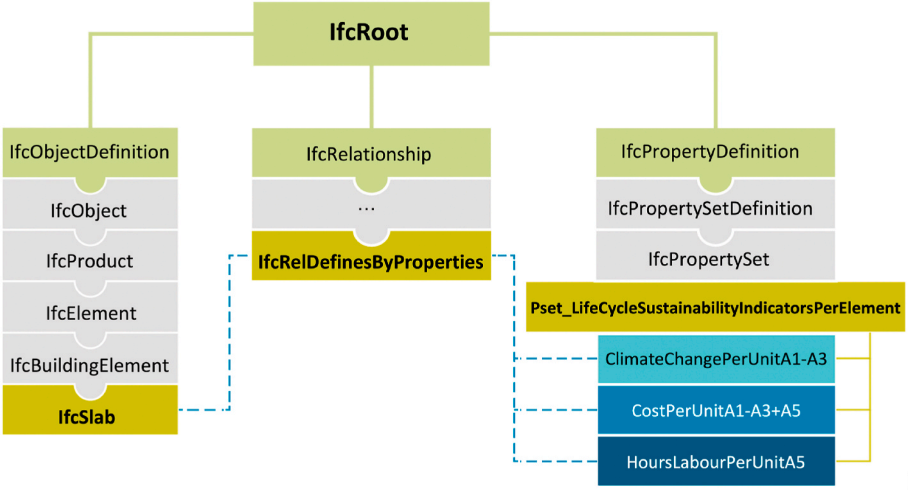

Fig. 1. Example of enriched IFC implementation scheme for conducting the LCSA in BIM. Source based on [8].

the various design stages (such as Arquímedes [16], Presto [17], TCQi/TCQ [18]). On the one hand, it is generally necessary to have a very detailed data structure for a comprehensive LCI. On the other hand, limitations in the Spanish classification system BCCA have been detected to obtain an elemental classification of the building, such as the IFC element classification [19].

1.2. Challenges in addressing the BIM-based LCSA application

One of the main advantages of the BIM-based LCA approach is the extraction of the LCI [20]. For instance, the LCI will be composed of material quantities extracted (also called the Bill of Quantities or BoQ) from the BIM model and related to an environmental, economic, and social database for obtaining the LCSA results. This phase consumes a lot of time and effort [21]. Thus, when implementing the LCSA in BIM, the inventory is composed of a data structure (BoQ) that has its physical correspondence with the elements extracted from the building (BIM model) [7]. This issue has been addressed in various ways by the literature. For example, Figueiredo et al. [22] developed an LCSA framework using BIM, which was limited to a detail defined BIM model (Level of Development (LOD) 400). In contrast, Panteli et al. [23] used simplified models to conduct the BIM-LCA for supporting the building overhang design. Najjar et al. [24], also examined BIM-LCA integration during the early design stages and recommended investigating elementary flow integration between BIM and LCA due to the limitations of the data and the challenges of comparing different scenarios. Röck et al. [25] used an element approach that included a limited number of items (main building elements) and omitted the details and small elements that compose the building, which was not modeled at early design stages. Moreover, the modeling and integration in the LCI of building services (installations) is not possible after the detailed stages, when the shape and building distribution are already defined. The elements method proposed in Ref. [8] enables the LCSA to be applied during the early design stage, including assumptions and predefined data that enrich the element data extracted from the BIM model to compose a more comprehensive inventory of material and energy flows. This approach has been validated in a structural system that included a limited number of items and enabled reliable results since the element decomposition directly correlates with the detailed data included in the BCCA [14]. With that said, what happens with the rest of the building systems, such as the envelopes and elements that are not modeled during the early design stages (such as the expansion joints)? To what extent can this enriched element approach, which that corresponds with the BIM model during the early design stage (BP), be reliable for implementing the LCSA during the detailed stage (EP)? What considerations should we have for building elements that cannot be modeled in detail during the early design stage (BP)? Is it possible to get consistent results for environmental, economic, and social dimensions throughout the design process? Is it possible to estimate representative results from the early design stages without investing too much effort in the BIM process?

Existing research [21] that compares the variation of the LCA results in the different design stages focuses on the environmental dimension and uses the BIM model as a comparison. However, the decomposition in building elements during the early design stage (BP) and materials during the detailed design stage (EP) were not investigated. The data disaggregation is not only the difference between the early and detailed stages. In the early stages, it is possible to estimate one main material per element. However, during the detailed stage, it is necessary to consider both the layering of those elements, and the materials (such as steel for concrete). Cavalliere et al. [26] developed a method using the data available in BIM to evaluate the LCA during the entire building design process, while focusing on the Swiss context. In this vein, Naneva et al. [27] proposed a BIM-LCA method for the entire building process aligned with the cost estimation used in this context. The study uses an existing element classification data structure provided by the eBKP-H [28] structure, environmental data from the “Bauteilkatalog/Component Catalogue” [29], data from BFE (Bundesamt für Energie/Federal Office of Energy) [30] and Hollinger Consult GmbH [31] as well as the LCA data from KBOB (Koordinationskonferenz der Bau-und Liegenschaftsorgane der Öffentlichen Bauherren/Coordination Conference of the Building and Real Estate Bodies of the Public Building Owners) [32], eco-bau [33], and IPB (Interessengemeinschaft Privater Professioneller Bauherren/Interest Group of Private Professional Builders) [34]. This study focused on the use of the eBKP-H [28] structure linked with the BIM workflow. This structure encompasses the building BIM and is composed of layering structures that go from generic volumetric aspects to more detailed ones (such as a nest or matryoshkas structure). Nevertheless, what happens when the element classification is not aligned with the BIM workflow, following the LOD (Level of Development) [35] principles? In some countries, such as Spain, the cost estimation data structure BCCA [14], (based on a building decomposition) is focused especially on a detailed design stage and does not include an element classification that can be easily associated with a BIM workflow. Thus, the first novelty of this study leads to the provision of a systematic method to deal with this.

Moreover, one of the main challenges is the consistency of results at different design stages. This issue has been highlighted by the literature, especially in the field of LCA. Hollberg et al. [21] demonstrated the importance of the quality of a model when calculating the embodied impacts along the design process. They also underlined the relevance of using predefined elements, and simplified or machine learning approaches to fill the gaps, provide automatic assumptions, and reduce the unexpected variability of the results during the various design stages. In this vein, none of the published studies are focused on comparing different levels of data granularity using an element (element LCI) and a material decomposition (based on a cost estimation data structure, which is most frequently used to organize the complete building LCI at detail stages) to implement the LCSA in BIM. Knowledge gaps in the literature provide evidence that the verification of the inventory consistency during the early (basic project) and detailed (execution Project) stages to conduct LCSA have not been addressed previously. The second novelty of the present work is its focus on proposing a method to reduce unexpected variability of the results during the building design process. The consistency of the method was demonstrated by analyzing the correlation between the LCI used for the cost estimation, environmental impact calculation, and social assessment of the building performance in BIM during different design stages (early and detailed). Thus, this study aims to identify the relevance of the unmodeled elements when conducting the LCSA in BIM. It is focused on comparing the LCSA results during the early (BP) and detailed (EP) design stages using three different inventory indicators, (environmental, economic, and social) at a rate of one per dimension.

1.3. *Goal of the study*

The present study aims to answer the following questions:

- **RQ1.** Is it possible to develop an “element method” based on the systematic building decomposition structure BCCA [36], while integrating the cost estimation items that can be included or related to a building element in the BIM model during the BP stage (element level)?
- **RQ2.** What are the limitations of the “element method” (early-stage (BP)) to calculate the LCSA? Are the results consistent regarding the detailed design stage (EP)?
- **RQ3.** What is the variability of the number of items of the cost estimation structure and inventory indicator results throughout the various building design stages (BP and EP)?
- **RQ4.** Considering the number of elements and items included in the cost estimation data structure, which are the relevant building systems, and how do they affect the material quantities the evaluated indicators used in the LCSA?

2. Materials and methods

This paper aims to propose an “element method” and verify its consistency by comparing the building inventory and LCSA results during the early and detailed design stages. This study is based on case study validation and includes two steps:

Step 1. **“Element Method” Development:** Based on the IFC scheme, correspondence between the IfcBuildingElement classes and the items of the data structure BCCA [14] was conducted. The element classification proposed by the IFC scheme is the most consistent and adapted to the BIM workflow (regardless of the BIM commercial software) [9]. Thus, this scheme was used as a basis to analyze the correspondence of an element building decomposition with a detailed (material) decomposition based on the cost estimation data structure BCCA [14]. The building elements that can be directly modeled at early design stages (BP) or related to a building element quantity take-off (e.g. shuttering) are identified here.

The BCCA [14] is organized in a nested or hierarchical structure (see Fig. 2), which includes “Chapters”, “Sub Chapters”, “Sections”, “Groups” and “Items” (composed based on the materials, labor, and machinery needed to construct a building element (measured in a certain unit such as a cubic meter or a square meter).

The IfcElement class includes the following classes: IfcBuildingElement, IfcCivilElement, IfcDistributionElement, IfcElementAssembly, IfcElementComponent, IfcFeatureElement, IfcFurnishingElement, IfcGeographicalElement and IfcTransportElement. IfcBuilding Element is the class related to the building elements that can have physical correspondence in the model. It is assumed that these classes are also related to the general conception of the building during the early design stages and describe the main characteristics of the main building parts. Thus, this section is focused on identifying the correspondence between both structures and verification in a case study application (see Figs. 2 and 3).

Step 2. **LCSA Implementation and Analysis of the Consistency of the Element Method”**. This step aims to identify the variation in items, material quantities, and the LCSA results during both the early (BP) and detailed (EP) design stages. The selected indicators to conduct the LCSA were CO_2 eq emissions, working hours, and cost (materials, machinery, and labor). The criteria to select them was based on [8]. The method [8] proposes a data structure that relates the embodied aspects of the building elements’ life cycle (product, construction, use, and end-of-life). The calculation procedure for the LCA, LCC and S-LCA is also based on previous studies in this field [7,8], and basically multiplies the bill of material quantities (extracted from BIM) with the following factors: CO_2 eq. emissions extracted from the BEDEC [37] database), cost (in euros, extracted from the BCCA [14] database) and working hours (in hours, extracted from the BCCA [14] database). In this study, the LCSA application and system boundary definition are focused on the embodied aspects during the product (A1-A3 modules) and construction stage (A5 module), considering the current standards and the LCA modularity principles of the building [38,39].

The list of items contained in the cost estimation data structure BCCA [14] that can be directly related to the building element (quantities take-off) during the early design stage (BP) was compared with the complete list of items used during the detailed stages and the LCSA results obtained during both stages. The analysis was based on the data structure of the BCCA [14] and aimed to detect

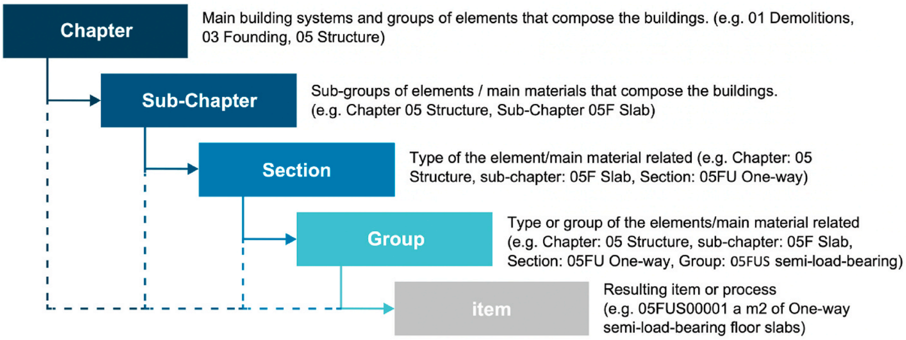

Fig. 2. Example of the hierarchical structure of the BCCA at different levels of decomposition.

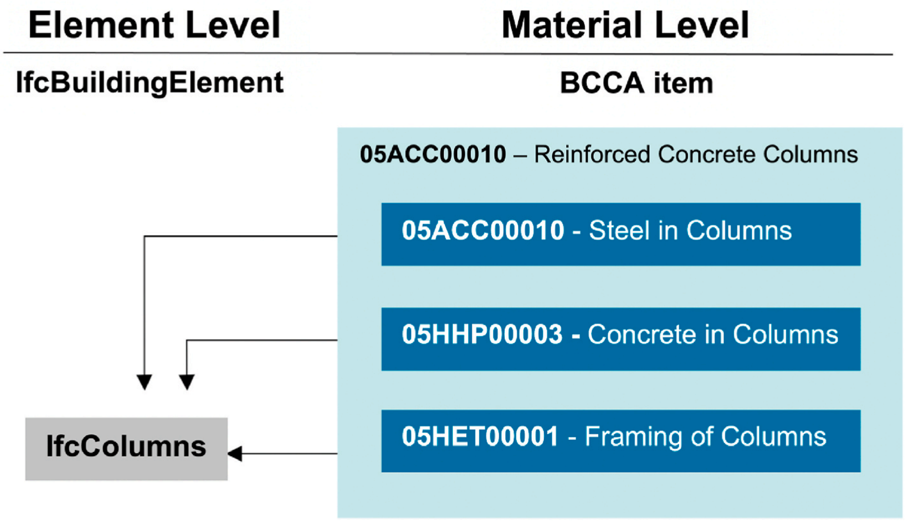

Fig. 3. Example of the IFC building element correspondence with the BCCA items at different levels of decomposition.

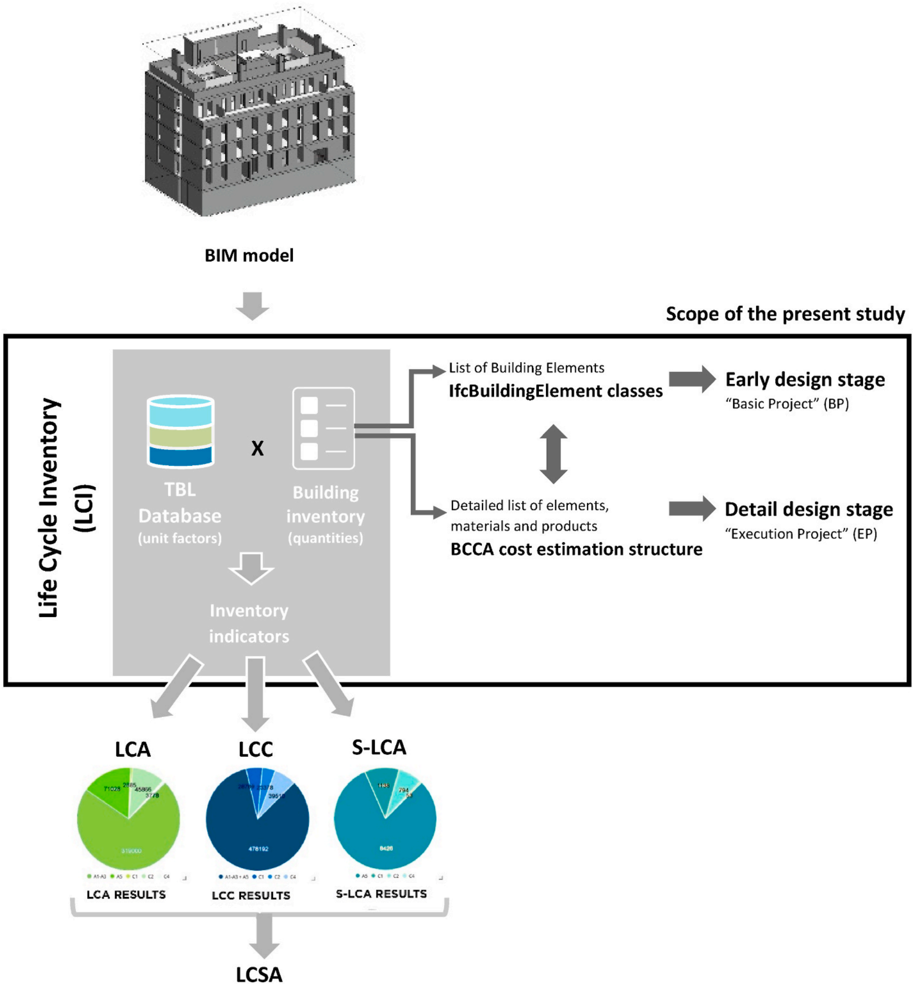

Fig. 4. Scheme of the proposed method.

the most relevant building systems (during the early (BP) and detailed (EP) design stages) as well as the consistency of the LCSA inventory indicator results throughout the various design stages (early (BP) and detailed (EP) (see Fig. 4).

2.1. *Case study description*

The case study is a residential building (called *La María)* located in Seville, Spain. The building's total GFA is 2119.24 square meters, distributed into 5 levels (including ground floor), and 16 apartments. The building uses frequent construction procedures for the structure (reinforced concrete) and building services for residential buildings in Andalusia (see Fig. 5). The building envelope was composed by masonry and External Thermal Insulation Composite Systems (ETICS).

3. Results

3.1. *"Element method" application to the case study*

During the modeling process in BIM, it is necessary to relate the drawn physics volumes to building elements (IfcBuildingElement). After analyzing the BCCA items included in the case study, it was determined that more than 40% of the items that compose the cost estimation detailed structure could be modeled during the early design process (BP) and related to an IfcBuildingElement. Thus, the manual analysis focused on identifying which main building elements can be modeled at an early stage and which information types (BCCA item) can be directly estimated by associating the physical building element volume with the BCCA item. Therefore, both the relation and association between the items of the cost estimation data structure BCCA and the IfcBuildingElement list, as well as the possibility of extracting the bill of material directly or indirectly from the IfcBuildingElement were analyzed. For example, the item "CA00620 Welded Steel Mesh B500 T" is associated with the IfcBuildingElement and IfcSlab. This item includes an estimated quantity of steel that is necessary to build the slab and is estimated as a percentage of the total square meters of the slabs included in the project.

Table 1 shows the number of items that can be directly related to the IfcBuildingElement. This means that the material quantities extracted from those building elements can estimate the material quantities of the BCCA [14] items. The total number of BCCA [14] items that compose the cost estimation detailed structure are 389, while the number of BCCA [14] items that can be directly related to an IfcBuildingElement class and modeled during the early design stage (BP) are 152 (complete list of items in the supplementary data).

3.2. *Correlation between the items of the cost estimation data structure BCCA (EP) and the element classification (BP) to compose the LCI*

During the LCI phase, a number of BCCA data structure items had their material level identified during the early (IFC building element correspondence) and detailed design stages. The quantities of several BCCA "Chapters" that can be potentially estimated (extracted from the BIM model) were detected by using an "element method" (since these are early design stages), such as the structure or carpentry. This means that the material quantity take-off extracted from the BIM model can estimate the BCCA items. For example, the quantity of the items "Steel in columns" or "Framing in the columns" can be estimated based on the volume of the columns. Nevertheless, other "Chapters", such as the installations (building services), would need a more detailed modeling stage extracted from the BIM model as shown in Fig. 5. This Figure demonstrate that the potential of using the BIM model extract the material quantities, during the early stages, is focused on several "Chapters" (such as the Structure or the Carpentry) and for other Chapters different strategies should be defined.

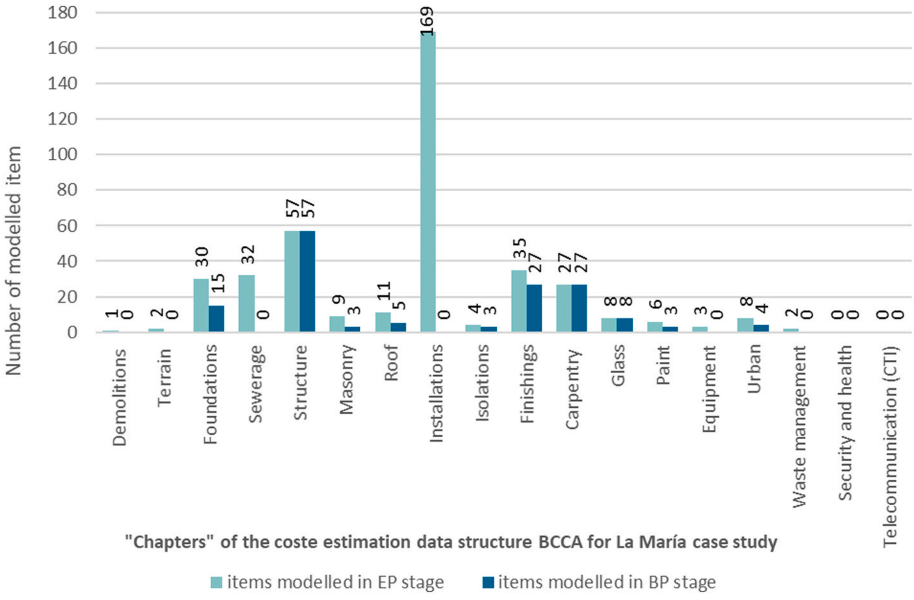

Fig. 5. Number of the BCCA items per "Chapter" and design stage (BP early and EP detail).

Table 1
Correspondence between the IFC classes and the BCCA items.

IfcBuildingElement Class	BCCA item
IfcBeam	11
IfcBuildingElementProxy	0
IfcChimney	0
IfcColumn	10
IfcCovering	5
IfcCurtainWall	0
IfcDoor	22
IfcFooting	0
IfcMember	12
IfcPile	0
IfcPlate	7
IfcRailing	1
IfcRamp	0
IfcRampFlight	0
IfcRoof	5
IfcShadingDevice	1
IfcSlab	30
IfcStair	2
IfcStairFlight	0
IfcWall	33
IfcWindow	13
Total Number of Items	**152**

Given that the calculation of the inventory indicators has a close relation to the material quantities that compose the LCI [21], a comparison was developed to compare the BCCA “Chapters” that are relevant in terms of the volume (generally used for the structure and envelope) and unit (generally used for the building services) of elements at both design stages. Thus, the volume was used to measure the material quantities (for example, those automatically extracted from BIM). In addition, the unit was used as a strategy to count the number of items that cannot be automatically extracted from the BIM model with the material quantity take-off function. For example, while using this function, it is not possible to automatically extract the quantity of ceramics contained in a lavatory or the quantity of metal in a lamp.

Fig. 6 shows the percentage of items that can be measured by volume and units during the detailed design stage (EP). The BCCA “Chapters” from which the highest material quantities can be extracted during the detailed stage (EP) are the Terrain Conditioning and Waste Management. Meanwhile, during the early stage (BP) the "Chapters" from which the highest material quantities can be extracted are the Foundations, Structure, Masonry and Finishing. For the units, the greatest incidence (91%) is given by the installations, because it is the “Chapter” that is mostly composed of the pieces and thus its influence on the bill of material quantities is directly related to the building program (in this case, a multi-family house) [40].

Fig. 7 shows the percentage of materials integrated into each “Chapter” by comparing them between the early stage (Basic Project (BP)) and detail stage (Execution Project (EP)), as well as the distribution of the “Chapters” from which material quantities can be extracted to determine the IfcBuildingElement. To analyze the accuracy of the element method related to the information that can be

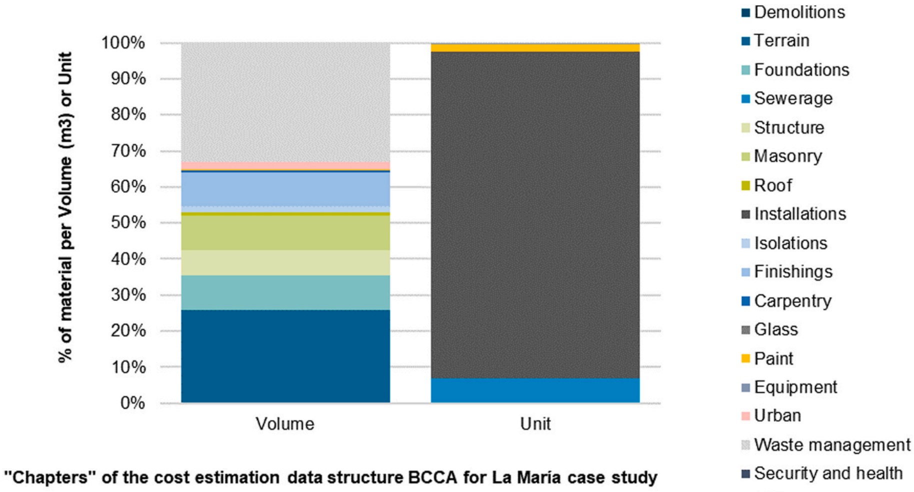

Fig. 6. Identification of the percentage of materials and units per BCCA “Chapter” during the detailed design stage (EP).

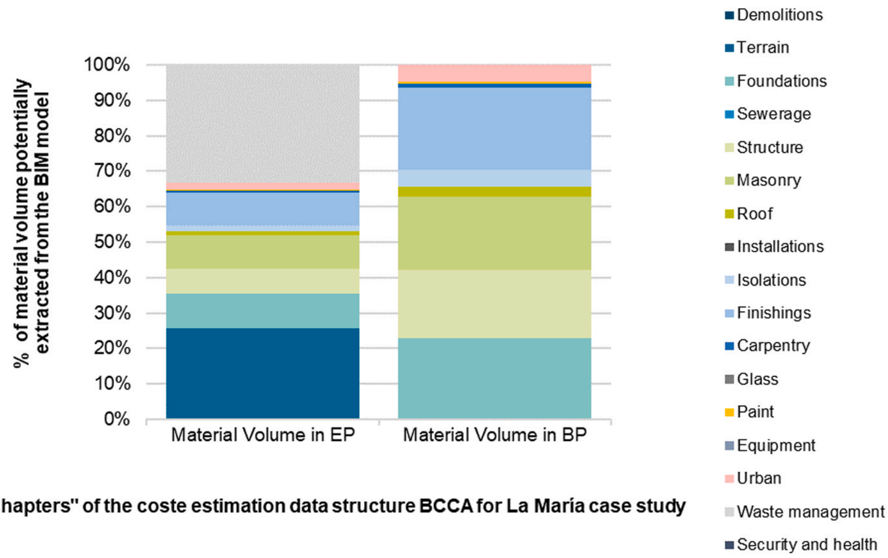

Fig. 7. Percentage of material volume that can be potentially extracted or related to a BIM element in the BP (early) and EP (detailed) stages.

directly extracted from the BIM model, Fig. 8 shows that more than 36% of the total cubic meters of the building element materials can be extracted or estimated in the BIM model at an early design stage (BP). The influence of the non-modeled elements during early design stages is greater than 60% (Fig. 8 Right). However, according to the origin (BCCA "Chapters") of the volume of these elements more than 92% of the volume difference, was detected in the Waste Management and Terrain "Chapters". These "Chapters" will probably have a lower related impact than other BCCA "Chapters" (such as Structure) because these imply the use of machinery (energy consumption). Thus, excluding these "Chapters", the percentage of material volumes that can be extracted from the BIM model reached 89% (Fig. 8 Left). Almost 90% of the material volume quantity take-off can be estimated using an "element method" at an early design stage (BP).

3.3. *Comparison of the inventory indicators results for LCSA along the design phases (early and detailed)*

Once estimated, the quantities of materials and units of products involved in the building inventory at the product and construction stage, the inventory indicators costs (materials, machinery, and labor), work hours, and CO2eq emissions necessary to conduct the LCSA were assessed. The LCSA implementation was limited to information modules A1-A3 (product), and A5 (construction), based on previous related studies [7]. The results were calculated based on the material quantity take-off results (volumes and units) in the early (BP) and detailed (EP) design stages. The priority of this section was to compare the inventory indicator results obtained by fixing the system boundaries and information modules to implement the LCSA change the design stage, and determine which data could be extracted or estimated in each design stage. Given the limited existing systematic data sources to conduct this LCI stage, the study included slight differences in the information modules depending on the sustainability dimension. This means the LCI was focused on modules A1-A3 and A5 for the environmental dimension, A5 for the social dimension, and A1-A3 and A5 for the economic dimension. The criteria to include the economic information in the context of the product was based on the standard EN 16627 [41]. Thus, the present study included the cost related to the building materials in modules A1-A3 the cost of construction activities (use of machinery

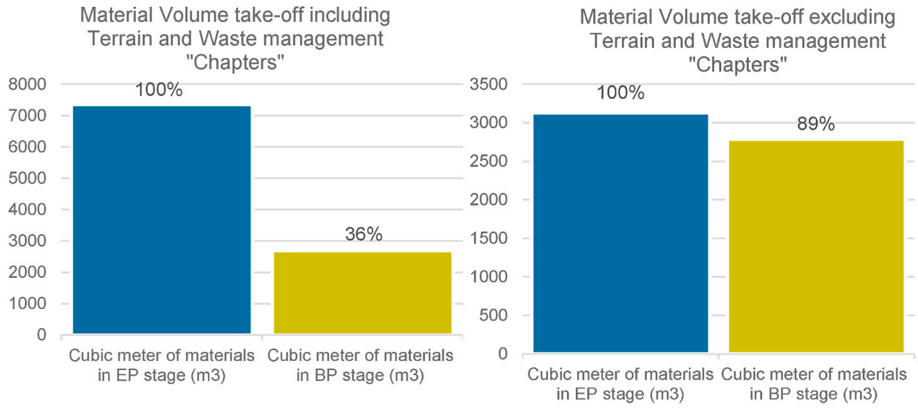

Fig. 8. Total cubic meters that can be potentially extracted or related to a BIM element in the BP early and EP detailed stages.

and workers), auxiliary materials and components, and transports inside the site and waste management in module A5.

The factors for estimating the CO_2eq emissions were extracted from the BEDEC [37] database (ITEC), while the cost and working hours were extracted from the BCCA cost estimation data structure [12]. The CO_2eq emissions, cost, and working hours were calculated by multiplying the emissions factors (CO2eq) per item, cost per unit, and working hours per item by the volume or unit of materials that compose the inventory.

Fig. 10 shows the influence of the different inventory indicators in each BCCA "Chapter" at the detailed design stage using the BCCA cost estimation data structure.

During the detailed stage (EP) the incidence of the inventory indicator for each sustainability dimension is different depending on the BCCA "Chapter" being considered. For example, the Finishing "Chapter" has the greatest influence on social aspects (working hours), due to the use of manually applied plasters and mortars compared to the foundations on environmental aspects (CO_2eq emissions). This is probable due to the use of concrete and steel. However, in the Installations "Chapter'' (building services) the incidence is similar for the economic and environmental dimensions.

The Finishing "Chapter" has the highest working hours compared to other types of works. This is, due to the intensive manual work needed to install the ceramics and plastering. Thus, changing the type of finishing can reduce these working hours.

Fig. 10 shows that the economic dimension presents the highest variability between the EP and BP results. This difference, between the costs in the EP and BP stages (Fig. 10), is mainly due to the contribution of the installations and other non-modeled BP items, such as sewerage, and the foundations (partially) in the total cost of the EP stage (see Figs. 5 and 9). Regarding the variability of the total inventory indicator results throughout the design stages, the results obtained are different depending on the design stage. The margin of error or dispersion of using the element method can be lower for estimating the environmental inventory indicator namely CO_2 emissions, (modules A1-A3 + A5) than the economic inventory indicator namely the cost of the product and construction, (modules A1-A3 + A5).

4. Discussion

4.1. Lessons learned from the present method

4.1.1. "Element method" development based on the correspondence of the systematic building decomposition structure BCCA cost estimation items and the building element in the BIM model at the BP stage (element level). (RQ1)

This study demonstrates that the proposed method helps to implement a systematic organization of the building information based on a cost estimation data structure. It supports the element decomposition of the building in a systematic and BIM-aligned way. Moreover, using the proposed method the data gaps concerning the elements not directly modeled in BIM at the element level (early design (BP)process) can be solved. The results shown in Table 1 prove that around 50% of the BCCA items of a detailed data structure can be modeled and associated with a building element at an early design stage.

4.1.2. Limitations of the "element method" (BP) to conduct the LCI in the LCSA (RQ2)

The study indicates that a significant number (over 60%) of the inventory indicator results for the environmental, economic and social dimensions can be obtained in an early design stage (such as BP) during which the designer can potentially reduce them at an element level. During the BP stage it was possible to estimate around 90% of the volume of the building materials. However, the results

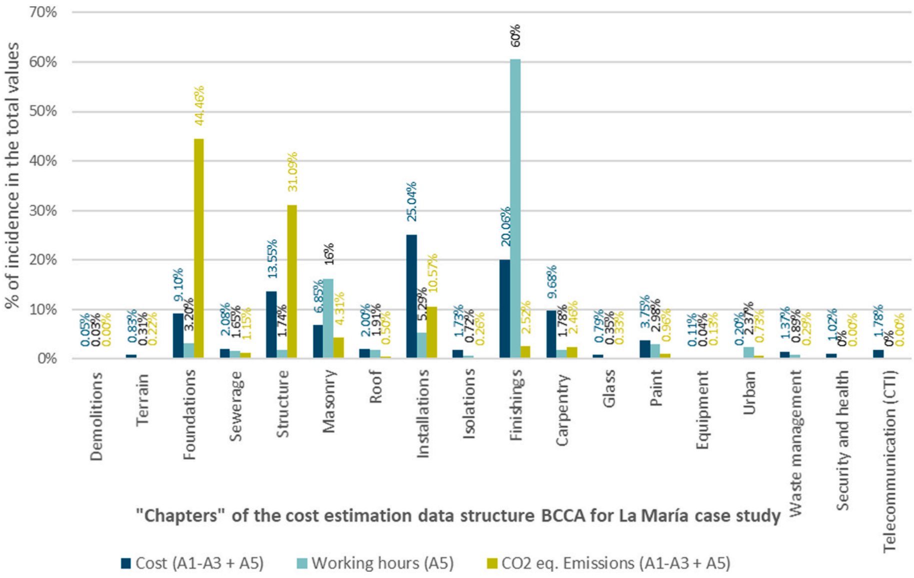

Fig. 9. Percentage of the inventory indicators (working hours, CO_2 emissions and costs) organized according to the BCCA "Chapters" as estimated during the detailed design stage (EP).

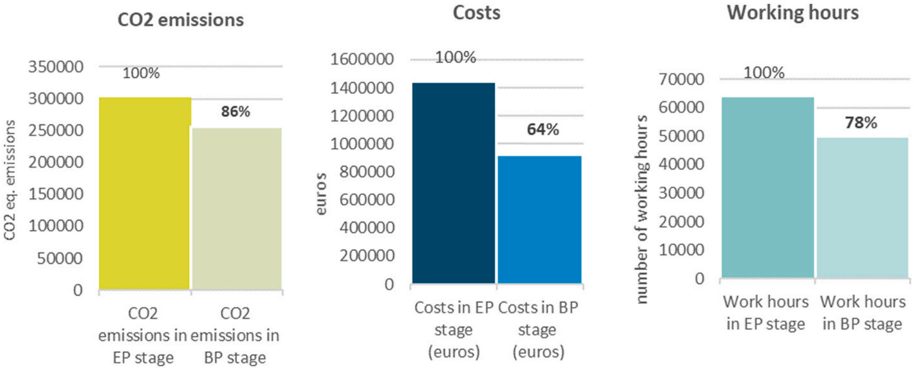

Fig. 10. Total percentage of work hours, CO2 emissions and costs at the product and construction stages.

indicate that the strategy of extracting the volumes can be used in most of the "Chapters" except for the installations and sewerage, in which other strategy types, described in Ref. [42], such as the use of information associated with the element unit must be implemented.

Regarding the LCSA system boundaries, the present study has limitations such as the integration of the information related to the complete building life cycle, since it focused on the product and construction stages. Future works can address the integration of information regarding the complete building life cycle stages. Furthermore, several limitations have been detected related to the harmonization of the system boundaries of the three dimensions. For example, the available data sources (BCCA [36] and BEDEC [37]) do not include systematic information, such as data related to the social inventory indicator working hours at the product stage. Moreover, the use of the working hours inventory indicator is limited in utility to only assessing the social dimension performance of the building. Despite this being one of the most frequently used indicators in S-LCA [43], it does not evaluate a specific impact. The proposed method provides a systematic method for collecting social data about the building which can later be used to assess the social life cycle performance. For instance, the collected information can be useful to assess, the effects on workers health, fair salaries, job creation, and other indicators included in Ref. [43].

4.1.3. Variability in the number of items for the cost estimation structure, material quantities and inventory indicators resulting along the building design stages (BP and EP) (RQ3)

The results indicate that over 60% of the cost estimation items can be estimated at an element level (BP), which helps fill the information gaps using the BCCA cost estimation. This means that many building elements can be estimated without obtaining a very highly detailed BIM model, which will save time and effort that would otherwise be spent creating a model checking accuracy and precision. Thus, during the BP stage, it is possible to estimate information related to the building element (such as the steel in columns, or the insulation in walls) systematically, without detailed modeling of the building element and by using a data structure that is aligned with that of the building at the detailed design stage (EP). Moreover, the obtained results indicate that the material quantity has a different influence depending on the sustainability dimension considered when calculating the inventory indicators. This means is that the potential estimation of the inventory indicators at early design stages is higher in the environmental dimension (CO$_2$eq emissions) and lower in the economic dimension (cost) (see Figs. 9 and 10). To solve these limitations and improve the robustness of results, it is recommended to define estimated ratios to include the installations and other non-modeled elements at the early stages. The ratios can be defined depending on the building typology and program.

4.1.4. Identification of the relevant building systems and how the results of the inventory indicators considered are affecting them (RQ4)

The present work demonstrates that the inventory affects the building systems (as defined by the **CTE)** [44]) differently depending on the sustainability dimension considered (see Table 2). So, the improvement potential for the building design can differ depending on the dimensions being considered. For example, the optimization of the structure can lead to a reduction in the environmental impacts, but scarcely affects the social dimension. However, the values of the economic dimension affect various building systems, especially the structure, finishing, envelope and installations.

Table 2 also provides evidence of the complexity that can derivate the triple-bottom-line sustainability assessment of the building, such as the challenges that must be addressed in the context of weighting and harmonization for the three dimensions in terms of the data collection, the definition of the LCSA and the potential utility of the results in the design process optimization of the buildings.

5. Conclusions

The study presents, validates, and demonstrates the consistency of an "element method" when conducting the LCSA in BIM, and demonstrates that consistent environmental, economic, and social assessment can be performed during the building design process. This method can help to provide a transparent data structure during the design stage as the designer can start with a reliable data structure to support any assumptions and fill in any gaps (the decisions that have not yet been taken) to obtain results in the early stages that are aligned with over 60% of the final results. The method proposes a systematic way to harmonize a cost estimation structure (not aligned with the element decomposition in BIM (such as the BCCA)) with the IFC scheme at the element level. This study

Table 2
Range of incidence of the results for the inventory indicators accounting to the CTE Building Systems [44].

Building System (CTE) [44]	Cost-Estimation BCCA "Chapter Related"	Environmental (CO_2eq Emissions)	Economic (Euros)	Social (Working Hours
Structure	03. Foundations	75.54%	22.65%	4.94%
	05. Structure			
Envelope and Partitions	09. Isolations	7.87%	21.05%	21.01%
	06. Masonry			
	07. Roof			
	11. Carpentry			
	12. Glass			
Finishing	13. Paint	3.48%	23.81%	63.48%
	10. Finishing			
Installations and Conditioning	08. Installations	11.95%	27.95%	7.25%
	04. Sewerage			
	02. Terrain Preparation			
Equipment	14. Equipment	0.86%	0.31%	2.41%
	15. Urban Equipment			
Others (not described in the CTE) That Describe the Construction Process and Activities	01. Demolitions	0.29%	4.22%	0.92%
	17. Waste Management			
	19. Security and Health			
	20. Telecommunications (CTI)			

Reference	Environmental	▓	▒	░	□
	Economic	▓	▒	░	□
	Social	▓	▒	░	□
	Range of Incidence	high	medium	low	very low
		100-60%	59-25%	24-10%	9-0%

also concludes that this process (based on relating and classifying the items BCCA according to the IFC scheme) is manually performed but can be automated with an API (Application Programming Interface).

One of the major findings of the present work is demonstrating the consistency of a method that enables the assessment of different design options, different components, and "what-if" scenarios without investing much time in the modeling process for BIM and reducing the possible variability/errors in the model check and quantity take-off procedure. The results obtained provide evidence of the distribution of the items and "Chapters" in the cost estimation data structure during the early and detailed design stages (BP and EP) when carrying out the LCI for the LCSA implementation. Thus, the results demonstrate that, for similar building typologies and building programs, the structure, envelope, and finishing can be the most relevant building systems for potential optimization during the early design stages.

The proposed method can be used in other similar Spanish cost estimation databases such as the BEDEC, CYPE, etc. Future research should be focused on verifying the accuracy of the method in other cost estimation structure types from other countries as well as comparing the accuracy of the method with other more detailed design stages such as the stage "as built", by extracting the information from BIM models.

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CRediT authorship contribution statement

B. Soust-Verdaguer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **I. Bernardino Galeana:** Conceptualization, Investigation, Methodology, Data curation, Software, Writing – original draft, Writing – review & editing. **C. Llatas:** Conceptualization, Data curation, Formal analysis, Methodology, Funding acquisition, Project administration, Validation, Writing – review & editing. **M.V. Montes:** Conceptualization, Investigation, Supervision, Formal analysis, Validation, Writing – review & editing. **E. Hoxha:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **A. Passer:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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.

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Appendix A. Supplementary data

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References

[1] Ipcc, I. Working Group, Contribution to the IPCC fifth assessment report, in: Climate Change 2013: the Physical Science Basis, Ipcc, 2013.
[2] International Energy Agency (IEA), Global Status Report for Buildings and Construction 2019, 2019, https://doi.org/10.1038/s41370-017-0014-9.
[3] M. Bahramian, K. Yetilmezsoy, Life cycle assessment of the building industry: an overview of two decades of research (1995–2018), Energy Build. (2020), https://doi.org/10.1016/j.enbuild.2020.109917.
[4] W. Kloepffer, Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95, Int. J. Life Cycle Assess. (2008), https://doi.org/10.1065/lca2008.02.376.
[5] S. Valdivia, C. Ugaya, G. Sonnemann, J. Hildenbrand (Eds.), Towards a Life Cycle Sustainability Assessment. Making Informed Choices on Products, 2011. Paris.
[6] ISO, ISO 14040, 2006 Environmental Management — Life Cycle Assessment — Principles and Framework, 2006.
[7] C. Llatas, B. Soust-Verdaguer, A. Passer, Implementing life cycle sustainability assessment during design stages in building information modelling: from systematic literature review to a methodological approach, Buid. Environ. 182 (2020), https://doi.org/10.1016/j.buildenv.2020.107164.
[8] C. Llatas, B. Soust-Verdaguer, A. Hollberg, E. Palumbo, R. Quiñones, Developing a BIM-based life cycle sustainability assessment application in the early design stages using industry foundation classes, Autom. Constr. (2021). Submitted for publication.
[9] buildingSMART, buildingSMART. https://www.buildingsmart.org/, 2020. (Accessed 30 December 2020).
[10] International Construction Information Society, Cost estimating and BIM. http://www.icis.org/publications/papers/, 2018.
[11] T. Lützkendorf, Application of "element"-method in sustainability assessment, Cent. Eur. Towar. Sustain. Build. 2019 (2019) 1–8.
[12] I. Bernardino-Galeana, C. Llatas, M.V. Montes, B. Soust-Verdaguer, J. Canivell, P. Meda, Life cycle cost (LCC) and sustainability. Proposal of an IFC structure to implement LCC during the design stage of buildings, Springer Ser. Geomech. Geoengin (2019) 404–426, https://doi.org/10.1007/978-3-030-61118-7_33.
[13] B. Soust-Verdaguer, A. García-Martínez, C. Llatas, J.C. Gómez de Cózar, K. Allacker, D. Trigaux, E. Alsema, B. Berg, D. Dowdell, W. Debacker, R. Frischknecht, L. Ramseier, J. Veselka, M. Volf, P. Hajek, A. Lupíšek, Z. Malik, G. Habert, A. Hollberg, S. Lasvaux, B. Peuportier, F. Pomponi, L. Wastiel, V. Gomes, O. Zara, M. Gomes, A. Gusson Baiocchi, L. Pulgrossi, C. Ouellet-Plamondon, A. Moncaster, R. di Bari, R. Horn, K. Lenz, M. Balouktsi, T. Lützkendorf, M. Röck, E. Hoxha, A. Passer, Implications of using systematic decomposition structures to organize building LCA information: a comparative analysis of national standards and guidelines- IEA EBC ANNEX 72, IOP Proc. Earth Environ. Sci. J. 588 (2020), https://doi.org/10.1088/1755-1315/588/2/022008.
[14] Andalusian Government, BCCA, Base de Costes de la Construcción de Andalucía. https://www.juntadeandalucia.es/, 2017. (Accessed 20 January 2020).
[15] A. García-Martínez, Análisis del Ciclo de Vida (ACV) de edificios. Propuesta metodológica para la elaboración de Declaraciones Ambientales de Viviendas en Andalucía, Universidad de Sevilla, 2010.
[16] Cype Ingenieros, Arquímedes. Mediciones, presupuestos, certificaciones y pliegos de condiciones. http://arquimedes.cype.es/, 2017. (Accessed 3 August 2021).
[17] Rib Spain, Presto presupuestos (n.d.), https://www.rib-software.es/presto_presupuestos. (Accessed 3 August 2021).
[18] Itec, TQMi GMA, 2020.
[19] IEA EBC, IEA EBC ANNEX 72. http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-72/, 2017. (Accessed 1 June 2017).
[20] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Critical review of BIM-based LCA method to buildings, Energy Build. 136 (2017) 110–120, https://doi.org/10.1016/j.enbuild.2016.12.009.
[21] A. Hollberg, G. Genova, G. Habert, Evaluation of BIM-based LCA results for building design, Autom. ConStruct. 109 (2020), 102972, https://doi.org/10.1016/j.autcon.2019.102972.
[22] K. Figueiredo, R. Pierott, A.W.A. Hammad, A. Haddad, Sustainable material choice for construction projects: a Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP, Build. Environ. 196 (2021), 107805, https://doi.org/10.1016/j.buildenv.2021.107805.
[23] C. Panteli, A. Kylili, L. Stasiuliene, L. Seduikyte, P.A. Fokaides, A framework for building overhang design using building information modeling and life cycle assessment, J. Build. Eng. 20 (2018) 248–255, https://doi.org/10.1016/j.jobe.2018.07.022.
[24] M. Najjar, K. Figueiredo, M. Palumbo, A. Haddad, Integration of BIM and LCA: evaluating the environmental impacts of building materials at an early stage of designing a typical office building, J. Build. Eng. 14 (2017) 115–126, https://doi.org/10.1016/J.JOBE.2017.10.005.
[25] M. Röck, A. Hollberg, G. Habert, A. Passer, LCA, BIM, Visualization of environmental potentials in building construction at early design stages, Build. Environ. 140 (2018) 153–161, https://doi.org/10.1016/j.buildenv.2018.05.006.
[26] C. Cavalliere, G. Habert, G.R. Dell'Osso, A. Hollberg, Continuous BIM-based assessment of embodied environmental impacts throughout the design process, J. Clean. Prod. 211 (2019) 941–952, https://doi.org/10.1016/j.jclepro.2018.11.247.
[27] A. Naneva, M. Bonanomi, G. Habert, A. Hollberg, D. Hall, Integrated BIM-based LCA for the entire building process using an existing structure for cost estimation in the Swiss context, Sustain. Times 12 (2020), https://doi.org/10.3390/su12093748.
[28] C.R.B. Schweizerische, S.I.A. Schweizerischer, Standards für das Bauwesen eBKP-H SN 506 511 Baukostenplan Hochbau, 2012.
[29] Bauteilkatalog (n.d.), www.bauteilkatalog.ch.
[30] Bundesamt für Energie, 34 BFE (n.d.), www.bfe.admin.ch.
[31] Hollinger Consult GmbH (n.d.), www.holligerconsult.ch.
[32] KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) (n.d.), www.kbob.admin.ch.
[33] eco-bau (n.d.), www.eco-bau.ch.
[34] IPB (Interessengemeinschaft privater professioneller Bauherren) (n.d.), www.ipb-online.ch.
[35] B.I.M. Forum, Level of Development (LOD) Specification Part I & Commentary, 2020.

[36] Andalusian Government, BCCA, Base de Costes de la Construcción de Andalucía. Clasificación Sistemática de Precios Básicos, Auxiliares y Unitarios, 2017.
[37] Itec, BEDEC. https://metabase.itec.cat/, 2020. (Accessed 30 December 2020).
[38] ISO, ISO 21931-2:2019 Sustainability in Buildings and Civil Engineering Works — Framework for Methods of Assessment of the Environmental, Social and Economic Performance of Construction Works — Part, vol. 2, Civil engineering, 2019.
[39] EN, EN 15978:2011 - Sustainability of construction works - assessment of environmental performance of buildings - calculation method, European Standard (2011).
[40] W. Peña, S. Parshall, Problem Seeking : an Architectural Programming Primer, 2012, p. 274.
[41] EN, EN 16627:2015 - Sustainability of construction works - assessment of economic performance of buildings - calculation methods, European Standard (2015).
[42] S. Theißen, J. Höper, J. Drzymalla, R. Wimmer, S. Markova, A. Meins-Becker, L. Michaela, Using open BIM and IFC to enable a comprehensive consideration of building services within a whole-building LCA, Sustainability 12 (2020), https://doi.org/10.3390/su12145644. In this issue.
[43] C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, G. Arcese (Eds.), UNEP. Guidelines for Social Life Cycle Assessment of Products and Organizations, 2020. https://www.lifecycleinitiative.org/wp-content/uploads/2020/12/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-sml.pdf.
[44] CTE, Spanish building technical code, real decreto 314/2006 17 marzo, BOE 74 (2006) 11816–11831 (CTE-DB-SE).