



The Open Construction & Building Technology Journal

Content list available at: <https://openconstructionandbuildingtechnologyjournal.com>



REVIEW ARTICLE

Current Opportunities and Challenges in the Incorporation of the LCA Method in BIM

Vera Durão¹, António Aguiar Costa¹, José Dinis Silvestre^{1*}, Ricardo Mateus², Ruben Santos¹ and Jorge de Brito¹

¹Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

²Department of Civil Engineering, ISEC, School of Engineering, University of Minho, Guimarães, Portugal

Abstract:

Background:

In the last years, Building Information Modelling (BIM) and Life Cycle Assessment (LCA) have been integrated to support the pursuit of sustainability in the built environment. However, the integration of environmental information with different specificity and reliability requirements on distinct Levels of Development (LOD) of BIM objects was not yet exploited considering several environmental impact categories.

Objective:

The objective of this paper is to discuss the complexity and depth of LCA information needed for BIM objects, considering different LOD, and to propose a parametrisation of environmental information to be included in BIM objects according to their LODs.

Methods:

A literature review on LCA methodology, sources of LCA information, integration of LCA in BIM, and LOD of BIM objects was initially performed, followed by a detailed characterisation of the different types of sources of LCA information to include in BIM models. These steps contributed to the development of the proposed parametrisation of environmental data.

Results:

A parametrisation of environmental information to be included in BIM objects was developed. This parametrisation considered the degree at which the element's information has been specified (LOD) and the respective detail and reliability of the environmental information to include.

Conclusion:

A new approach is proposed that allows an evolutive integration of environmental information in BIM objects according to their growing LODs.

Keywords: Building information modelling (BIM), Building sustainability, Environmental information, Level of development (LOD), Life cycle assessment (LCA), Parametric objects.

Article History

Received: March 09, 2020

Revised: August 25, 2020

Accepted: September 24, 2020

1. INTRODUCTION

The construction sector has significant relevance in the European economy. It generates almost 9% of the Gross Domestic Product (GDP) and provides 18 million jobs [1]. In the EU, approximately half of all extracted materials and energy consumed and roughly a third of water consumption are due to buildings [2]. This sector also generates about one-third of the waste and is responsible for potential environmental

impacts resulting from all stages of the Life Cycle (LC) of a building [3]: manufacturing of construction products, building construction, use, renovation and construction waste management.

Professionals, decision-makers and investors throughout the European Union (EU) need empirical-based, reliable, transparent and comparable data, based on building performance indicators, to consider impacts related to the whole LC of a building [3]. Life Cycle Assessment (LCA) is a commonly accepted and well-established methodological tool that quantitatively applies life cycle thinking in the environmental

* Address correspondence to this author at Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal; Email: jose.silvestre@tecnico.ulisboa.pt

analysis of activities related to processes or products [4]. LCA is a structured, comprehensive and standardised method (ISO 14040 series, namely ISO 14040 and ISO 14044). It quantifies all relevant emissions, consumed resources and the potential impacts caused by a product or service [5].

Building Information Modelling (BIM) may become a valuable tool to improve the energy performance and resource efficiency of buildings [6]. Although there are different definitions, BIM is commonly defined as “a digital representation of physical and functional characteristics of a facility” as well as the base for a shared knowledge (and decision support) resource for information during its life cycle (from earliest conception to the end of life stages) [7]. An essential characteristic of BIM is its collaborative and life cycle approach, considering the several phases of the buildings (or infrastructures) LC [8]. This feature allows for more accessible information management and potentiates optimised approaches to facilities management.

Great potential has been identified in the use of combined BIM and LCA methodologies, and some research works have been published regarding this synergy [9 - 14]. The first approach followed by the researchers focused on the integration of BIM with numerous programs to conduct an LCA study of a building, e.g. by Basbagill *et al.* 2013, Jalaei and Jrade 2014, Sharif and Hammad 2019 or Wang *et al.* 2011 [15 - 18]. However, the lack of interoperability and considerable manual work were some of the limitations of this approach. More recent studies have a different approach,

though. Nowadays, BIM models are used for the automatic materials’ quantity take-off and connected with external LCA databases (e.g. Tally or others) [19 - 23]. Even though this approach has fewer limitations than the first, it is still important to discuss the practical use of these approaches by Architecture, Engineering and Construction (AEC) professionals. To the extent of the authors’ knowledge, only one study [24] has treated the option of having LCA-based information evolving since the early stages of design, for instance, LOD100, until the later and more detailed ones, as LOD 400 or even 500. A model LOD 300 is referred to in the literature as a requirement for the use of the bill of materials to perform the LCA [25]. Currently, few publications [24, 26 - 28] explicitly relate the integration of LCA and BIM methods to the specificity and requirements of different stages in the design and construction process (different Levels Of Development - LOD). In parallel, the environmental LCA methodology, concepts and terminology are still not commonly used by these professionals and need to be further explained and integrated into their practice. This work will, thus, explore the BIM-LCA integration from a different perspective, *i.e.*, by discussing the type of LCA information that is relevant to be integrated into BIM objects, depending on their LOD. Although the use of different sources and formats of environmental information may hinder the understanding of varying LCA results for different LODs, a solution is proposed for the parametrisation of environmental information in BIM objects, according to their LOD.

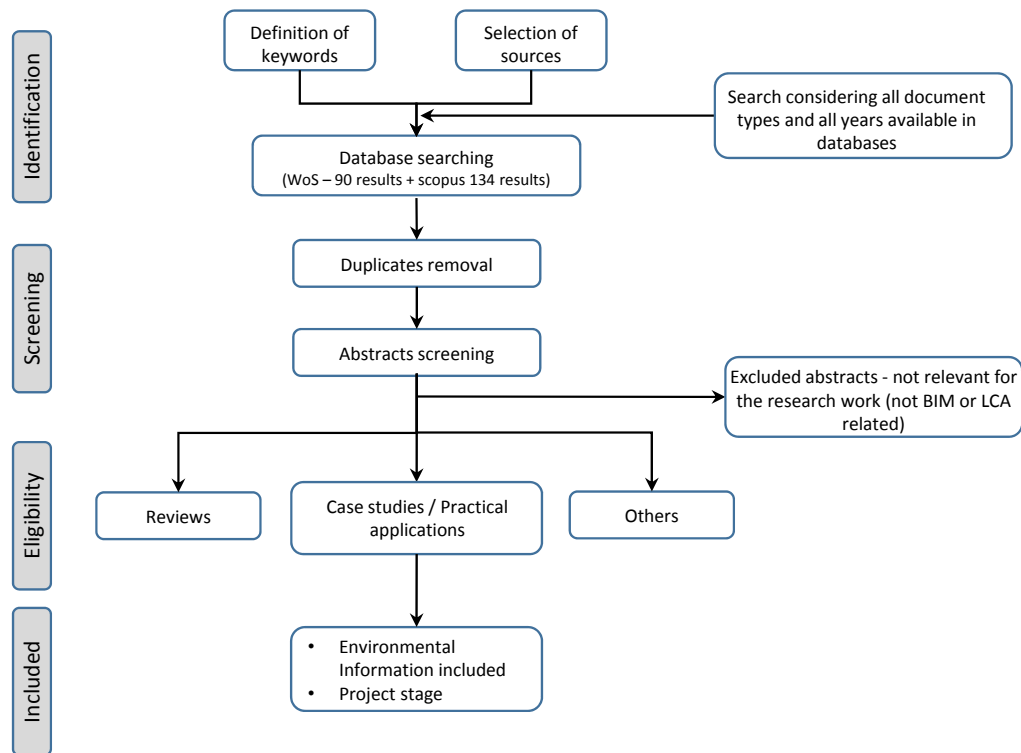


Fig. (1). Literature search strategy.

2. INTEGRATION OF LCA AND BIM

2.1. Literature Review Procedure

For this paper, a critical review was developed, including the applicable normative framework and the research works previously published. For that, several sources of scientific data were considered, with a higher focus on Scopus, Web of Science (WoS) and Google Scholar databases, due to their recognition within the scientific community and coverage. According to previous studies [29], Google Scholar has the benefit of higher coverage. Nevertheless, it includes non-peer-reviewed information, as well as project reports, thesis and other documents from academic repositories, as well as some redundancies. Thus, for this research work, only the results obtained in Scopus and WoS were analysed. In January 2020, a search using the same keywords and without time restrictions returned the following results: “bim+lca” returned 90 results in WoS (all databases) and 134 in Scopus database; “bim+lca+lod” returned 5 and 8 results in the same databases, respectively. Furthermore, some works were not considered because their focus was neither BIM nor LCA.

Case studies were analysed concerning the relationship between BIM and LCA methods and the kind of environmental information included, as well as the project stage in which the studies were conducted. The literature search strategy is represented in Fig. (1).

Based on the results of this review, the authors propose a parametrisation of the environmental information to be included in BIM objects to automatise the BIM-based LCA procedures for the complete design process.

2.2. Literature Review

The integration of BIM and LCA methodologies is a growing research area, and there are numerous research works published in this context [10, 11, 15, 17, 27, 28, 30, 31], namely several reviews [6, 11, 14, 32, 33].

The BIM methodology supports the development of construction projects comprising both geometric and semantic information about building elements [11]. In general, BIM standards and guidelines focus on the planning, design, construction, energy consumption, operation and maintenance of buildings [33], and the need for the development of new BIM tools for assessing sustainability criteria was identified. Some authors [10, 15, 23] highlight the relevance of working with LCA in a BIM environment, especially at the early stages of design, using both a whole life cycle approach and a material-oriented (cradle-to-gate) approach [10]. Sharif and Hammad [17] worked in building renovation. These authors present a model that, along with environmental impacts, integrates energy efficiency and life cycle costs in a BIM model to optimise the renovation scenario for existing buildings. Dupuis *et al.* [27] present a method to automatically perform LCA calculations at the early stages of design, allowing updates during the evolution of the model, through the link of higher LOD objects with existing LCA databases. This is one of the few works that consider the evolution of the model throughout the design stages of the project, although without showing it in practice.

Santos *et al.* developed several research works related to the integration of LCA and BIM, namely with the emphasis on the interoperability of the several software tools used for both methods [28]. In what concerns interoperability, they concluded that the cooperation between manufacturers (who develop Industry Foundation Classes - IFC objects of their products), designers and LCA practitioners are crucial to avoid information loss and to lead to the development of a totally automatic BIM-LCA tool. In their bibliometric analysis and review [6], the authors concluded that sustainable performance is among the subjects that can be considered a new trend or that still has potential. However, there is a lack of research that discusses all dimensions of sustainability [14] since this research topic is still recent.

Jrade and Jalaei have also developed several research works related to the integration of sustainability issues in BIM [9, 16, 30]. They have developed a model [30] that, besides LCA environmental information, also considers the LEED (Leadership in Energy and Environmental Design) sustainability certification scheme and cost modules within the BIM model at the conceptual stage of the design. Limitations were found related both to available information on the existing “green” elements and on the impossibility to use it in detailed design stages because of the incompleteness of the databases used.

Concerning the possible ways to integrate LCA information with BIM, it is possible to divide them into two main alternative approaches [10]:

1. Approach 1. To use the LCA tool to import the environmental information to the BIM model – the LCA tool can extract data automatically from the BIM project about the type and quantities of materials and combines it with the LCI databases available, to perform the LCA of the building. This process can also be done manually when the BIM models are used to provide the bill of materials for the development of the LCA study in an independent tool. One disadvantage of this approach is that each change in BIM model implies a new LCA calculation (the relation is not dynamic, since each time the BIM model changes, the LCA tool needs to be updated with information related to the used materials and quantities);

2. Approach 2. Environmental properties are included in BIM objects - this would allow an automatic calculation of LCA of the building based on the environmental information contained in the objects used. In this case, the properties of BIM objects include environmental information based on LCA results; this would allow an eco-design approach because the environmental information can be used to support decision-making since the early design stages of the project.

According to Bueno and Fabricio [34], these approaches may deliver discrepant results for the same building project, namely because of the limitations regarding the databases on environmental information available for each of them. Several previous studies were identified that tested the integration of LCA information in BIM tools. Table 1 identifies those studies as well as the design stages and approaches used. Moreover, BIM has also been identified as an essential tool to integrate the life cycle sustainability assessment by combining environmental LCA, life cycle costing and social LCA [35].

Table 1. Studies integrating LCA and BIM.

Reference	Approach	Design stage / LOD	LODs evolution?	LCA software	LCA / LCI Databases	LCA impact categories considered or LCIA method
Abanda <i>et al.</i> , 2017 [36]	Approach 1	Early design stage / 200	No	Prototype tool, for REVIT environment	Inventory of Carbon & Energy (ICE)	Embodied energy and CO ₂
Ajayi <i>et al.</i> , 2015 [37]	Approach 1	-	No	Athena Impact Estimator	Athena's databases	Global warming potential and health impact
Ansah <i>et al.</i> , 2020 [38]	Approach 1	-	No	Excel spreadsheet	Inventory of Carbon & Energy (ICE)	Energy use intensity and Global Warming Potential
Basbagill <i>et al.</i> , 2013 [15]	Approach 1	Early design stage	No	Athena EcoCalculator, SimaPro	Athena's databases	Global warming potential (100 years)
Bueno <i>et al.</i> , 2018 [39]	Approach 2	Early design stage	No	GaBi 4.4	Ecoinvent Version 2.01	ReCiPe 2008 environmental indicators, applying the midpoint impact categories
Bueno and Fabricio, 2018 [34]	Both approaches (comparison)	Early design stage	No	GaBi 4.4	Ecoinvent Version 2.01	Acidification, eutrophication, global warming, ozone depletion and smog formation potentials, primary energy demand, non-renewable energy, renewable energy
Cavalliere <i>et al.</i> , 2019 [24]	Approach 1	Several stages / 100-400	Yes	-	Swiss buildings database, Bauteilkatalog, KBOB-Ökobilanzdaten	Global warming potential and non-renewable primary energy
Eleftheriadis <i>et al.</i> , 2018 [40]	Approach 1	Early design stage	No	-	EPDs	Global warming potential
Gardezi and Shafiq, 2019 [41]	-	Early design stage	No	-	Malaysian Energy Statics Handbook 2014	Operational carbon footprint
Georges <i>et al.</i> , 2015 [42]	Approach 1	Early design stage	No	SimaPro 7.3	Ecoinvent Version 2.2	Global warming potential
Hasik <i>et al.</i> , 2019 [43]	Approach 2	-	No	Autodesk Tally	GaBi LCI database	Acidification, eutrophication, global warming, ozone depletion and smog formation potentials and non-renewable energy demand
Hollberg <i>et al.</i> , 2020 [44]	Approach 1	Early design stage	No	-	KBOB-Ökobilanzdaten	Global warming potential
Hollberg <i>et al.</i> , 2019 [45]	Approach 1	Early design stage	No	-	Ökobaadat database	Operational environmental impact (use phase of the building) based on energy demand, embodied impact from the material production, replacements and the end-of-life
Houlihan Wiberg <i>et al.</i> , 2014 [46]	Approach 1	Early design stage	No	SimaPro 7.3	Ecoinvent Version 2.2	Global warming potential (both embodied and operational)
Iddon and Firth, 2013 [47]	Approach 1	-	No	Excel	Inventory of Carbon & Energy (ICE)	Embodied and operational energy and carbon emissions
Jalaei and Jrade, 2014 [16]	Approach 1	Early design stage	No	Athena Impact Estimator	Athena's databases	Primary energy consumption, acidification, global warming, human health respiratory effects, ozone depletion, photochemical smog and eutrophication potentials, weighted raw resource use

(Table 1) *contd....*

Reference	Approach	Design stage / LOD	LODs evolution?	LCA software	LCA / LCI Databases	LCA impact categories considered or LCIA method
Jrade and Jalaei, 2013 [30]	Approach 1	Early design stage	No	Athena Impact Estimator	Athena's databases	Primary energy consumption, acidification potential, global warming potential, human health respiratory effects potential, ozone depletion potential, photochemical smog potential, eutrophication potential, weighted raw resource use
Kulahcioglu <i>et al.</i> , 2012 [48]	Approach 1	-	No	Prototype software, Gabi	Ecoinvent	Global warming potential
Lee <i>et al.</i> , 2015 [25]	Approach 2	- / 300	No	-	Korean LCI database	Global warming, abiotic depletion, acidification, eutrophication, ozone potential, and photochemical ozone creation potentials
Marzouk <i>et al.</i> , 2017 [49]	Approach 1	-	No	Athena Impact Estimator	Athena's databases	Greenhouse gases, sulfur dioxide, particular matter, eutrophication particles, ozone-depleting particles and smog potential
Najjar <i>et al.</i> , 2017 [50]	Approach 2	Early design stage	No	Tally	GaBi LCI database	Acidification, eutrophication, global warming, ozone depletion and smog formation potentials; primary, non-renewable and renewable energy demand.
Nizam <i>et al.</i> , 2018 [51]	Approach 2	-	No	Prototype tool	Inventory of Carbon & Energy (ICE)	Embodied energy
Peng, 2016 [52]	Approach 1	Detailed stage	No	Ecotect Analysis	Literature - several research papers	CO ₂ emissions
Rezaei <i>et al.</i> , 2019 [53]	Approach 1	Several design stages / 100 and 300	Yes	openLCA	Ecoinvent 3.3	Climate change, ecosystem quality, human health and resources
Rock <i>et al.</i> , 2018 [26]	Approach 1	Early design stage / 200	No	-	Swiss SIA MB 2032 database	Global warming potential
Santos <i>et al.</i> , 2020 [54]	Approach 2	Early design stage and Detailed stage	No	BIMEELCA prototype tool	Generic databases (IBU, Ökobaudat, MRPI, Ecoinvent) and specific data (EPDs)	Life cycle costs, acidification, global warming, eutrophication, ozone depletion and photochemical ozone creation potentials; abiotic depletion potential of materials and for fossil fuels; renewable and non-renewable energy
Shadram <i>et al.</i> , 2016 [55]	Approach 1	-	No	Prototype tool developed	EPDs, transportation information	Embodied energy, carbon footprint
Shadram and Mukkavaara, 2018 [56]	Approach 1	-	No	-	Inventory of Carbon & Energy (ICE)	Embodied and operational energy
Shafiq <i>et al.</i> , 2015 [57]	Approach 1	Early design stage	No	-	Inventory of Carbon & Energy (ICE)	Embodied carbon footprint
Shin and Cho, 2015 [21]	Approach 1	Early design stage	No	Excel	Korea Life Cycle Inventory	Global warming potential (GHG emissions)
Soust-Verdaguer <i>et al.</i> 2018 [31]	Approach 1	Detailed stage / 300	No	Spreadsheet software	Ecoinvent V2.0	Global Warming Potential, freshwater aquatic ecotoxicity, human toxicity and Ozone Depletion Potential
Yang <i>et al.</i> , 2018 [58]	Approach 1	- / 300	No	eBalance, by IKE Environmental Technology Co. Ltd	CLCD (Chinese Life Cycle Database), ELCD, Ecoinvent	Global warming potential (carbon footprint)

An important conclusion from the case study analysis is that only one study [24] considers the continuous assessment of environmental impacts throughout the building design process and only another one considers the application of the same methodology to growing LOD (100 and 300) of a project [53]. The first one considers a growing specificity and refinement of the information used for the LCA analysis along with the development of the project. However, it only considers one environmental impact category for all analysed design stages: Global Warming Potential (GWP). The second one compares the LCA for two specific moments of the project design, concluding that the results for LOD 300 are within the uncertainty intervals of LOD 100. The remaining papers reviewed do not consider the entire design process, and only some of them establish a specific LOD and/or design stage for the analysis. In the analysed studies, it is evident that the environmental impact categories considered are not consensual, going from only one category (*e.g.* embodied energy or GWP) to a complex set of categories, including those usually stated in EN 15804 compliant Environmental Product Declarations (EPDs) or other information sources. Moreover, it was noted a high discrepancy in the boundaries of the LCA studies, with some cases considering only the embodied impacts of the materials (*e.g.* [25, 26, 36]), other considering the construction and transportation stages, and others much more comprehensive, including all life cycle stages (*e.g.* [21, 54, 59]). In most cases, it was not identified the automation of the LCA-BIM integration since the BIM model is usually used only to provide the bill of materials that feed the LCA study in a different environment (approach 1).

In the available guidelines for practitioners, the recommendation is to integrate environmental information on BIM according to the second approach above mentioned, as expressed in the draft UNI 11337 - Part 3 [60]. This draft document is aimed at identifying standard criteria to describe construction products, through structured models for collecting and processing the technical information based on the harmonised standards for CE marked products or in agreement with other relevant reference standards. In the proposed model for CE marked construction products, the technical information comprises “Information about sustainability according to EN 15804” (EN 15804:2012+A1:2013). In the proposed form, the information on sustainability is consistent with that included in Type III EPDs:

- Parameters describing environmental impacts (7 impact categories);
- Parameters describing resource use (17 parameters);
- Environmental information describing output flows (4 parameters);
- Environmental information describing waste categories (3 parameters);
- Parameters describing pollutant emission from materials (3 parameters).

This approach considers the embodied impacts of specific building components and respective material quantities. However, in early-stage BIM models, this data is only approximated, which makes practicable to implement it only

for later design stages.

For the early design stages, Dupuis *et al.* (2017) [27] suggested a method to automatically perform LCA calculations, at the first level of development (*i.e.*, LOD100) of the BIM model. The proposed method assumes the link of each object to a unit process in the LCA model, or of each object's type to the unit process that contains information on the LC of the material and its assembly. However, in LOD100 objects, the linkage to LCA data is uncertain because the level of specification and detail is low, and it is difficult to identify the best match between LCA information (or module) and each BIM object. For that reason, the suggested method uses the probability of the existence of specific object types and considers the contribution of the building elements to the overall uncertainty of the LCA results. It allows the update of the calculation throughout the development of the model, based on the new data layer and format. It still needs to be further experimented and validated to provide, in the future, LCA estimations for decision support at early design stages [27]. In addition, for early design stages, a different approach is described based on the modularity of the environmental information, *i.e.*, considering that the building is the sum of building assemblies (*e.g.* walls, floors) with its sub-elements (*e.g.* structure, insulation and finishing), composed of the respective building materials [26]. In this approach, the authors aggregated detailed environmental information of each material at the building element level.

In what concerns standardisation, the International Standardisation Organisation (ISO) is currently developing the standard ISO/CD 22057 - Enabling use of EPD at construction works level using BIM. In work coordinated by the Technical Committee (TC) ISO/TC 59/SC 17 Sustainability in buildings and civil engineering works, this standard is expected to explore the possibility of machine-readable information further. Using already available environmental data, like the one in EPDs and generic databases, this information shall be presented in a harmonised way so that BIM tools can read it. Again, like in the previously mentioned draft UNI 11337 - Part 3 [60], environmental properties are expected to be included in BIM objects. Considering the availability of information in EPDs, this standard is expected to consider environmental impact categories according to EN 15804 [61].

In line with the expected standardisation developments, the Norwegian project “Building the bridge” intends to make EPD data available through BIM [62]. For that, an application programming interface (API) was developed to allow building information from BIM to be available for other software. Another API was developed to make EPD information, usually presented in PDF format, readable in a database format and accessible to be used in BIM models.

Moreover, in what concerns the information management using BIM, the new EN ISO 19650-1 [63] introduces the new concept of LOIN (Level of Information Need). According to this, LODs are a simplification of reality as they try to divide the project into 4 or 5 moments in which information is growing (LOD 100, 200, *e.g.*). The LOIN defines the information that is needed at each moment of project development and for each BIM use. One of the objectives is to

prevent the inclusion of unnecessary information at a specific project stage.

2.3. Available Tools

Some of the BIM-based LCA tools available in the market were already identified by other researchers [12]: Tally [64], IMPACT [65], eveBIM-ELODIE [66] and Arquimedes [67]. Each of these tools integrates distinct databases, e.g. a set of Environmental Product Declarations (EPDs), database of *GaBi* software, BRE (Building Research Establishment) database or INIES database (the French National Reference Database of Environmental and Health Declarations for Products). It is worth mentioning that in Arquimedes, only two environmental impact categories are considered (total embodied energy - EE_{Tot} , and GWP), instead of presenting the complete set of environmental impact categories recommended by the standards, namely EN 15804 [61].

IMPACT and eveBIM-ELODIE are stand-alone programs that analyse the output of BIM modelling to estimate the potential environmental impacts. Tally, a plug-in for Autodesk Revit, generates an automatic report regarding the environmental performance of the BIM model.

Another BIM-based tool connected to the Revit software (a new plug-in) was developed [51] but, in this case, assessing only the embodied energy of the project (in the material production, transportation and construction stages). The authors argue that the decision process that leads to a low environmental impact in a building is put straightforwardly by the integration of embodied energy information in the BIM model. Thus, they propose a methodology to use this impact category for decision-support concerning both the design (spatial configuration, materials, e.g.) and construction stages. In summary, there is not a common source of environmental information, and none of the existing solutions allows the manipulation of the environmental information in BIM objects or depends on their LOD. This situation means that the interpretation of results will be limited, as it is very likely that the materials used in the BIM project will be different from those available in the databases.

3. LCA METHODOLOGY AND SOURCES OF LCA INFORMATION FOR BUILDING MATERIALS AND ASSEMBLIES

LCA method quantifies resources consumption, relevant emissions, and the related impacts (both on the environment and human health) that are associated with any goods or services throughout their LC [5]. Thus, LCA is a complex and data-intensive methodology that includes impacts from the extraction of resources to the end of life, also considering manufacturing, use, and recycling or disposal of remaining waste [68]. Due to the specificities and data intensity, it is usually applied by experts from the research or consultancy area and not directly by the production companies. Therefore, the sources of LCA data may be found in: 1) published research works, such as those previously mentioned; 2) national or international databases (distinct levels of reliability and representability), e.g. [69, 70]; 3) specific LCA studies promoted by the companies to comply with an environmental

labelling system, such as Environmental Product Declarations (EPD). In each of these sources, LCA data presents different levels of representativeness (namely, technological or geographical) and specificity (from generic to site-specific data).

3.1. National or International Generic Databases

The ISO standards applicable to the development of LCA do not specify which impact categories shall be assessed and which impact assessment methods shall be used [71]. Thus, even if following the applicable standards, not all LCA data available are comparable or based on the same assessment criteria, since depending on the LCIA method applied, the results of the assessment will be different (distinct impact categories, units, e.g.).

Commonly, national and international databases used for the development of LCA studies are not based on LCA results, but rather on life cycle inventory (LCI) data. This situation allows LCA practitioners to start from the LCI stage and perform LCIA by applying distinct impact assessment methods to obtain the respective LCA results. These databases provide generic data, which can be defined as “surrogate data used if no system-specific data are available” [68] and/or can be developed using, at least partly, other information than the one measured for the specific process [72].

A recent study [69] summarised the currently available international generic databases that include environmental information related to construction products, including several ones in Europe and North America:

Europe:

- Ecoinvent [73] was developed by the Swiss Centre for Life Cycle Inventories. It is included in or is compatible with most LCA software and provides practitioners with the reports on the information contained in the database (methodology, flow charts, life cycle inventories, and references). It provides LCI data on a broad range of processes (extraction of raw materials, production processes, waste management, e.g.), as well as the most commonly recognised assessment methods, allowing the calculation of LCIA results [73];
- ELCD database, supported by the European Commission, comprises LCI data from front-running EU business associations and others for key materials, energy carriers, transport, and waste management. The respective data sets were officially provided and approved by industrial associations [68]. ELCD database was discontinued in June 2018, but it is still downloadable as a zip package on the online page of the European Platform on Life Cycle Assessment;
- GaBi Database [74] was developed by PE International for GaBi software and is described as one of the largest LCA databases in the market. It contains over 12,000 ready-to-use LCI profiles based on primary industry data;
- PlasticsEurope Eco-Profiles [75], initiated by PlasticsEurope in 1991, has been continuously

updated. It is a free LCA database containing LCI information specialised in plastic materials and is included in the SimaPro and GaBi software;

North America:

- Athena [76] is the database included in the tool Athena Impact Estimator for Buildings [77]. It comprises LCI data for construction materials, energy, transport, construction and demolition processes, maintenance, repairing, and waste disposal;
- US Life Cycle Inventory Database [78] was developed by the National Renewable Energy Laboratory (NREL) of the US Department of Energy and provided information on the energy and material flows associated with the manufacturing of a material, component, or assembly in the US.

Besides these, some more databases are identified [69] at the national level, namely: Base Carbone (France), BEDEC (Spain), CPM LCA (Sweden) and ProBas (Germany). The representability and use of these databases are limited to their geographic scope and, in some cases, to the language used.

Moreover, an informal non-profit group of interested stakeholders has established a working group that aims at making available an online-based international open data network structure for EPD / LCA data using a standard data format and open-source software [79]. This group is called the International Open Data Network for Sustainable Building (InData). InData working group has not yet made available that database, but developed a document with Compliance-Core Rules and Requirements of the International Open Data Network for Sustainable Building - WG InData [80]. This database is expected to provide information based on the established ILCD data format created by the European Commission [68], limited to those parts which are necessary and suitable for describing EPD data following the EN 15804.

The European Commission (EC) is also developing and purchasing data to ensure that default secondary datasets can consistently be freely used by all companies that would like to develop Product Environmental Footprint Category Rules (PEFCRs) and Organization Environmental Footprint Category Rules (OEFSRs) approved during the pilot phase of the PEF methodology development [71].

3.2. Specific Information from Production Companies

The Construction Products Regulation (CPR) [81], published in 2011, highlights the importance of the environmental characteristics of construction products (presence of hazardous materials, sustainable use of natural resources/use of compatible raw and secondary raw materials) and their impacts over the LC of a construction work. Concerning the communication of these characteristics, the CPR states that “for the assessment of the sustainable use of resources and of the impact of construction works on the environment, Environmental Product Declarations should be used, when available”.

In Portugal, research works have been developed on LCA

of building materials and assemblies for some years now [82 - 87]. Nevertheless, at the national level, there is only a small number of EPDs that make this specific information available to the AEC professionals (architects, designers, material specifiers) on a standardised, objective, easy-to-read and easy-to-compare document. By February 2020, only thirteen EPDs were available on the Portuguese EPDs program manager website [88]. This context is probably because the program is more recent when compared to others in Europe and because companies in the construction materials sector in Portugal are not yet aware of the competitive advantages of investing in this kind of communication tool.

However, at the international level, the development of EPDs by the construction materials companies is established for some years now, and several EPD programmes provide verified EPDs, despite its voluntary nature. The development of EPD in Europe is supported by the CPR [81], by the standardisation work of the Technical Committee (TC) 350 of the European Committee for Standardization (CEN) - TC350/CEN, and by the ECO Platform. The latter is the European umbrella of the EPD Programme, comprising eighteen national EPD programmes and guaranteeing the mutual recognition of EPD from these countries [89]. This way, in Europe, it is possible to obtain EPDs on construction materials and assemblies under the ECO Platform Programme or from individual programmes [89]. Besides being a standardised method, there is a recognition from a common Platform, *i.e.*, the information provided in EPDs from all individual programmes are recognised by the ECO Platform and will have a standard structure.

Out of the ECO Platform scope, there is also specific information on construction materials and assemblies from EPDs.

Although EPDs are developed based on European standards, the European Commission (EC) has made efforts for the development of a different approach for the calculation and communication of life cycle environmental information of products and organisations: the Product Environmental Footprint (PEF) methodology [4, 90]. Currently, there is only one PEF available for construction materials or assemblies that the authors are aware of: PEF pilot on insulation materials [91]. The EN 15804 standard, which is a core product category rule for the development of EPDs for construction products and services, was updated in a recent review process that brought it very close to the PEF method [92]. Nowadays, the concept of machine-readable EPDs is already in the market [93] as a way of facilitating the use of the information. Digitised databases are already available with machine-readable data from EPDs: Inies Oekobau.dat, Environdec, EPD-Norge Digi, IMPACT and NMD [94]. This information, however, is not yet specifically prepared to be used in BIM, although being an expected development [62, 95].

4. INCORPORATION OF LCA INFORMATION ACCORDING TO THE LOD OF BIM OBJECTS

4.1. LOD of BIM Objects and LCA

BIM objects are classified as belonging to a given LOD depending on the degree to which the element's geometry and

on how its information have been settled [96]. The LOD is a reference for the specification and combination of the content and reliability of BIM models. However, LOD specifications do not apply to models but rather to objects in the models.

While the project develops, the available information on materials and elements to integrate is better defined, and the LOD of objects becomes higher [97].

The BIM Forum recognises five LOD (LOD 100, LOD 200, LOD 300, LOD 350, LOD 400), with growing levels of information [96]. LOD100 elements present the lowest level of information, and LOD 500 has the highest specificity and more detailed information. As mentioned in the Introduction, LOD 300 is the minimum required to perform an LCA. However, considering that the use of this LCA assessment based on BIM models may become a decision support process, it is essential to have in mind that in later stages of the project, possible changes may be more expensive. Thus, several authors [15, 23, 39] have studied the application of BIM-based LCA at the early stages of the project design for lower LODS.

This specification suggests that the incorporation of environmental information in BIM models should be as detailed as the LOD of the model: it could provide approximate and generic environmental information for lower LOD and more specific and reliable information for higher LOD.

4.2. LCA Information for Each Specific LOD

LCA application within the building sector, as a strategy to reduce environmental impacts, is commonly identified as complex and time-consuming. In parallel, most of the impact assessment methods result in a set of environmental categories that are not readily understandable or interpretable [11]. This problem is also shown in the list of parameters and environmental information specified in the draft UNI 11337 - Part 3 [60] (see Section 3 Integration of LCA and BIM). Taking this into account, to use the environmental information efficiently in BIM models, designers and materials specifiers need specific training [10].

Soust-Verdaguer *et al.* (2017) [11] concluded that the integration of LCA information in BIM models is suitable for models that have already specified most of the materials and components, including wall thickness (and component layers), and defined structural elements in their actual engineered sizes, shapes, and locations, which is the case of LOD 300 or higher.

Therefore, it is essential to simplify LCA results at the early stages of the project development, allowing important support in decision-making processes at these stages. That simplification may be done by considering:

- [1] Growing specificity on used LCA information (generic databases vs. specific information);
- [2] Growing number of parameters and environmental information presented;
- [3] Decreasing aggregation of environmental information (*e.g.* weighted single scores for lower LOD and complete disaggregated information for higher ones).

As mentioned in Section 2, LCA calculations may be developed based on LCI data from generic databases, site or

company-specific LCI, or in average LCI (country average, sector average, or company average for several sites). It would be natural that, in lower LOD, the environmental information available would be from generic databases, either at the material level or even at the building elements level, as average current walls, average current roofs, *e.g.* However, this approach simplifies only the LCI data collection process and not the interpretation of LCA results for use in decision-making processes by AEC professionals.

A common approach to simplify the interpretation of results is to consider only one or some of the environmental parameters as representative of all environmental impacts. CO₂ and embodied energy, for instance, are commonly used as the first approach for environmental impacts assessment and communication (as in the case of Arquimedes software tool, Section 3). Although this option raises the question about one or a limited set of parameters being representative of all others in an environmental impact assessment process, for several reasons, there is public awareness about Global Warming Potential (GWP - expressed in equivalent CO₂ emissions), and individuals from outside the scientific community are familiar with its associated language. Moreover, the Carbon Footprint, which is a measure of the total amount of greenhouse gas emissions generated over the life cycle of a product [98], represents currently around 60% of the overall human Ecological Footprint and it is the greatest rapidly growing component. Thus, the use of GWP as a representative impact category may be an added value to raise the awareness of professionals not familiarised with the LCA practice. Using only one or a limited set of environmental parameters could be a recommended approach for lower LOD BIM objects or elements. The number of parameters included would grow with the evolution of objects' LOD.

An alternative for simplification, besides the element level aggregation proposed by Röck *et al.* (2018) [26], is to use endpoint indicators (focused on environmental burdens or final consequences, *e.g.* biodiversity reduction or respiratory diseases) instead of midpoint indicators (related to the environmental intervention, *e.g.* eutrophication, acidification, greenhouse effect). This method, which may be used to obtain a single indicator (easier to understand and to use in comparisons), implies higher uncertainty and lower reliability since it is based on complex characterisation models. The uncertainty of this method also derives from the needed weighting process that allows the normalisation and aggregation of different impact categories (with different units), using numerical factors based on value judgments and value-choices (subjective process). Within this approach, lower LOD objects or elements would include environmental information based on a single indicator or endpoint indicator. Considering the uncertainty and lack of reliability of this approach, it is concluded that the previously mentioned use of CO₂ and embodied energy representative information is generally a better (more reliable) solution than using endpoint indicators. However, the lower LODs objects may contain more subjective but easier to understand the information in the form of single indicators, to support the earlier stages of project decision-making.

Table 2. Detailed environmental LCA impacts, as included in EPDs (EN 15804+A1:2013+A2:2019).

Group of parameters	Environmental parameter declared
Parameters describing environmental impacts	Global warming potential, GWP / Climate change; Depletion potential of the stratospheric ozone layer, ODP; Ecotoxicity for aquatic freshwater Human toxicity - cancer effects Particulate matter / respiratory inorganics Ionising radiation - human health effects Acidification potential, AP; Eutrophication - terrestrial; Eutrophication - aquatic; Formation potential of tropospheric ozone, POC; Resource depletion - fossil / Resource use, Energy carriers; Resource depletion - non-fossil / Resource use, minerals and metals; Land use.
Parameters describing resource use	Use of renewable primary energy excluding renewable primary energy resources used as raw materials; Use of renewable primary energy resources used as raw materials; Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials); Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials; Use of non-renewable primary energy resources used as raw materials; Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials); Use of secondary material; Use of renewable secondary fuel; Use of non-renewable secondary fuel; Water use; Pre-consumer recycled content (ISO 14021); Post-consumer recycled content (ISO 14021); Renewable raw materials.
Environmental information describing output flows	Components for re-use; Materials for recycling; Materials for energy recovery; Exported energy.
Environmental information describing waste categories	Hazardous waste; Non-hazardous waste; Radioactive waste.
Parameters describing pollutants emission from materials	VOC content. VOC concentrations in indoor air; Radioactivity index.

Table 3. Proposed solution for environmental information parametrisation on BIM objects.

Object LOD	LOD100	LOD 200- LOD 300	LOD 400- LOD 500
LCA information on BIM object	Single indicator such as Eco-indicator (unit: Eco-indicator point) or Eco-costs (unit: monetary unit, e.g. EUR)	CO ₂ (or global warming potential, GWP, in CO _{2eq}), and embodied energy (in MJ)	Parameters describing environmental impacts; resource use and pollutants emission from materials and Environmental information describing output flows and waste categories, as defined by EPDs contents - see Table 2
Type of data	Generic databases	Generic databases	Product-specific/sector-specific (sectorial EPDs)

With this approach, higher LOD objects would include more midpoint indicators, for instance, based on the results published in EPDs, as proposed in the Draft standard - Building and Civil Engineering Works - Models for Collecting, Organizing and Archiving Product Technical Information [60]. The environmental information from the EPDs can only be included in LOD 400 and LOD 500 objects since only these levels include information on chosen materials brands [28]. According to this, LOD 400 BIM could contain detailed and complete information on environmental impacts, as listed in Table 2.

On the other hand, lower LOD objects would include less detailed and less specific information on environmental aspects (Table 3).

Moreover, further analysis is required in the incorporation of LCA data within BIM models. It was observed that the existing literature on the integration of BIM with LCA focused mostly at the element level, which indicates that only simplified LCA studies (*i.e.*, cradle-to-gate approach) can be performed within a BIM-based environment. It is not realistic to assume that complete elements are going to be replaced at the same moment in time (*e.g.* the service life of the finishing

materials is not the same as the structural elements). Therefore, if no information for the use stage is incorporated at the material and / or project level (e.g. energy consumption), the benefits of LCA studies within a BIM-based environment will still be very limited. In this sense, further work must be done in the identification of the required information that should also be added at the material and project level and how open schemas (e.g. IFC) should be adapted to allow sustainable-related data exchange.

Based on this analysis, the following approaches are recommended:

- Final LCA results are directly used for integration in BIM objects, elements or materials, and models, and not as LCI databases information;
- Environmental information included in each object depends on the LCA purpose at each design stage; the definition of the information needs at each of those stages is supported by the objects' LODs.

According to the proposed approach, the holistic impacts of the project may be directly calculated in the BIM model as the sum of the environmental impacts per unit of product [61 - 99] and are automatically updated with the creation of different modelling scenarios. AEC professionals using this approach in BIM modelling will be provided with environmental information to support decision-making, based on the respective LCA data of the objects used in the model. This information will be as complete and detailed as the stage of modelling they will be working on, *i.e.*, according to the LOD of the BIM objects and elements they are using.

CONCLUSION

Considering the environmental relevance of the construction sector, there is a growing need to provide AEC professionals with tools that support the improvement of its sustainability. As discussed throughout the article, BIM and LCA are important and complementary methodologies with great potential. However, LCA is a data-intensive, time demanding and complex method that is not normally used by these professionals.

In this work, it was possible to identify several existing sources of LCI information that may be used in the environmental assessment of the construction sector (national and international databases and specific information from producers), as well as some solutions for the integration of LCA and BIM methods (namely four software tools with distinct characteristics and associated databases). Some limitations were found in all studied solutions, namely related to the need to extract information on material bills and then assign it to generic databases of environmental information. The fact that environmental information is not automatically associated with the objects requires the step of assignment of environmental information to the project materials and increases uncertainty of the real environmental impacts of the project. It also forces the repetition of the process each time the BIM model is changed.

Considering the different LODs and the complexity of

impact assessment results interpretation, it is possible to observe that LCA results must be simplified so that AEC professionals can understand and use them in their regular practice. Specifically, when BIM tools are used for the LCA analysis, it is advisable to use LCA data according to the LOD of the project. In this sense, generic information should be used if professionals are working with a lower LOD project (*i.e.*, below LOD 300). For higher LODs, it is more suitable to use more specific, complete and reliable information (e.g. based on EPDs).

Future developments should include:

- The development of libraries of BIM objects including environmental information, namely through the stimulation of the development of such objects by the manufacturers;
- Information at the material level and/or at the project level, including the environmental performance of the materials (cradle-to-gate), energy performance at the building level (operational energy consumption of the building), expected service life (or number of substitutions in the building life cycle), end-of-life alternatives and impacts *etc.*;
- Revision of BIM object standards according to the developments in the construction sector that are increasingly taking environmental information into account in its decision processes, namely considering the standards related to EPD;
- Development of complete automated tools for the integration of LCA information in BIM models to support informed decision-making of designers and other actors.

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

Fundação para a Ciência e Tecnologia (FCT) supported this work [grant number PD/BD/127850/2016] under the Doctoral Program EcoCoRe - Eco-Construction and Rehabilitation. Support from CERIS and Instituto Superior Técnico is also acknowledged.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Support from CERIS and Instituto Superior Técnico is acknowledged.

REFERENCES

- [1] EC, *Internal Market, Industry, Entrepreneurship and SMEs - Sectors: Construction*. https://ec.europa.eu/growth/sectors/construction_en
- [2] EC, *Communication from the comm to the european parliament and the council: Strategy for the sustainable competitiveness of the construction sector and its enterprises.*, European Commission, 2012.
- [3] EC, *Communication from the commission to the european parliament, the council, the european economic and social committee and the*

- committee of the regions: Resource efficiency opportunities in the building sector., European Commission, 2014.
- [4] EC, *Commission recommendation of 9 april 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.*, Official Journal of the European Union, pp. 1-210, 2013.
- [5] ISO, "Environmental management — Life cycle assessment — Principles and framework", *ISO 14040:2006*, vol. 14040, International Organization for Standardization: Geneva, 2006. <https://www.iso.org/standard/37456.html>
- [6] R. Santos, Costa A.A., and A. Grilo, "Bibliometric analysis and review of building information modelling literature published between 2005 and 2015", *Autom. Construct.*, vol. 80, pp. 118-136, 2017. <http://dx.doi.org/10.1016/j.autcon.2017.03.005>
- [7] NBIMS-US V3 Technical; Terminology; Implementation; Development Subcommittees, S. P., *National BIM Standard - United States® Version 3 - 3 Terms and Definitions; United States of America*, 2015.
- [8] R. Miettinen, and S. Paavola, "Beyond the bim utopia: Approaches to the development and implementation of building information modeling", *Autom. Constr.*, 2014.
- [9] F. Jalaei, and A. Jade, *Integrating Building Information Modeling (bim) and leed system at the conceptual design stage of sustainable buildings.*, Sustain. Cities Soc., 2015. <http://dx.doi.org/10.1016/j.scs.2015.06.007>
- [10] L.Á. Antón, and J.J. Díaz, "Integration of life cycle assessment in a BIM environment", *Procedia Eng.*, vol. 85, pp. 26-32, 2014. <http://dx.doi.org/10.1016/j.proeng.2014.10.525>
- [11] B. Soust-Verdaguer, C. Llatas, and A. García-Martínez, "Critical review of bim-based lca method to buildings", *Energy Build.*, vol. 136, pp. 110-120, 2017. <http://dx.doi.org/10.1016/j.enbuild.2016.12.009>
- [12] R. Santos, E. Neves, J.D. Silvestre, and A.A. Costa, Integration of bim with life cycle assessment: Analysis of the state of the art and available tools. *CINCOs 2016 - Congress of Innovation on Sustainable Construction.*, Centro Habitat - Sustainable Habitat Cluster: Lisbon, 2016.
- [13] R. Santos, A.A. Costa, J.D. Silvestre, and L. Pyl, "Integration of lca and lcc analysis with-in a bim-based environment: A systematic approach. automation in construction", *Autom. Construct.*, 2019. [February]. <http://dx.doi.org/10.1016/j.autcon.2019.02.011>
- [14] R. Santos, A.A. Costa, J.D. Silvestre, and L. Pyl, "Informetric analysis and review of litera-Ture on the role of BIM in sustainable construction", *Autom. Construct.*, 2019. [February]. <http://dx.doi.org/10.1016/j.autcon.2019.02.022>
- [15] J. Basbagill, F. Flager, M. Lepech, and M. Fischer, "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts", *Build. Environ.*, vol. 60, pp. 81-92, 2013. <http://dx.doi.org/10.1016/j.buildenv.2012.11.009>
- [16] F. Jalaei, and A. Jade, "An automated BIM model to conceptually design, analyze, simulate, and assess sustainable building projects", *J. Constr. Eng.*, 2014.
- [17] S.A. Sharif, and A. Hammad, "Simulation-based multi-objective optimization of institutional building renovation considering energy consumption, life-cycle cost and life-cycle assessment", *J. Build. Eng.*, vol. 21, pp. 429-445, 2019. <http://dx.doi.org/10.1016/j.jobe.2018.11.006>
- [18] E. Wang, Z. Shen, C. Barryman, and C. Berryman, *A building lca case study using autodesk ecotect and bim model papers presented on research topics a building lca case study using autodesk ecotect and bim model*, 2011.
- [19] A.H. Oti, and W. Tizani, "BIM extension for the sustainability appraisal of conceptual steel design", *Adv. Eng. Inform.*, vol. 29, no. 1, pp. 28-46, 2015. <http://dx.doi.org/10.1016/j.aei.2014.09.001>
- [20] D. Kehily, and J. Underwood, "Embedding life cycle costing in 5D BIM", *J. Inf. Technol. Constr.*, vol. 22, pp. 145-167, 2017.
- [21] Y-S.Y.S. Shin, and K. Cho, "BIM application to select appropriate design alternative with consideration of LCA and LCCA", *Math. Probl. Eng.*, vol. 2015, 2015. <http://dx.doi.org/10.1155/2015/281640>
- [22] H. Kreiner, A. Passer, and H. Wallbaum, "A new systemic approach to improve the sustainability performance of office buildings in the early design stage", *Energy Build.*, vol. 109, pp. 385-396, 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.09.040>
- [23] M. Nilsen, and R.A.A. Bohne, "Evaluation of bim based lca in early design phase (low lod) of buildings", *IOP Conference Series: Earth and Environmental Science*, vol. 323, , 2019p. 012119 <http://dx.doi.org/10.1088/1755-1315/323/1/012119>
- [24] C. Cavalliere, G. Habert, G.R.G.R. Dell'Osso, and A. Hollberg, "Continuous bim-based assessment of embodied environmental impacts throughout the design process", *J. Clean. Prod.*, vol. 211, pp. 941-952, 2019. <http://dx.doi.org/10.1016/j.jclepro.2018.11.247>
- [25] S. Lee, S. Tae, S. Roh, and T. Kim, "Green template for life cycle assessment of buildings based on building information modeling: Focus on embodied environmental impact", *Sustain.*, vol. 7, no. 12, pp. 16498-16512, 2015. <http://dx.doi.org/10.3390/su71215830>
- [26] M. Röck, A. Hollberg, G. Habert, and A. Passer, "LCA and BIM: Visualization of environmental potentials in building construction at early design stages", *Build. Environ.*, vol. 140, pp. 153-161, 2018. <http://dx.doi.org/10.1016/j.buildenv.2018.05.006>
- [27] M. Dupuis, A. April, P. Lesage, and D. Forgues, "Method to enable lca analysis through each level of development of a bim model", *Procedia Eng.*, vol. 196, pp. 857-863, 2017. <http://dx.doi.org/10.1016/j.proeng.2017.08.017>
- [28] R. Santos, and A.A. Costa, Information integration and interoperability for BIM-Based life-cycle assessment. *Integrating Information in Built Environments.*, Routledge: London, 2018, p. 18.
- [29] G. Halevi, H. Moed, and J. Bar-Ilan, "Suitability of google scholar as a source of scientific information and as a source of data for scientific evaluation—review of the literature", *J. Informetrics*, vol. 11, no. 3, pp. 823-834, 2017. <http://dx.doi.org/10.1016/j.joi.2017.06.005>
- [30] A. Jade, and F. Jalaei, "Integrating building information modelling with sustainability to design building projects at the conceptual stage", *Build. Simul.*, vol. 6, no. 4, pp. 429-444, 2013. <http://dx.doi.org/10.1007/s12273-013-0120-0>
- [31] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, and J.C.J.C. Gómez De Cózar, "BIM-Based LCA method to analyze envelope alternatives of single-family houses: Case study in uruguay", *J. Archit. Eng.*, vol. 24, no. 3, 2018. [http://dx.doi.org/10.1061/\(ASCE\)AE.1943-5568.0000303](http://dx.doi.org/10.1061/(ASCE)AE.1943-5568.0000303)
- [32] S. Eleftheriadis, D. Mumovic, and P. Greening, "Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities", *Renew. Sustain. Energy Rev.*, vol. 67, pp. 811-825, 2017. <http://dx.doi.org/10.1016/j.rser.2016.09.028>
- [33] H.Y. Chong, C.Y. Lee, and X. Wang, "A mixed review of the adoption of Building Information Modelling (BIM) for sustainability", *J. Clean. Prod.*, 2017. <http://dx.doi.org/10.1016/j.jclepro.2016.09.222>
- [34] C. Bueno, and M.M. Fabricio, "Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in", *Autom. Construct.*, vol. 90, pp. 188-200, 2018. <http://dx.doi.org/10.1016/j.autcon.2018.02.028>
- [35] C. Llatas, R. Angulo Fornos, N. Bizcocho, I. Cortés Albalá, R. Falcón Ganfornina, I. Galeana, A. García-Martínez, J.C. Gómez de Cózar, S. López Alonso, P. Meda, J.M. Mercado Martínez, M.V. Montes, R. Periañez Cristobal, R. Quiñones, T. Rojo, C. Rubio Bellido, and M. Ruiz Alfonso, "Soust-Verdague, B. Towards a life cycle sustainability assessment method for the quantification and reduction of impacts of buildings life cycle", *IOP Conf. Ser. Earth Environ. Sci.*, 2019
- [36] F.H. Abanda, A.H. Oti, and J.H.M. Tah, "Integrating BIM and new rules of measurement for embodied energy and CO2 assessment", *J. Build. Eng.*, vol. 12, pp. 288-305, 2017. <http://dx.doi.org/10.1016/j.jobe.2017.06.017>
- [37] S.O. Ajayi, L.O. Oyedele, B. Ceranic, M. Gallanagh, and K.O. Kadiri, "Life cycle environmental performance of material specification: A BIM-enhanced comparative assessment", *Int. J. Sustain. Build. Technol. Urban Dev.*, vol. 6, no. 1, pp. 14-24, 2015. <http://dx.doi.org/10.1080/2093761X.2015.1006708>
- [38] M.K. Ansah, X. Chen, H. Yang, L. Lu, and P.T.I. Lam, "An integrated life cycle assessment of different façade systems for a typical residential building in ghana", *Sustain. Cities Soc.*, vol. 53, 2020. <http://dx.doi.org/10.1016/j.scs.2019.101974>
- [39] C. Bueno, L.M. Pereira, and M.M. Fabricio, "Life cycle assessment and environmental-based choices at the early design stages: An application using building information modelling", *Archit. Eng. Des. Manag.*, vol. 14, no. 5, pp. 332-346, 2018. <http://dx.doi.org/10.1080/17452007.2018.1458593>

- [40] S. Eleftheriadis, P. Duffour, and D. Mumovic, "BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives", *Energy Build.*, vol. 173, pp. 587-600, 2018. [http://dx.doi.org/10.1016/j.enbuild.2018.05.042]
- [41] S.S.S. Gardezi, and N. Shafiq, "Operational carbon footprint prediction model for conventional tropical housing: A Malaysian prospective", *Int. J. Environ. Sci. Technol.*, vol. 16, no. 12, pp. 7817-7826, 2019. [http://dx.doi.org/10.1007/s13762-019-02371-x]
- [42] L. Georges, M. Haase, A. Houlihan Wiberg, T. Kristjansdottir, and B. Risholt, "Life cycle emissions analysis of two NZEB concepts", *Build. Res. Inform.*, vol. 43, no. 1, pp. 82-93, 2015. [http://dx.doi.org/10.1080/09613218.2015.955755]
- [43] V. Hasik, E. Escott, R. Bates, S. Carlisle, B. Faircloth, and M.M. Bilec, "Comparative whole-building life cycle assessment of renovation and new construction", *Build. Environ.*, vol. 161, 2019.106218 [http://dx.doi.org/10.1016/j.buildenv.2019.106218]
- [44] A. Hollberg, G. Genova, and G. Habert, "Evaluation of BIM-Based LCA results for building design", *Autom. Construct.*, vol. 109, 2020.102972 [http://dx.doi.org/10.1016/j.autcon.2019.102972]
- [45] A. Hollberg, I. Agustí-Juan, T. Lichtenheld, and N. Klüber, "Design-integrated environmental performance feedback based on early-BIM", A. Houlihan Wiberg, L. Georges, T.H. Dokka, M. Haase, B. Time, A.G. Lien, S. Mellegård, and M. Maltha, "A net zero emission concept analysis of a single-family house", *Energy Build.*, vol. 74, pp. 101-110, 2014. [http://dx.doi.org/10.1016/j.enbuild.2014.01.037]
- [47] C.R. Iddon, and S.K. Firth, "Embodied and operational energy for new-build housing: A case study of construction methods in the UK", *Energy Build.*, vol. 67, pp. 479-488, 2013. [http://dx.doi.org/10.1016/j.enbuild.2013.08.041]
- [48] T. Kulahcioglu, J. Dang, and C. Toklu, "A 3D analyzer for BIM-enabled life cycle assessment of the whole process of construction", *HVAC & R Res.*, vol. 18, no. 1-2, pp. 283-293, 2012. [http://dx.doi.org/10.1080/10789669.2012.634264]
- [49] M. Marzouk, E.M. Abdelkader, and K. Al-Gahtani, "Building information modeling-based model for calculating direct and indirect emissions in construction projects", *J. Clean. Prod.*, vol. 152, pp. 351-363, 2017. [http://dx.doi.org/10.1016/j.jclepro.2017.03.138]
- [50] M. Najjar, K. Figueiredo, M. Palumbo, and 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.*, vol. 14, pp. 115-126, 2017. [http://dx.doi.org/10.1016/j.jobbe.2017.10.005]
- [51] R.S.R.S. Nizam, C. Zhang, and L.L. Tian, "A BIM based tool for assessing embodied energy for buildings", *Energy Build.*, vol. 170, pp. 1-14, 2018. [http://dx.doi.org/10.1016/j.enbuild.2018.03.067]
- [52] C. Peng, "Calculation of a building's life cycle carbon emissions based on ecotect and building information modeling", *J. Clean. Prod.*, vol. 112, pp. 453-465, 2016. [http://dx.doi.org/10.1016/j.jclepro.2015.08.078]
- [53] F. Rezaei, C. Bulle, and P. Lesage, "Integrating building information modeling and life cycle assessment in the early and detailed building design stages", *Build. Environ.*, vol. 153, pp. 158-167, 2019. [http://dx.doi.org/10.1016/j.buildenv.2019.01.034]
- [54] R. Santos, A.A. Costa, J.D. Silvestre, T. Vandenbergh, and L. Pyl, "BIM-Based life cycle assessment and life cycle costing of an office building in western Europe", *Build. Environ.*, vol. 169, 2020. [http://dx.doi.org/10.1016/j.buildenv.2019.106568]
- [55] F. Shadram, T.D.T.D. Johansson, W. Lu, J. Schade, and T. Olofsson, "An integrated BIM-based framework for minimizing embodied energy during building design", *Energy Build.*, vol. 128, pp. 592-604, 2016. [http://dx.doi.org/10.1016/j.enbuild.2016.07.007]
- [56] F. Shadram, and J. Mikkavaara, "An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy", *Energy Build.*, vol. 158, pp. 1189-1205, 2018. [http://dx.doi.org/10.1016/j.enbuild.2017.11.017]
- [57] N. Shafiq, M.F. Nurrudin, S.S.S. Gardezi, and A.B. Kamaruzzaman, "Carbon footprint assessment of a typical low rise office building in Malaysia using Building Information Modelling (BIM)", *Int. J. Sustain. Build. Technol. Urban Dev.*, vol. 6, no. 3, pp. 157-172, 2015. [http://dx.doi.org/10.1080/2093761X.2015.1057876]
- [58] X. Yang, M. Hu, J. Wu, and B. Zhao, "Building-information-modeling enabled life cycle assessment, A case study on carbon footprint accounting for a residential building in China", *J. Clean. Prod.*, vol. 183, pp. 729-743, 2018. [http://dx.doi.org/10.1016/j.jclepro.2018.02.070]
- [59] C. Peng, and X. Wu, "Case study of carbon emissions from a building's life cycle based on BIM and ecotect", *Adv. Mater. Sci. Eng.*, vol. 2015, 2015. [http://dx.doi.org/10.1155/2015/954651]
- [60] UNI/CT 033/GL 05, "Draft - Building and civil engineering works - Models for collecting, Organizing and archiving product technical information", *Italian Standardisation Institute, Technical Commission 033, GL 05 Codification criteria for construction products and process*, pp. 1-29, 2016.
- [61] CEN/TC 350., "Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products", In: *EN 15804:2012+A1:2013+A2*, Comité Européen de Normalisation: Brussels, 2019.
- [62] *Building the Bridge (Use of EPD in BIM)*, Standard Norge, 2016.
- [63] *ISO/TC 59/SC 13. Organization and digitization of information about buildings and civil engineering works, Including building information modelling (BIM)-Information management using building information modelling-part 1: Concepts and principles.*, International Organization for Standardization: Geneva, 2018, pp. 1-44.
- [64] KT Innovations; Thinkstep; Autodesk.,
- [65] B.R.E. Group, *IMPACT - Integrated Material Profile and Costing Tool*, BRE Global Ltd.: Watford, 2018.
- [66] CSTB ÉDITIONS, EveBIM-ÉLODIE. CSTB ÉDITIONS: Marne la Vallée
- [67] CYPE Ingenieros, S. A.; Top-Informática, L. Arquimedes., *CYPE Ingenieros, S.A: ALICANTE*, 2018.
- [68] EC - JRC, *ILCD Handbook: General Guide for Life Cycle Assessment -Detailed Guidance*, 1st ed. Publications Office of the European Union: European Commission: Luxembourg, 2010.
- [69] A. Martínez-Rocamora, J. Solís-Guzmán, and M. Marrero, "LCA databases focused on construction materials: A review", *Renew. Sustain. Energy Rev.*, vol. 58, pp. 565-573, 2016. [http://dx.doi.org/10.1016/j.rser.2015.12.243]
- [70] S. Lasvaux, G. Habert, B. Peuportier, and J. Chevalier, "Comparison of generic and product-specific life cycle assessment databases: Application to construction materials used in building LCA studies", *Int. J. Life Cycle Assess.*, vol. 20, no. 11, pp. 1473-1490, 2015. [http://dx.doi.org/10.1007/s11367-015-0938-z]
- [71] A. Kerkhof, W. Terlouw, M. Vieira, C. Alexandre, and R. Bagard, "Evaluation report: Technical evaluation of the EU EF pilot phase", *European Commission*, 2017.
- [72] J.D. Silvestre, S. Lasvaux, J. Hodková, J. de Brito, and M.D. Pinheiro, "NativeLCA - A systematic approach for the selection of environmental datasets as generic data: application to construction products in a national context", *Int. J. Life Cycle Assess.*, vol. 20, no. 6, pp. 731-750, 2015. [http://dx.doi.org/10.1007/s11367-015-0885-8]
- [73] C. Wernet Gregorand Bauer, *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218-1230, 2016. [http://dx.doi.org/10.1007/s11367-016-1087-8]
- [74] T. Kupfer, Baitz Martin Colodel C. M. Kokborg M. Schöll S. Rudolf M. Thellier L. Gonzalez M. Schuller O. Hengstler J. Stoffregen A. Köhler A. Thylmann D. , *GaBi database.*, Leinfelden-Echterdingen, 2017.
- [75] PlasticsEurope, <http://www.plasticseurope.org/plastics-sustainability-14017/eco-profile.aspx>
- [76] Sustainable materials institute, *Athena Database Details.*, Ontario, Canada, 2013.
- [77] *Morrison Hershfield. Impact Estimator for Buildings.*, Athena Sustainable Materials Institute: Ottawa, Ontario, 2017.
- [78] NREL, *US Life Cycle Inventory Database*.<https://www.nrel.gov/lci/>
- [79] InData Working Group GbR, [https://www.indata.network/accessed Feb 6, 2020](https://www.indata.network/accessed/Feb%206,%2020)
- [80] WG InData, *InData Compliance-Core Rules and Requirements International Open Data Network for Sustainable Building WG InData*, 2018.
- [81] *EU, Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 on TheThe Construction Products Regulation (CPR)*, European Parliament, European Union Council, 2011, pp. 5-43.
- [82] M.I. Almeida, A.C. Dias, M. Demertzi, and L. Arroja, "Environmental Profile of Ceramic Tiles and Their Potential for Improvement", *J.*

- Clean. Prod.*, vol. 131, pp. 583-593, 2016.
[http://dx.doi.org/10.1016/j.jclepro.2016.04.131]
- [83] L. Bragança, and R. Mateus, *Life Cycle Assessment of Buildings: Environmental Impact of Building Assemblies (In Portuguese)*, First edit.; Author edition, Ed 2011.
- [84] R. Mateus, S. Neiva, L. Bragança, P. Mendonça, and M. Macieira, "Sustainability assessment of an innovative lightweight building technology for partition walls – comparison with conventional technologies", *Build. Environ.*, vol. 67, pp. 147-159, 2013.
[http://dx.doi.org/10.1016/j.buildenv.2013.05.012]
- [85] A. Brás, and V. Gomes, "LCA Implementation in the selection of thermal enhanced mortars for energetic rehabilitation of school buildings", *Energy Build.*, vol. 92, pp. 1-9, 2015.
[http://dx.doi.org/10.1016/j.enbuild.2015.01.007]
- [86] R. Garrido, J.D. Silvestre, and I. Flores-Colen, "Economic and energy life cycle assessment of aerogel-based thermal renders", *J. Clean. Prod.*, vol. 151, pp. 537-545, 2017.
[http://dx.doi.org/10.1016/j.jclepro.2017.02.194]
- [87] E.R. Teixeira, R. Mateus, A.F. Camões, L. Bragança, and F.G. Branco, "Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material", *J. Clean. Prod.*, vol. 112, pp. 2221-2230, 2016.
[http://dx.doi.org/10.1016/j.jclepro.2015.09.124]
- [88] DAPHabitat System, http://daphabitat.pt/?page_id=315
- [89] ECO PLATFORM, <https://www.eco-platform.org/eco-epd-40.html>
- [90] *Communication from the commission to the european parliament and the council: Building the single market for green products.*, European Commission, 2013.
- [91] P. Ravel, L. Gross, P. Typpö, E. Meuwissen, P. Vitse, P. Boogman, K. Allacker, N. Adibi, Q. de Hults, G. Castelan, O. Loebel, A. Duviolguerbigny, S. Kotaji, F. Van der Burgh, and E. Van de Moorte, V. Durão, J.D. Silvestre, R. Mateus, and J. de Brito, "Assessment and communication of the environmental performance of construction products in europe: Comparison between PEF and EN 15804 Compliant EPD schemes", *Resour. Conserv. Recycling*, vol. 156, 2020.104703
[http://dx.doi.org/10.1016/j.resconrec.2020.104703]
- [92] Environdec, *Machine-readable EPD*.<https://www.environdec.com/What-is-an-EPD/Different-types-of-EPD/Machine-Readable-EPD> accessed Jan 21, 2020
- [93] J. Anderson, "EPD numbers", *EcoPlatform Board*, vol. 2019, pp. 1-24, 2019.
- [94] S. Welling, T. Billstein, and M. Erlandsson, *Increased availability of machine-readable epds in the ILCD+EPD+ format.*, STOCKHOLM, 2019.
- [95] BIM Forum, "Level of development specification guide", *BIMForum*, 2017.
- [96] *NATSPEC, the A. N. B. S. system.*, NATSPEC BIM Object/Element Matrix. NATSPEC BIM Object/Element Matrix: Australia, 2011.
- [97] D. Caro, Carbon footprint. *Encyclopedia of Ecology.*, Elsevier, 2019, pp. 252-257.
[http://dx.doi.org/10.1016/B978-0-12-409548-9.10752-3]
- [98] CEN/TC 350, "Sustainability of construction works -Assessment of environmental performance of buildings -Calculation method", In: *EN 15978:2011. Comité Européen de Normalisation: Brussels*, 2011.

© 2020 Durão et al.

This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International Public License (CC-BY 4.0), a copy of which is available at: <https://creativecommons.org/licenses/by/4.0/legalcode>. This license permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.