Key Parameters Featuring BIM-LCA Integration in Buildings: A Practical Review of the Current Trends

Tiziano Dalla Mora [1],* , **Erika Bolzonello [1], Carmine Cavalliere [2]** and **Fabio Peron [1]**

[1] Department of Architecture and Arts, University IUAV of Venice, Dorsoduro 2206, 30123 Venezia, Italy;
    bolzonelloerika@gmail.com (E.B.); fperon@iuav.it (F.P.)
[2] Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of
    Bari, Via Edoardo Orabona, 4, 70125 Bari, Italy; carmine.cavalliere@poliba.it
*   Correspondence: tdallamora@iuav.it

check for updates

Abstract: The construction sector is responsible for 40% of carbon emissions, 14% of water consumption and 60% of waste production in the world, generating a state of unsustainability. In order to keep these values under control and make the most sustainable choices starting from the earliest stages of building design, a Life Cycle Assessment (LCA) can be used. This consists of an analysis of the environmental impacts of a product, activity or process throughout all phases of the life cycle. The fundamental problem of implementing this analysis process in the construction sector is the difficulty in managing the fragmented building information that covers all aspects of buildings life stages in an integrated way. The Building Information Modeling (BIM) approach offers the possibility of managing a complex information system in an integrated manner. The BIM-LCA integration solutions proposed in recent years made LCA analysis faster, cheaper and usable by more professionals. This paper proposes an analysis of the state of the art of the research published in the last ten years regarding the integration of BIM-LCA as a methodology whereby the BIM approach can support and simplify data management for LCA analysis. The aim was to present the work methodologies tested so far and to describe all the factors that were considered in applying the BIM-LCA integration. The novelty of this review consists of identifying a series of more recurrent parameters and measures used by most researchers deriving a trend of possible and consolidated workflows. The result is, therefore, to present evidence of a general heterogenous framework and to define the common and widespread approaches identifying the main features.

Keywords: life cycle assessment (LCA); building information modeling (BIM); sustainability; integrated approach

1. Introduction

Increasing awareness in the scientific research community highlights the serious risks of climate change and the need for urgent action toward reducing carbon emissions [1]. It is a common opinion among researchers that emissions of greenhouse gases emitted by buildings should be as low as possible. In the communication "A clean planet for all" [2] adopted on 28th November 2018, the European Union presented a plan to achieve zero emissions. In particular, the emission values of buildings should be reduced by 80–95% compared to 1990, by 2050. For many years, efforts have focused on mitigating the impacts of building operations through the design of energy-efficient building envelopes and systems. However, this has led to an increase in the impacts inherent in the production of materials and their disposal [3,4].

Official statistics indicate that the architecture, engineering and construction (AEC) sector persists as the largest consumer of energy: for example, approximately 10% of global energy is used during the

production phase of building materials, energy consumption in the operational phase of the building produces 30–40% of greenhouse gas (GHG) emissions and construction and demolition waste account for 40% of solid waste in developed countries [5–7].

According to the European Union Directive [8], land is the scarcest resource on Earth, making land development one of the fundamental components in effective sustainable building practice [9]. Over 50% of the world's population live in cities. The environmental damage caused by urban sprawl and building construction is severe and the development of building construction and human facilities are growing at speeds that the Earth cannot compensate for [10]. Buildings affect ecosystems in different ways, and they are increasingly overtaking agricultural lands and wetlands or bodies of water, compromising the existing wildlife. Energy is the building resource that has gained the most attention within the built environment research community. Building materials represent another limited resource within a building's life cycle [11].

A design meeting sustainability requirements is often a challenge for professionals. Designing and constructing new buildings should be an opportunity to reduce the environmental impact, operating costs and energy consumption concerns [12]. Several tools and methodologies have been developed to evaluate the environmental impact of buildings, and there is a growing interest in integrating life cycle assessment (LCA) into building design decision-making [13]. LCA allows a scientific assessment of the life cycle of buildings, based on the impacts generated by the production and the disposal of materials used for construction and in the operational phase of the building itself. This methodology, according to EN 15643: 2012 [14], applied to the construction sector makes it possible to understand, at each design stage, where to intervene to reduce the impact on the environment. However, LCAs for buildings have not been widely applied due to their complexity and time-consuming nature. Several studies have attempted to address this issue with the use of building information modelling (BIM) and parametric tools, which make it possible to face specific issues arising on projects [15].

BIM [16] is seen as an approach that can assist the building community in accomplishing sustainability objectives. The use of BIM in AEC is growing globally. According to the European Directive 2014/24/EU [17], the use of BIM for public buildings is mandatory in the EU as of October 2018. Many studies have underlined the importance of simplifying and improving the application of LCA analysis on buildings, and found that BIM-LCA integration optimised the performance of the LCA [18].

BIM-LCA integration helps to make the design process of a sustainable building more efficient and optimizes the required time to manage the necessary data, enabling the results to be obtained in a short time [19,20]. Traditional design environments typically provide less support for visualizing the feasibility of initial design decisions. Linking BIM to a sustainability-based tool enables detailed environmental compromise analyses to be conducted in the early stages of design [20]. BIM programs have the ability to simultaneously manage both the graphical and non-graphical aspects of the project. These features allow designers to quickly manage the amount of information needed to perform the LCA analysis.

This review aims to analyse the research on the topic of BIM-LCA integration, by presenting the most recent studies. The novelty of this review focuses on identifying the critical key factors of BIM-LCA integration and their connection during the various phases of the building and design process. More specifically, the present review schematizes the adopted workflow of the previous published studies on BIM-LCA integration, using key parameters (explained in depth in the next section). The goal of this paper is to provide a framework of all possible adopted approaches in the scientific community in order to guide designers towards the suitable choices against their own goals and the data available.

1.1. Life Cycle Assessment

LCA analysis is a method for quantifying the environmental impact of processes and products during the whole life cycle. The standards governing its use are ISO 14040 and ISO 14044 [21].

These standards define a four-step procedure, namely: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and results interpretation.

In the first step are defined two fundamental elements: the functional unit and the system boundaries [22,23]. The functional unit is used as a reference unit for quantitative evaluations and the system boundary defines the unitary elements included in the assessment [24]. The second step (LCI) consists of collecting, as well as describing and verifying, all data regarding the inputs, processes, emissions, etc., of the whole life cycle. Third (LCIA), the environmental impacts and used resources are quantified, based on the inventory analysis. Although the ISO standards describe the overall framework of LCA analysis, the exact method for calculating the environmental impacts is not defined. Different methods can be chosen depending on the nature of the research, defined by the environmental mechanisms as described in ISO 14044 [4]. The last step is the Life cycle interpretation, which allows for understanding of the meaningfulness of the results, drawing conclusions, explaining the limitations of the results obtained and providing recommendations to decision-makers.

The life cycle assessment of buildings has been a widely researched area over the past decade due to the high environmental impact of this sector. LCA for buildings can be conducted at different levels of design, from individual materials and assembly to the whole building. Standard EN 15978:2011 [25] is a methodological guide for the quantification of the environmental impacts of buildings. It is structured according to the life-cycle modules of buildings, including the product phase, construction process phase, use phase and end of life.

Using LCA analysis in the early stages of the design process, it is possible to direct the designer to make choices aimed at improving the environmental performance of buildings in order to compare, in real time, different technological and geometric solutions. In addition, the use of LCA analysis in the preliminary design phase leads to a reduction in the future costs related to possible design variants. However, the application of LCA analysis in the preliminary design phase is still limited primarily due to the difficulties involved in requesting too specific input data in an embryonic phase of the project.

1.2. BIM Approach

BIM is rapidly advancing as an efficient approach to shared building design and construction [26]. To date, BIM is a consolidated approach to building design, although many steps must be made. BIM represents, but is not limited to [27]:

- Added value, i.e., creating value for the client beyond the minimum deliverables.
- Improved cooperation, i.e., a high level of communication, transparency and collaboration for the best interest of the project as a whole.
- Improved time management, i.e., optimized workflows, fully automated low-level processes and focusing on high value-add services.
- Holistic decision-making across disciplines and design domains.
- The achievement of high design quality through the automated use of interoperable software tools [28].

Information modelling, design and management systems, such as BIM, are vital for the AEC industry. BIM is forecast as the next generation of information technology (IT) to replace drawing production-focused computer aided drafting (CAD) and involves the processes of generating, storing, managing, exchanging and sharing of building information in an interoperable and reusable way [29]. As a digitized representation of the building artefact, BIM has tendencies for continuous expansion to closely mimic the vast amount of information embedded in a typical building project. Such information, referred to as n-dimensional (nD), includes the time, cost, accessibility, sustainability, maintainability, acoustic, crime, thermal requirements, health, safety, etc. [29]. Modelling nD aspects, such as sustainability, requires issue-specific approaches and involves the extension of the building information model to incorporate the various building life cycle designs, which are vast and cut across the various building professional platforms.

BIM is not merely a type of software but a human activity that involves paradigmatic process changes in design, construction and facility management [30]. BIM is oriented to the modelling and to the communication of both graphical and non-graphical information, allowing the extraction of quantities, cost estimations and material properties for buildings, facilities and infrastructures [31]. Interoperability is one of the key aspects related to BIM and relies on ICT issues, business processes and contractual issues among the interacting parties [5]. The sharing of intelligent information contained in the BIM is made possible using open standard models, such as the industry foundation classes (IFC) [32].

Recent studies showed that BIM provides an effective way to investigate the options for the mitigation of emissions with regards to the material processing, delivery and construction methods. A 3D BIM model represents a repository of information and data that could be used to conduct analysis on the model, once extracted. BIM can manage the information flow by simplifying the data input and implementing the environmental information into the digital model. Furthermore, BIM can reduce the time-consuming nature of the LCA for collecting data as it allows for performing quick quantity take-offs [31].

1.3. BIM—LCA Integration

In recent years, the integration between the BIM approach and the LCA methodology has been studied by researchers [33–35]. On one hand, there is the representation of a building information model consisting of parametric objects improved by semantic information of the whole lifecycle of the building to simplify the design, construction and operation processes [30,36]. On other hand, there is a method that evaluates the environmental impact of the building over its lifecycle [24], and whose application in the construction industry has increased considerably in recent years thanks to its inclusion in certification schemes such as BREEAM [37] and LEED [38].

The BIM-LCA integration is a powerful approach for the simplification of the LCA, representing an operation that leads to the solution of the problems due to the difficulty of managing the amount of data required for the LCA analysis [39]. However, one of the detected weaknesses of the integration of BIM-LCA is the data lacking from the BIM software to LCA applications [40].

The concept of a fully integrated approach to the eco-efficiency assessment of commercial buildings concerns on the information of a complete 3D CAD building model, allowing a report of environmental impacts from the combination of design and choice of materials used in construction. The key to assessing a proposed design is a 3D object-oriented CAD model that contains a wealth of building information not commonly utilised to any great extent.

To perform such an environmental impact analysis of a building, each component of the building must be represented in the model. LCA design is fully automated from the 3D CAD drawing of a building to enable the calculation of the environmental impacts resulting from the choice of materials to be reflected in the design assessment. The automated take-off provides the quantities of all building components created from an extensive list of materials, such as concrete, metals, timber, glass, plastics, etc. This design information is combined with a life cycle inventory of construction materials to estimate key internationally recognized environmental indicators, such as Eco-indicator 99 [41].

Seo [41] describes this integration in three steps: input encompasses the building and materials data processing stage; analysis involves the calculation of the required performance indicators; and solution covers the user decision-making process involved in selecting the preferred solution from a range of potential options.

Several studies show the interactions between BIM and sustainability as well as the growing number of applications on BIM-LCA integration are highlighted in recent papers. The literature recognizes the advantages of BIM-LCA integration. The integration of LCA in BIM is a method of improving the sustainability performance of buildings due to the potential of BIM, which provides effective methods to explore options for the mitigation of environmental impacts in regard to the material processing, delivery and construction methods [42,43]. Despite the strengths, several weaknesses

should be highlighted when referring to BIM-led LCA. From the tool perspective, the interoperability between BIM and LCA software requires improvement. When referring to the method, the lack of environmental data and assumptions lead to increased uncertainties when conducting an LCA.

Bueno et al. [39] compared the results of the analyses conducted with two different programs: the first one carried out with GaBi [44], and the second one carried out with the Tally Revit plugin [45,46]. From this analysis, the software plugin Tally presented limitations, mainly regarding the availability of the environmental data, as the number of constructive alternatives available in the plugin databases was quite limited, leading to the need for assumptions on the most similar types of building components.

Despite the research efforts towards equalizing the scope of the studies to provide a fair comparison among the BIM software plugin and the GaBi software, the results were not consistent. The seriousness of the discrepancies in the results is the fact that they were not only absolute, but other relative differences among the environmental profiles for the alternatives compared, i.e., the programs pointed to different directions, leading the user to different—and often misleading—optimal constructive choices. Bueno et al. [39] stated how GaBi and Tally are both LCA target software, but with extremely different purposes, applications and targeted users.

The same difficulty in comparing the results was expressed by Schultz et al. [47]: the Athena IE and Tally programs were compared, and the programs were found to work differently making it difficult to compare the results. Likely, the reason lays in the simplifications and assumptions necessary for the development of a simpler BIM-based tool for application during the design process by any building designer, with no particular expertise in LCA.

Dalla Mora et al. [48] compared two methods of integration for BIM-LCA, through the use of two plugins for Revit: Tally [49] and One Click LCA [50]. The comparison of the results obtained from different software was not easy, due to the assumptions of the tool and, in particular, the adoption of different databases that give different results. Tally and One Click LCA present different building material databases (with consequent mode of selection and different organization of the building structures) and calculations. While One Click LCA considers all materials separately, in Tally, the default procedure gives the possibility to choose how to consider a component. For example, a masonry wall could be treated as a single whole impact, or as sum of different layers; thus, the mortar and the finishing are considered as distinct materials. This is a positive plus for Tally, but also requires more attention into the construction of the building model in both tools.

Other studies developed reviews on the same topics but adopted different approaches and focused on other aspects of the interoperability between the BIM and LCA processes, which is reported as follows. In the last two years, this topic increased in relevance and publications; therefore, this review aims to clarify certain remarks according to the main keywords and consolidated approaches.

For example, Chong et al. [51] provided a mixed review to determine the current state of the art of BIM development for sustainability in a broader sense. The approach investigated different categories (planning, design, construction, operation and maintenance, refurbishment and demolition, the use of products and materials and the energy consumption). The reviews underline the complexity in terms of the software connections with life cycle assessment information and reported certain experiences that considered the LCA method to evaluate and identify the environmental impact of material choice.

A recent study developed by Soust-Verdaguer et al. [52] addressed a critical review on studies regarding BIM-LCA integration. They conducted a methodological analysis and focused on the way that BIM can contribute to simplifying the input data and optimizing the output data during the LCA application in buildings.

One more recent literature review by Obrecht et al. [53] identifies some major issues preventing a widespread application (LCA methodology synchronization, information database conformity, and information exchange automation) and shows that an automated link between LCA and BIM simplifies the assessment of the embodied impacts.

The review by Soares et al. [54] evaluated various research topics on the improvement of the energy and environmental performance of buildings. The review considered various studies and underlined

the increasing relevance and application of the LCA methodology in the built environment context due the provision of valuable insights toward selecting improved construction options. The study noted that significant challenges should be addressed in future research due to the complexity and variability.

Eleftheriadis et al. [55] study combined the LCA theory and the capabilities of BIM to survey the current developments in the energy efficiency of structural systems. The review identified eleven practical applications of BIM LCA and discussed the integration in terms of the adopted software, service life and life cycle stages (embodied, operational and end of life).

A detailed review was provided by Wong et al. [20] that examined the concept of green BIM and environmental sustainability across the various stages of building development in order to manage buildings during their whole life cycle.

Lastly a systematic literature review by Llatas et al. [56] recognises the opportunities to integrate the life cycle sustainability assessment (LCSA) into the building design process and also proposes a methodological approach to implement LCSA in BIM.

1.4. Structure of the Paper

This paper is structured as follows. Section 2 present the general framework of the literature review among the publications that integrate BIM and LCA to calculate the environmental impacts using applications on case studies. A brief description of the parameters of evaluation is listed to show how the papers have been selected and analyzed to understand the current trends on the integration of modeling and assessment. Section 3 presents a critical discussion of each criterion focusing on the methodological aspects and solutions to the issues proposed by the researchers. The review concludes in Section 4, summarizing the main remarks and future developments for the research.

2. Materials and Methods

In this review, the methodological approach aims to respond to the research gap and the objective of schematizing the adopted workflow from the published studies.

Different phases have been recognised. First, a comprehensive literature search was conducted through a scholarly publication search engine. The literature search was based using the following keywords: life cycle assessment (LCA), building information modeling (BIM), sustainability and integration.

In a subsequent phase, the collected papers were filtered considering those presenting a case study and supported by a description of the adopted workflow. Then, the analysis of papers produced a list of the most recurrent key parameters (seven measures, more deeply descripted in the next sections), even if related to different workflows, that represented the main characteristic measures of a workflow that considers LCA analysis in a BIM process.

Last, this paper evaluated the results and collected data to describe the available consolidated approaches, through a discussion of the abovementioned key parameters and the relations between them. This paper took into consideration the recent studies dealing with BIM-LCA integration published in the last 12 years, from 2007 to 2019, giving an overall view of the changes and the developments of the studies and applications.

The analysis considered 50 papers characterized by a case study, published on the main scientific article collection platforms (Science Direct, Scopus, Research Gate, Springer Link and Google Scholar): mainly journal papers (38) were considered and, in a minor part, conference proceedings, particularly those exposed in a conference of the two last years.

The chart in Figure 1 shows the trend of the published studies based on building information modeling to perform lifecycle analysis, and it reveals the growing interest on this topic. This fact is surely related to the publication of the European standard EN 15978:2011 [25] regarding the LCA application to buildings.
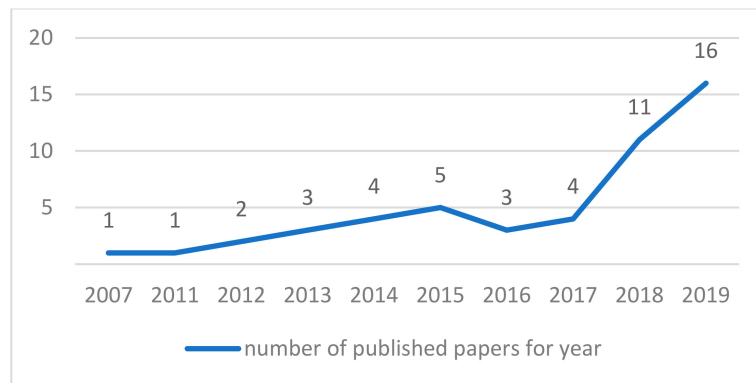
Figure 1. Trend of the published studies regarding building information modeling (BIM)—life cycle assessment (LCA) integration from the 2007 to 2019, revealing how the interest on this topic has grown in recent years.

Analysis Criteria

Using a methodological point of view, more specifically the review schematizes the adopted workflow by published studies, using key parameters in order to offer the scientific community a framework of all possible approaches and the possibility of evaluating which ones may be more useful or widespread in relation to the goals and data availability.

Different parameters were adopted to evaluate the state of the art regarding BIM-LCA integration: the first group of parameters considered the BIM model input, comprising the physical model; the second group referred to the LCA input data, composing the environmental characteristics of a building (Figure 2).
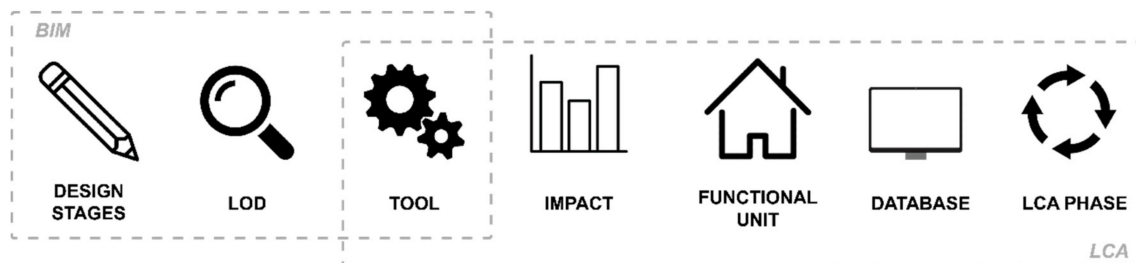

Figure 2. Analysis criteria were adopted considering two groups: BIM model input and LCA input. The dashed line indicates the relevance area of the topics and highlights how the software component is shared in the field of digital modeling and assessments.

The first parameter concerns the design stages of the BIM model that evaluated the LCA application, analysing for relation to an early or a detailed phase of the process. Here, the definitions of the design phase is according to Cavalliere et al. [57]: the early design stage referred to the project planning (PP) and project (P) phases, while the detailed stage referred to the building permit application (BPA) and tendering (T) phases.

The second refers to the definition of the level of development (LOD), which defined the minimum information content for each element of the BIM at the different progressively detailed levels of completeness. According to Soust-Verdaguer [52], LODs are of high importance when conducting a BIM-LCA integration as they indicate the LCA data requirements of the model.

Then, the tools used for building modelling are reported due to the crucial relevance in the case of analysis of different approaches, different exchange information files, and also in the case of design workflows that involve different software. For example, the type and the number of tools represent the complexity of the adopted approach.

The second group considers four criteria regarding the LCA. The first parameter reports the environmental impacts (orthe categories describing the impacts) considered for the LCA analysis.

The functional unit (FU) is taken as a criterion to compare the reviewed papers. The FU is a quantified performance of a system used as defined by standard ISO 14040 and ISO 14044 [21]. In this regard, for each case analyzed, the FU is reported to point out if simplifications are made according to the different approaches [15].

The adopted LCA database has an equal relevance to the BIM tools, because the digital data collection contains the environmental information for the construction materials, and this choice determines the whole LCA analysis and the evaluation of each building component. Last, the LCA stages describe the different lifecycle stages considered in the analysis. Table A1, presented in Appendix A, shows the results of the analysis of selected papers and reports the information according to the declared parameters.

3. Result and Discussion

This paper evaluated the state-of-art of LCA integration in a BIM environment due the potential to include information to assess the decision making [20], including the energy, environmental and costing data among others, in order to improve the project information flow.

In this section, the paper aims to present the general trend of each key parameter, introduced in the previous section, and to determine analytically the interconnections in terms of the approach and development. The analysis of this paper showed how the scientific research grew over recent years, but this analysis could also reveal how the selection of specific and accurate assumptions could affect the development of the study and the adoption of the next parameters, affecting the results and outputs. For example, the adoption of BIM software and LCA tools could influence the research, as well as the constraint of adopting a specific database compatible with the main software. or the development of a study in a defined design phase that must be compared with the level of development of the model and with the request for the calculation of the environmental impacts.

3.1. Design Stages

The analysis of the selected papers showed that the LCA assessment was included in the BIM design: except for a couple of studies, all the case studies defined the boundary conditions of the process, focusing on the early and detailed stages.

Figure 3 shows how the two approaches were analyzed in the reference period; highlighting how the early stage was the subject of in-depth research starting with the first case studies. Only in the last period did the most advanced stage of the process, the detailed stage, become a topic of interest for researchers, indeed becoming the most developed topic. A plausible explanation is that research has acquired more accuracy due to the advancement of knowledge and the definition of BIM standards.

In a more detailed point of view for Figure 3, the authors developing both stages [57–60], especially in the most recent research, aimed to show the design progress, to evaluate how the impacts have changed in a more detailed phase, but, above all, to affirm that the defined choices involved accurate values.

According to Cavalliere et al. [57], two different trends existed for the performance of LCA for buildings based on the digital model. The first trend was concerned with performing detailed LCA with refined processes and specific building simulation tools, as for example Houlihan [58], Abanda [61] and Georges [62]. On the contrary, the second trend involved simplified approaches for the early design stages, as in Ajayi [63], Basbagill [64] and Bueno [65]. LCA analysis from the earliest stages of design makes the LCA a design tool, with the opportunity to modify the project by preferring the most sustainable choices. The challenge is to find a way to use sustainable tools based on BIM even in the early stages of design, when many of the variables for the building systems are not yet available, because they are not set, and to provide quantitative performance forecasts [19,30,66,67]. During the early phases, there is also more potential for studying different alternatives, reducing

costs, implementing changes and improving the performance [66]. This issue was also exposed by Brahme et al. [67], as the problem of providing performance feedback to the designer as early as possible in the design process, while considering the technical sub-systems as well.
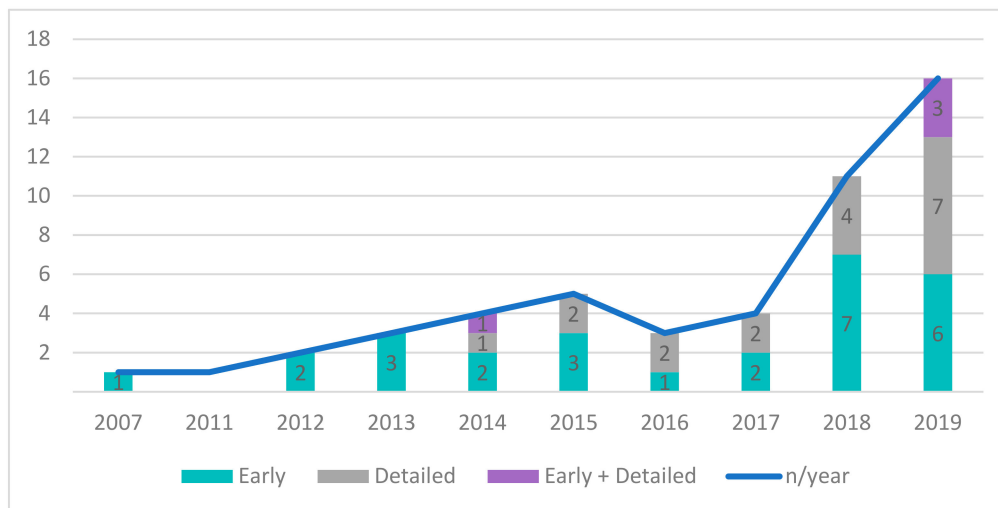

Figure 3. According to the published studies for the years selected for the review, the chart shows how many studies defined the level of design stage in BIM models, showing the recent interest in the detailed stage, in particular to analyze both stages in the same case study.

Integration in order to build environmental assessment processes in the BIM platform was studied by the researchers Ilhan and Yaman [19], who presented a framework to help the provision of documentation for achieving a green building label. The authors stated that the shifting approach to the building design, construction and maintenance requires interdisciplinary collaboration. BIM for integrated sustainable design would simplify the certification process in terms of the time and cost due to early stage interactions.

Oti et al. [29] also declared that integrating sustainability decision modelling into BIM is still at the initial stage. These authors classified the main challenges into two categories: the first was focused on the complexity of the sustainability definition and the difficulty of including it in the initial modelling process stages, and the second described the difficulty related to the techniques for mapping objects, data and rules from holistic sustainability definitions into BIM. The authors proposed a sustainability modelling framework that targeted combining sustainability requirements with systems implementation in order to ensure that both are not conducted separately [29]. Typical aspects of planning, construction, operation and end-of-life of materials involved in the building life cycle were considered, and the approached implementation was limited to the economic and environmental dimensions of sustainability [29]. They proposed a BIM extension that provided support for sustainability-based decision making on structural solutions. This extension comprised a modelling framework and combined three key indicators—namely, the life cycle cost, carbon footprint and ecological footprint measures—to assess the sustainability of buildings.

A novel approach considers the available information in the BIM model to be as accurate as possible in every design phase [57]. This was achieved by mixing LCA databases for building elements and materials with different levels of detail and matching them according to the individual LOD of the various BIM components. The research demonstrated that the use of increasingly refined data reduced the range of variability from the early to detailed phase. The Global Warming Potential (GWP) at one specific phase was always within the variability of the previous phase. This outcome allowed the prediction of the final environmental impact of the construction phase from the early phases of the building process. In the early phases, the impact was overestimated compared to the results,

which showed that the variability decreased from the early design phases to the final ones for most building elements as more refined data were used at higher LODs.

The environmental impact results can be provided during the first decision making process and before the early design stages. A peculiarity of such a framework is the necessity of sustainability expertise and respective tools supporting the project manager and providing construction alternatives and GWP values starting from the early stages [68]. As shown in the case study section, such tools have to handle issues due to data requirements and inaccuracies. The majority of them are caused by missing information about specific energy consumptions as well as refurbishment or renovation measures, which depend on the user's habits and choices and are all considerable sources of uncertainties for LCA analyses.

3.2. Level of Development (LOD)

The origin of the level of development (LOD) is linked with the intent to help the approach and access into the world of BIM through a shared method. The primary task of the LODs, associated with the BIM approach, is to define whether the model, or even just a part of it, is or is not reliable compared to the initial idea, defining, moreover, to what extent and in which areas the information can be used. To do this, also taking note of the vastness of definitions of the project, the American Institute of Architecture (AIA) in document G202-2013 [69] identified five different levels of LOD. LODs describe the minimum dimensional, spatial, quantitative, qualitative and other data included in a model element: LOD 100 (Initial/conceptual idea), LOD 200 (Generic models and quantity indication), LOD 300/350 (Executive Design), LOD 400 (Construction Design), LOD 500 (As Built Project).

Each LOD should include progressively more detailed data in the corresponding BIM model. For example, in the Autodesk Revit BIM software, this information can be obtained from the following entities: object, object type (sometimes referred to the object class) and the building material itself. An object in a BIM model represents a real-life object with its specific properties. All objects included in a BIM model are associated to an object type. The object type regroups all the common rules and parameters of a group of objects, for example: a wall assembly. A useful property of an object type is that it allows the building designer to change it in one location, and this change is reflected in all the linked objects in the corresponding 3D model. Another important information requirement in a BIM model is the building material itself. To accurately describe an assembly in an object type, the designer must specify ever layer of a material and specify the thickness of these layers [70].

The advantages linked to the LOD system are numerous and can reach exponential growth. Among the many advantages offered by LODs, the clarity toward the customer and the members of the working group could be the main interest. This allows the customer to choose which alternative is the most appropriate, while communication within the working group allows avoiding waste of time in the transmission of unnecessary, incorrect or incomplete data. The advantage of clarity is strongly linked to the concepts of precision and speed in determining the costs and project times, as well as the clear definition of the professionals in the field and the relationships that bind them. At the same time, the advantages brought by the LODs could improve the comparison with the Public Administration, thus avoiding misunderstandings and differences in interpretation of the rules relating to the quantity and quality of the works.

Soust-Verdaguer at al. [52] recommend the integration of BIM-LCA models involving a definition of the most relevant materials and components, including the thickness of the walls (including the levels of the components) and the definition of structural elements in their dimensions, shapes and engineered positions. Based on this, they indicated LOD 300 as the most appropriate for verifying environmental impacts during the early stages of design.

Cavalliere et al. [57] proposed a methodology based on the LOD. This study showed that it was possible to continuously assess the embodied environmental impacts in all phases of the building design process using BIM and combining LCA databases with different levels of detail. The suggested approach consisted of structuring the building into functional elements and construction categories

as these are typically modelled at different LODs in the different planning stages. The novelty of the method is the consistent mixing of different LCA databases according to the LOD of the building elements at different design stages. By using different LCA databases that match the LOD of the elements, the embodied impacts can be continuously assessed with the maximum level of detail of the information available at the current design stage.

This review shows how most papers do not approach the topic of LOD, despite having developed an articulated BIM model of the case study. A statement of the detail level or reference to the adoption of design criteria is not affirmed, even if the models were established by inputting the information of various materials and components into the tool to perform an automatic take-off quantity survey to perform the LCA assessment.

Only a small number of studies (13 papers) introduced the concept of LOD and followed precise indications in terms of the definitions: Ajayi [63], Soust-Verdaguer [40], Rezaei [59], Lee [71], Dalla Mora [48], Rock [72], Santos [73], Nilsen and Bohne [74], Lu [75], Lu and Wang [76], Gomes [77] and Sharif and Hammand [78].

The data in Table A1 and Figure 4 allow for a couple of notes: the interest in LOD in the BIM-LCA integration developed mainly in the last year (eight studies in 2019), likely in relation to the fact that, since 2015, BIM has become the object of application in design and legislation in various countries. Researchers [57,59,74], investigated the embodied environmental impacts in relation to various levels of development in order to underline how assumptions could increase or decrease the accuracy in calculations and provide different levels of information for decision-making throughout the entire design process.
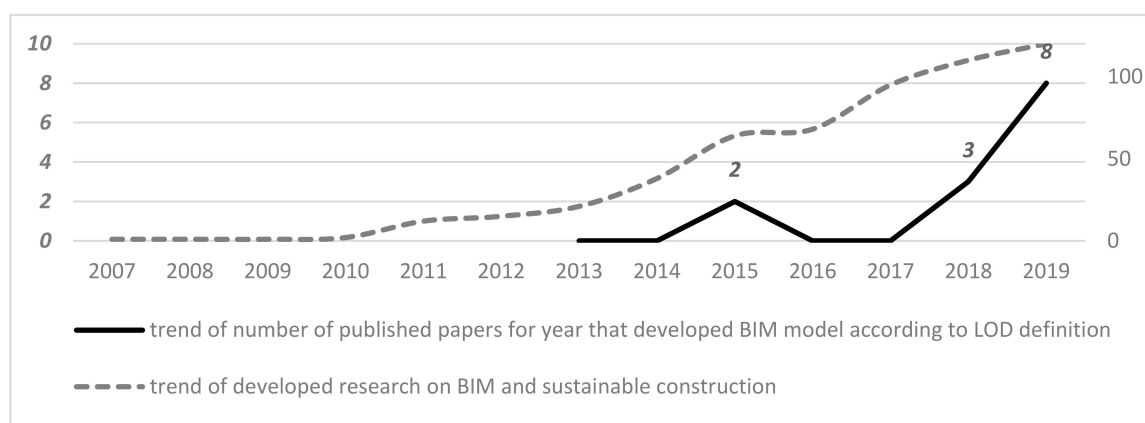

Figure 4. Trend of published studies focusing on LOD in BIM-LCA integration (black continuous line), revealing a growing interest in 2019 in relation to the development of research regarding BIM and sustainable construction (grey dashed line) according to the study of Santos et al. [79].

Rock [72] and Ajayi [63], developed a case study with LOD 200 based on the American Institute of Architect (AIA) standard, stating that the BIM model—produced at Level of Detail 200 for the approximate quantities, size, shape, location and orientation—was required both for energy analysis and quantity estimation.

Lee [71] set LOD 300 as the reference LOD for the evaluation of the embodied environmental impact of a building because the Japanese national normative [80] reported that the embodied environmental impact evaluation of the main building materials (except for steel) could be calculated at this level. In Soust-Verdaguer [40], their case study was developed with LOD 300, selected to obtain general information regarding the main materials and characteristics of the building during the design process.

The research of Dalla Mora et al. [48] focused on the evaluation of different BIM tools and LCA plugins; their case study was modelled with LOD 200 because the aim was to investigate the different LCA database information for each component and structure. The choice of LOD 200 was selected to

evaluate the environmental impacts of three different building structure types (masonry, xlam and steel) during the first step of the design process to support the selection of a structure characterized by minor environmental impacts for the next step of design.

Santos [73] developed a case study according to Level of Development Specification Guide by the BIM Forum [81]. The model was set at LOD 300 because the project aimed to investigate the life cycle costing (LCC) and LCA in a detailed design phase when the brands of materials and relative costs were already fixed. Nilsen and Bohne 2019 [74] evaluated BIM based LCA in early design stages (low LOD) through literature reviews and a case study. This case study executed LCAs at different LOD levels using the LCA software One Click LCA (OCL). Assessments at LOD 200, LOD 300, LOD 350 and an additional LOD 350 were utilized.

Reviews show that LOD 300 was used as the values and parameters for whole building LCA [52,75,77], demonstrating that LOD 300 model is aligned to the accuracy level currently practiced in whole building LCA and that BIM models can indeed be prepared to facilitate LCA through a low complexity, high effectiveness operational measure.

The choice of the LOD is closely related to the design stage set for the case study. Therefore, for an early design phase, the LOD 200 was sufficient to determine a generic quantity of the stratigraphy's and materials to be analyzed, even if the information used to perform the LCA study was the average of the EPD (Environmental Product Declaration) documents available or generic materials in LCA databases. Instead, for a detailed design phase, the LOD should be at least 300 or higher to have a greater definition of the components and an already detailed choice at the executive design level. This thesis was confirmed by Santos [73] who stated that a LOD lower than 300 could contain only generic LCA data from the average data of each material, while at LOD 300 or above EPDs can be used as a source since the brands of materials are known in this phase. At LOD 400, the exact quantities of each materials should be known and specific data can be applied [74].

3.3. LCA and BIM Tools

From the analysis, the integration of BIM-LCA can be developed on three levels. The first level integrates the BIM as a tool during the LCI phase for the quantification of materials and the construction of elements, for example in the case quantitative data are exported and then used in dedicated LCA programs. The second level, in addition to using BIM as a tool to quantify and organize building materials and components, integrates environmental information to the BIM software or to the energy assessment model. The third level involves the development of an automated process that combines different data and software.

In the literature review, several approaches and tools for LCA in BIM are available. However, not all issues have been so far solved, and new challenges also arose. From the technical point of view, the creation of such tools as support instruments for decision-making showed problems, such as the missing interoperability between BIM interfaces and environmental databases, the import of BIM information into LCA software and the complexity of many actors in the treatment of a BIM model. The use of the IFC format proved advantageous by facilitating building description and construction industry data exchange through an open file format and neutral platform [68].

In recent years, many software programs were developed to carry out LCA (Figure 5), such as: SimaPro [82], a LCA tool for calculating the carbon footprint of products and components [83,84]; Building for Environmental and Economic Sustainability (BEES) [85]; Tally, a BIM plugin; Athena Impact Estimator [86]; One Click LCA [74]; and Open LCA [87]. Whole-building assessment tools are generally able to compare different design options and are useful during the initial design phases by providing a quick overview of the impacts of building construction [69].
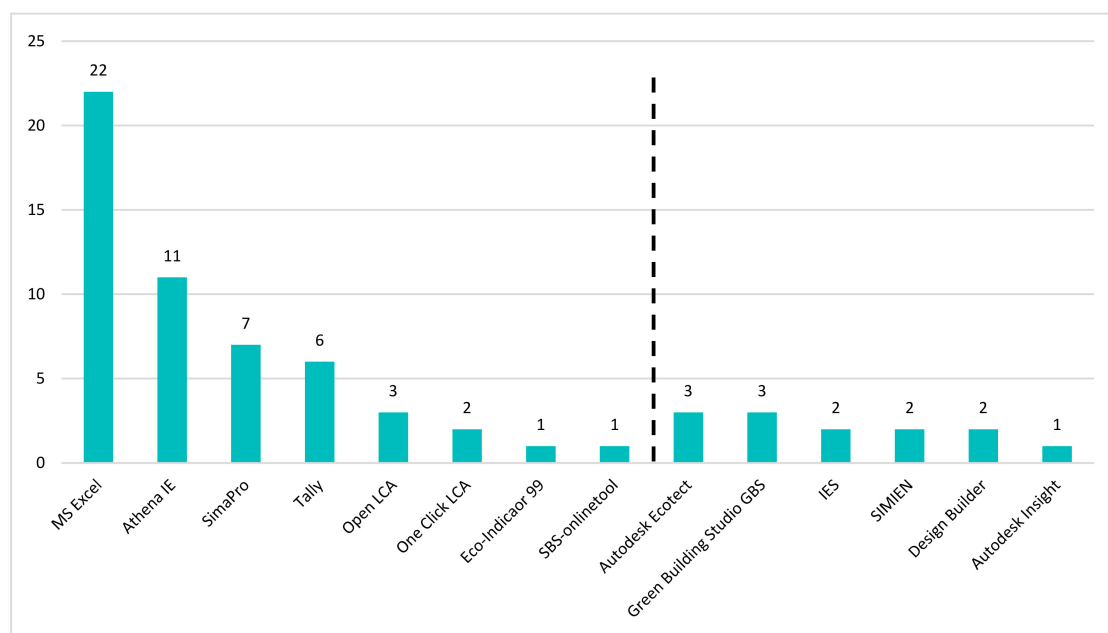
Figure 5. Adopted tools for LCA analysis through the calculation of data exported from a BIM model; a dashed line separates the LCA dedicated software from those that also calculate the building energy performance, often used for embodied energy calculations. The number of tools is over the total amount of considered papers (50) because there is not a strict connection between the number of papers and number of tools. As shown in Table A1, the authors of certain case studies adopted a workflow for exporting data from BIM models involving different tools and different exchange formats.

Researchers performed comparisons of the tools. Schultz et al. [47] tested the methodology of the Athena IE and Tally packages to determine in a BIM-LCA integration process level of interoperability, the take-off methods, the database availability and the flexibility. In a different case study, Santos et al. [24] compared the LCA outputs given by Tally and a general EPD to underline how Tally was likely the best integrated within a BIM environment as it recognized the types (i.e., walls, doors, windows and floors) and the number of layers (i.e., materials) in each element. However, Tally did not recognize the chosen materials in the Revit project and it was difficult to verify the accuracy of the LCA analysis of the projects, mainly due to the lack of different materials, as most materials were generic (taken by the GaBi database), and it was not possible to edit the material information.

The review gives evidence regarding the use of the Athena Impact Estimator for Buildings [88], revealed as the most widespread among the authors and researchers, especially in American countries, and the adoption was mainly coupled with Revit. The choice of Athena is due to a powerful and complicated database prevalently used in North America, which is able to evaluate all building components based on the international LCA methodology and also to edit design scenario supplanting materials.

Among the BIM tools in the analysed papers (Figure 6), Autodesk Revit appeared as the most used (80%) while other studies adopted Graphisoft Archicad, such as Seo et al. [41], Shin et al. [89] and Soust-Verdaguer [40], or DProfiler [90]. The choice of Revit may depend on the diffusion of the Autodesk brand; it is a very developed and highly commercialized BIM software. Moreover, the benefit of easy access of the free license increases the interest in adoption. One further benefit for users is related to the concept of suite for Autodesk; thereby, all software are well integrated and flexible in exchanging data. Last, Revit users are supported by a series of owned plugins and Application Program Interfaces (APIs), a set of routines, protocols, and tools for building software applications, directly connected and integrated to the main software.
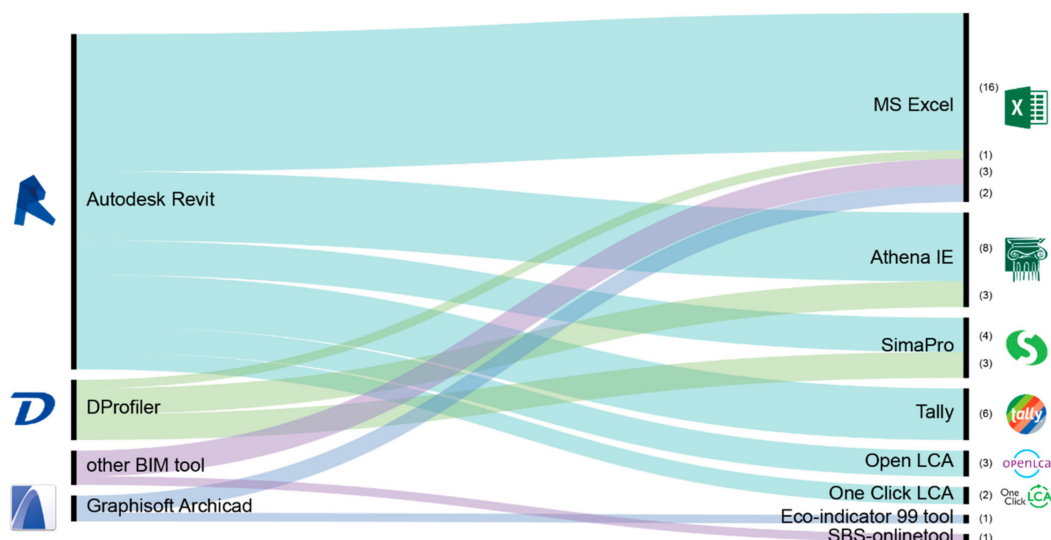
Figure 6. Software adoption in the selected cases studies; the colored flow lines indicate the relationships between tools in data exporting from the BIM model to LCA analysis; on the left side, the chart gives evidence of the widespread adoption of Autodesk Revit (more than 80%) for BIM models; on the right side, the LCA tools are listed, counting in brackets the number of cases linked to each BIM software.

In the considered papers, some referred to LCA tools that were strictly connected to BIM tools, mainly as Tally plugins in Revit. Often, for performing LCA analysis, the users applied external post processing tools, including spreadsheets, such as Microsoft Excel or similar, to export the quantity take-off and then to perform LCA. For example, One Click LCA, in Nilsen [74], is an online LCA application that requires reports, such as a BIM model inventory file in either an MS Excel or gbXML format. The cases studied that used a plugin for specific BIM software (Tally/One Click LCA) had the advantage of immediate results, and the disadvantage of not being as precise as a dedicated software.

From the literature review, regarding the general workflow from the BIM model to LCA assessment, most researchers applied Revit and half of the users exported in Microsoft Excel (22 studies on 50 selected papers). Although this is considered as basic tool, it lends itself well to be fully integrated and easily managed with Revit take-off quantities without any particular use of external plugins, thus, allowing an agile calculation with the values obtained from the LCA databases or to be imported in external LCA tools.

In another case, the authors proposed their own framework. Santos [73] developed an external prototype tool to perform LCA and LCC analysis, which was automatically linked in the exchange of information with the BIM model. With respect to the current state of the art, the novelty of this approach consisted of the use of IFC (Industry Foundation Classes) schema for the integration and exchange of information within a BIM-based environment. The IFC format allowed the user to manually edit or add any information, without resorting to linking to non-editable external databases. However, the adoption of EPD did not require the user to acquire licenses for the LCA databases.

The paper review also showed that the integration was not fully defined due to a lack of alignment, both in terms of the nomenclature and in terms of the detail level, between the BIM material database and LCA tools. There was also a lack of an automatic data extractor from BIM to LCA, meaning a digital format (IFC or gbXML), which included fields and names for encoding BIM classes adaptable to LCA databases.

3.4. Functional Unit

The functional unit (FU) serves as a reference for all flows in and out of the system and for the potential environmental effects [91]. The functional unit is an ISO standard term defined in ISO

14044 [92] as "the quantified performance of a product system for use". Comparing materials based on their weight or volume is the first step to gaining an understanding of the ecological qualities of building materials.

The analysed case studies, as shown in Table A1, used different functional units. In most cases the whole building was taken as a reference. On the other hand, the analysis was sometimes conducted on individual building components, such as the walls [24,31,39,47,65]. This type of analysis was adopted in case studies that aimed to compare various technological solutions from decision makers during the design process and to understand the most suitable one from the environmental point of view.

In other cases, the functional unit for the entire life cycle analysis process was assumed to be 1 m^2 of gross floor area (GFA) [93] or 1 m^2 of heated floor area (HFA) [58,62]. In this case, the FU could differ from area units, given in m^2 and often applied in paints, window and carpet products, or volume units, given in m^3, or mass units, given in tons. For this reason, it is important that the information regarding the material densities be considered and embedded in the relevant conversion function in BIM [93]. In case studies where the FU referred only to a single building component, researchers investigated the achievement of near zero impact on the overall building. It is, therefore, justifiable that studies with complete buildings presented a macro-process and hardly detailed the impact categories of single component or materials, except to describe the scenarios and the choices adopted.

As the environmental impacts in the construction sector operate by macro-processes, the study is easier if it is focused on the effects of certain choices of materials and components, leaving out detailed investigations on the components leading to minimal variations on the overall impact. If the case studies based on components are oriented toward the method and not the result, then the component type should also be considered irrelevant for the purposes of the analysis.

Authors who addressed the components aimed to show a specific method and the component was irrelevant from the point of view of the analysis. The others aimed to show the incidence of a particular type of building or a particular structure, such as in the case of papers that analyzed the costs, or energy performance linked to interventions on the building envelope. In this case, it depends on the incidence of the individual components. A possible criterion is the adoption of the same FUs for energy and cost, such as the square meter of floor area. In other cases, such as in Santos et al. [73], in the case of LCC cost assessment, the functional units were multiple: the whole building for the results report and the square meters of building components in the analysis stage to control the costs and impacts.

3.5. LCA Stage

The LCA process is defined by four principal life cycle stages according to EN 15643: 2012 [14]. The building lifecycle-oriented analysis considers the impacts related to the product and construction stage (module A1–A5: from the raw material extraction to the processing and product installation), and use stage (module B1–B7: the consumption flows, maintenance and reconfiguration), which spans the period from the completion of the construction works to the point when the building reaches its end of life. The system boundary in the use stage includes the use of construction products (maintenance/replacement) and services for operating the building [94], and the end of life stage (module C1–C4: demolition or disassembly, transportation to the treatment site and end of life scenario) [31]. There is also an additional and separate module (module D: advantages and loads beyond the system limit).

Each phase is further divided into different modules. A distinction is also made between the embodied and operational impacts. The impacts related to the operational energy use are defined by stage B6 and those to the operational water use, by stage B7, with the other 14 sub-stages together comprising the 'embodied' impacts [95]. This is now the most common basis for calculating the embodied impacts of buildings within academic studies from Europe.

In order to conduct the LCA analysis, contemplating all phases is not necessary. However, the definition of the system boundary is most relevant phase. The review shows that the motivations

and choices of the study phases are not always declared, as described in Figure 7. In most of the case studies, the production and construction phases (A) were investigated, especially according to a cradle to gate objective; while the usage phase (B) was developed in the case of evaluation of the primary energy consumption of buildings and, therefore, considering the installation of systems and the general applications.
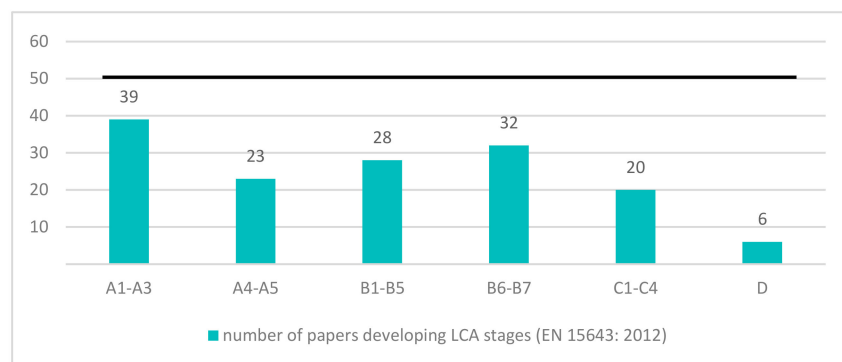

Figure 7. The chart represents the development of the topic of the LCA phases, defined according to the standard EN 15643: 2012; the columns show the number of papers that analyzed each phase organized by modules; the solid line represents the total number of selected papers (50).

Considering this review, phase A was included due the material evaluation and the agile calculations for the availability of data in databases, especially relating to production phases A1–A3, which represent the most considered stages in the studies, such as [24,93].

For the construction phase (A), the production stage (A1–A3) entails the highest energy consumption and the highest production rate of emissions; this stage fundamentally impacts the embodied energy (EE) and GWP. While in the construction stage (A4–A5), the construction context has yet to be defined for a material evaluation; therefore, the construction stage was not included and not relevant for the EE and GWP. In fact, the review shows how all subcategories are rarely considered, such as for [64,66,89,90,96,97], and the most of papers focused on the production stage and so provided attention to the material characteristics and the relative impact in the case of scenario comparisons.

For the usage phase (B), buildings and building products have a different nature when comparing life phases, highly dependent on the building context. Building materials and component elements consumed a major part of production and only required small amounts for maintenance, repair and at the end of life. This phase is of minor relevance for EE and GWP. In general it is noted that when addressing the B phase only few subcategories are taken into account, such as B1—Use/Application of installation product, B6—Operational Energy Use, and B7—Operational water Use [62,98,99], without considering maintenance, repair, replacement and transport. This implies the loss of information regarding specific energy consumptions or refurbishment or renovation measures caused by a dependence on the user's habits and choices.

End of life phases (C) are more complicated to develop since the is a need to model hypothetical scenarios. Therefore, only few case studies include this final evaluation [62,71,97,100].

A possible interpretation is provided by Rezaei [59]. When comparing the LCA results of the early design (LOD 200 or below) and detailed (LOD 300 or above), the material production phase (A) was significant for evaluating scenarios, next decisions and building steps, but the effects of construction and end of life were not considerable or were out of topic and irrelevant for the actual research.

However, the operation and maintenance stage (B) was the most critical stage in the LCA study especially in a comparison of scenarios. The environmental impact of the operation stage could be hardly modified by applying different adjustments (e.g., using renewable energy facilities, increasing the building thermal performance or decreasing the indoor temperature) and these decisions were defined only in a detailed design or better in a LOD 300 or above.

3.6. Databases

The database is one of the essential elements of LCA analysis. When comparing LCA analyses carried out on the same building or component, but using different databases, the results underline substantial differences. Schultz et al. [47] conducted an analysis on a building using two different software programs, Tally and Athena IE [101] to highlight discrepancies in the results due to the use of two different databases: Ecoinvent [102] and GaBi. They concluded that more databases and standardized calculation methods should be provided for comparable LCA analyses.

The studies that attempted to compare results according to the adoption of different databases and tools [48,60] affirmed that the calculation engine was less relevant with respect to the databases and simplifications that influence the decision-making process in building design.

The choice of the database is fundamental for the purpose of the LCA analysis. When possible, the database should be selected in relation to the specific information connected to the building site, local market and materials. Soust-Verdaguer et al. [40] did not determine a local database for a building design located in Uruguay, and, therefore, Ecoinvent was adopted. According to similar case studies, the decision was influenced because the Ecoinvent database is the most used in LCA applications of this building typology, regardless of the geographical area of the project. The Ecoinvent database disposes of various processes considered within each life cycle stage, including the construction materials, transport and energy. The hypothesis for the energy consumed for construction and deconstruction is based on the process by Kellenberger et al. [22] for traditional construction.

Santos et al. [24] compared analyses conducted with Tally and EPD. EPD provides manufacturers with a single scheme to structure and harmonize their product's information. As EPD typically only includes a product's environmental impact until its manufacturing phase, only the "Cradle-to-Gate" approach will be considered in this study, i.e., the embodied environmental impacts [24]. In this case, difficulties also arose in the results comparison; the author evaluated the output declaring the impossibility to verify whether Tally offered an accurate LCA analysis of the projects, mainly due to the lack of different materials, because most materials are generic, and it was not possible to edit the material information.

Moncaster [103] stated that the existing databases provided limited data for the product stage (stage 1) of the process regarding the embodied energy and carbon in the building materials. There is less data still for composite components, such as windows, service components and innovative materials and products. There is also a shortage of data across the construction sector in the embodied energy used and carbon emitted during stages 2 (construction), 3 (in use) and 4 (end of life).

However, a direct comparison of databases is debatable, because the data is collected from various sources and it is based on different calculation methodologies according to their purpose. In principle, there are two different basic approaches to LCA, a process-based approach and an Economic Input–Output (EIO) based approach. The process-based approach is the original method of LCA that computes the environmental input and output as it follows the actual process flow, while the EIO method is an inter-industry economic input–output analysis based on monetary transactions and resource consumption data. Several researchers conducted a comparison of LCA databases modelled by the two different approaches [20,35], and the results commonly indicated fundamental gaps in the modelling of data, which, in some cases, resulted in significant differences in the assessment results. Most of the values from the two approaches were of the same order of magnitude [104].

Globally Ecoinvent and Athena were the most used databases: Ecoinvent is extensively adopted thanks to the availability for many platforms and tools, such as SimaPro, One Click LCA and Open LCA; Athena is widely used for the disposal of exhaustive database and calculation tool for the American building sector (Figure 8).

The review underlines how the adoption of databases and tools are strictly connected, leading to implications in the BIM interoperability. For example, most of the cases performing analysis with Athena Eco Calculator, also adopted Athena LCID. The same remark is verified in the case of SimaPro software and Ecoinvent, even if the tool is able to adopt additional data by different database or EPDs.

One Click LCA allows using a much wider international catalogue and makes available EPDs of materials and products at a national level (Figure 9).
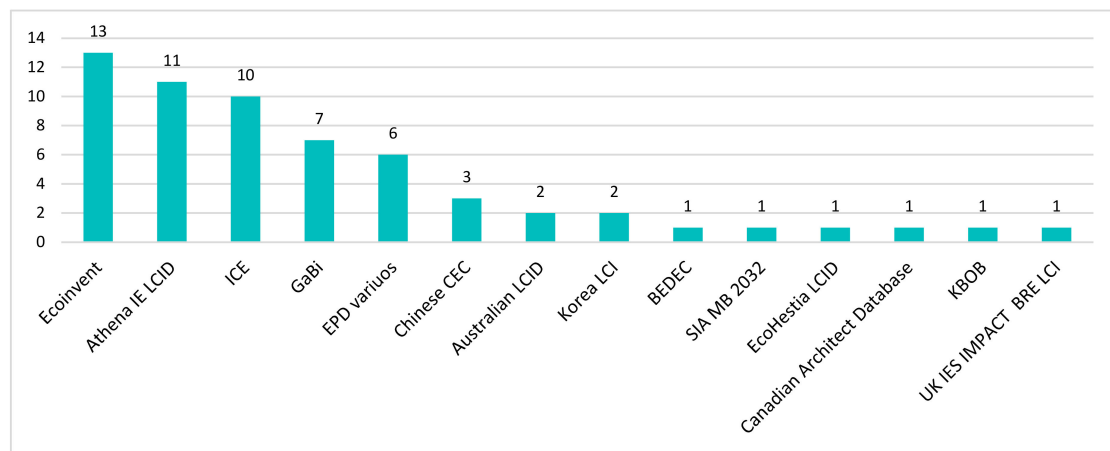

Figure 8. The database adoption in BIM-LCA assessment; the chart considers the amount of databases considered in the case studies, underling the widespread use of Ecoinvent, Athena IE and ICE. The number of databases is over the total amount of considered papers (50) because there is not a strict connection between the number of papers and number of databases; as shown in Table A1, some case studies proposed the adoption of more than one database for LCA assessment.
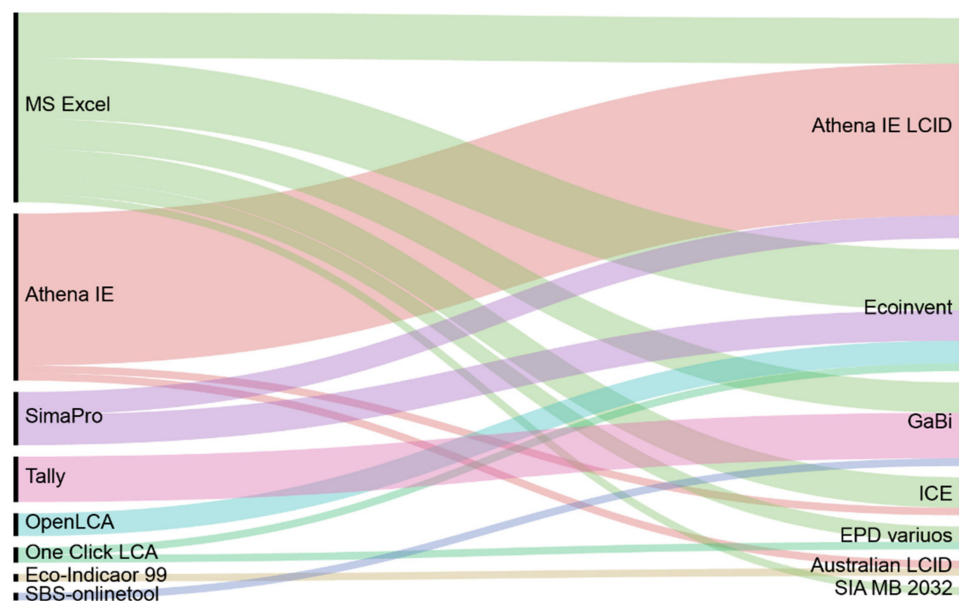

Figure 9. Database adoption in the selected cases studies in relation to the LCA tool adopted; the colored flow lines indicate the relationships between the tools (left side) and database (right side).

Concerning the adoption of the open source Inventory of Carbon & Energy (ICE) by the University of Bath [105]: the database is one of most used, in 10 case studies; this database provides information regarding the total CO_2 and embodied energy. However, the primary benefit is the open format and the accessibility by spreadsheet. The adoption of ICE is remarkable in the case of environmental impacts related to energy calculated by elaboration of the take-off BIM data in MS Excel or similar programs [60,61,78,96,99,106–109].

There are some constraints facing BIM-LCA integration in the construction sector, such as the insufficient BIM database that requires improvement at the early design stages of construction projects

in terms of developing the LCA applications. Hence, more information on the material properties should be adapted in BIM models in terms of the LCA analysis. Another challenge is that users of the Tally application must define the materials properly for the buildings under study. Hence, more effort is desirable to utilize technologically similar entries to the modelled materials. As well, geographical sources in Tally must be adapted to cover more regions worldwide. There is a limitation of the data that are related to building elements in BIM, and the difficulty of comparing scenarios are additional challenges facing this type of integration [64]. The proposed implementation of BIM tools requires more evolving technologies in response to the limitation of knowledge in order to support the sustainable construction and decision-making processes in the construction sector [100].

3.7. Impact

The impact categories can be generally traced back to four main areas: the use of natural resources (resource depletion), effects on human health (human health and safety effects), effects on the ecosystem (ecological effects) and greenhouse effects (climate change). Each effect interacts with the environment related to different geographical scales, which could be used for a further classification of the impact categories: global (greenhouse effect and depletion of the ozone layer); regional (acidification, eutrophication and photochemical smog formation); and local (formation of photochemical smog and land use).

The data in Figure 10 report the major impacts calculated—the Global Warming Potential (GWP), Operational Energy (OE), Acidification Potential (AP), CO_2 Emissions (COE), Ozone Depletion Potential (ODP) and Eutrophication Potential (EP)—and underlines the great relevance given to the calculation of impacts strictly connected to energy issues, such as the Embodied Energy (EE), Non-Renewable Energy Demand (NRED), Operational Energy (OE), Primary Energy Delivery (PED), Total Primary Energy (PET), Primary Energy Consumption (PEC) and Total Non-Renewable Primary Energy (PENRT). This aspect found a link with studies that conducted an LCA analysis in relation to the embodied energy [108], the scenarios of decreasing energy consumption [60] and operational costs [109], the renovations of existent buildings [78], or fulfilling the requirements for green building labels [110,111].
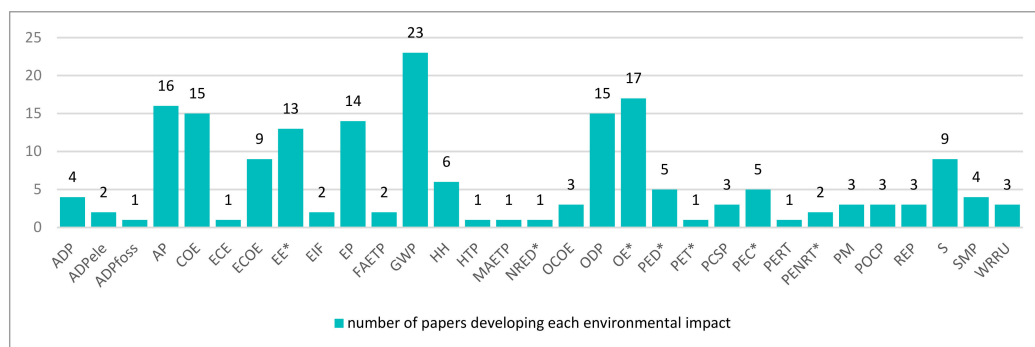
Figure 10. The chart represents the number of papers developing each environmental impact, underlining the great relevance of the Global Warming Potential (GWP). The graphic symbol * is shown for impacts that are related to energy issues. The definitions of abbreviations are the same as reported in Table A1.

Regarding specific choices of environmental impacts, the review found no particular approaches in the selection criteria. However, it can be highlighted that specific assessment methods affected the calculation of impacts. For example, for the environmental impact measures consistent with the US EPA TRACI methodology [112], the impact list regarded six impact categories (global warming potential, acidification potential, human health particulate, ozone depletion potential, smog potential and eutrophication potential), which are commonly used in North America, while the other tools use various environmental impacts assessment methods that are more suitable for European countries [87,110,113].

The subscription to green building labels or the environmental certification process could require the list of impact categories to be assessed. This occurs, for example, with LEED [38] certification, which requires the evaluation and the reduction of environmental impacts (the same with TRACI) in the building process in comparison to a baseline design, as in Hasik et al. [110], Gomes et al. [77]. One more example is given by the adoption of LCA indicators in the DGNB protocol [114] concerning the LCA optimization during the planning process and the comparison with the benchmark value, fixed for the impact categories [68]. The adoption of the certification system addressed the LCA methodology. However, in practice, the case studies confirmed the fact that such certifications are still applied at the detailed stage of the process [115].

One more aspect should be mentioned. Different studies, such as Kim et al. [109] and Sharif et al. [78], described case studies performing energy simulations for making a connections between energy use and environmental impacts, such as the embodied energy, primary energy demand and others. In general, the aim is for a high energy standard but also to reduce the operational CO_2. Thus, the optimized solution is to adopt recycled materials, characterized by low embodied CO, as the minimization of energy demands in the use phase resulted in an increase in the embodied CO_2 of the building due to the increase in materials and other installations.

As mentioned in Sharif et al. [78], the research on this topic regarding LCA and the impact categories required in rating system assessment could increase in the next years, and in future developments, to make a connection between the BIM integration of impact data and the specific requirements for mandatory building labels or voluntary rating systems.

4. Conclusions and Main Remarks

This paper was based on a paper review regarding the integration of BIM-LCA, by selecting scientific papers published during the period 2007–2019 and analysing different parameters related to the BIM model data and LCA approach. With a methodological point of view, the review schematized the adopted workflow of published studies using key parameters to offer the scientific community a framework of all possible approaches used. Some general remarks arose from the review according to each parameter considered.

First, the review presented evidence of a general framework of the topic. The workflows adopted by the research were heterogenous, even if valid in relation to the context and background. A possible explanation is due to the aim of the research, the data availability, and the boundary conditions of the research related to the design stage and to the database choice. In this sense, the review showed and described the research trends and discussed the common and widespread approaches, identifying the main features.

Certain BIM-LCA integration approaches referred to the early design modeling while others focused on the detailed stage since BIM provides capabilities to model basic and detailed building case-studies. The review shows how the trend of recent years has shifted from a focus on the early stage to the detailed stage, and in some cases the authors take into consideration both approaches. The early stage is characterized by less effort and more flexibility to allow stakeholders in the evaluation of different scenarios and a choice of materials to achieve sustainable buildings and low environmental impacts. The detailed stage, instead, provides an advanced knowledge of the building. Therefore, the application on detailed stages requires more accurate data to define the LCA analysis and needs different workflows in terms of the tools and database. This approach can lead to halving the environmental results previously assessed in the early stage as an obvious consequence. Complex workflows will be one of the most developed scenario in future research in terms of the interoperability in BIM, especially in the development of tools and methodology to establish the automatic quantity take-off as recently introduced in research by Hollberg et al. [12,116].

The LOD was demonstrated to be the key concept of BIM-LCA integration. The review remarked on the close relation between the choice of the LOD and the design stage set for the case study. A low level (LOD 100 or 200) could help to estimate the environmental impacts in the earlier design stage.

This led to the effective comparison of the different buildings design scenarios on the environmental point of view, and it could help to select more sustainable materials for different building assemblies and modify the detailed building (LOD 300 or above) to reduce the environmental impacts.

One of the major problems is the lack of available LCA software integrated in BIM tools. The BIM integration certainly simplifies and facilitates the execution; however, the integration must be improved to obtain more reliable and comparable results to those obtained from dedicated software for LCA (GaBi or SimaPro for example).

Regarding tool adoption, Autodesk Revit is the most used by researchers, supported by owned plugins and APIs, such as Tally, and has a satisfactory performance despite not being as reliable as dedicated LCA software. It simplifies the work by allowing the designer to perform environmental assessments of the construction choices directly from the BIM environment, without having to make other intermediate steps. The ability to use LCA analysis from the earliest stages of design gives the opportunity to improve the long-term sustainability of buildings. A different widespread workflow used the export take-off data, provided by Revit, managed by spreadsheet (such as Microsoft Excel) or by developing external tools to achieve LCA analysis by external software.

The choice of functional unit is more coherent in case of analysis of complete building because it describes the overall environmental impact. Moreover, a complete building gives an exhaustive frame of design options to identify the categories and the components where to reduce the environmental impact.

The analysis of the LCA stage suggested a link with the design stage and the LOD. In the case of early design, or in the case of LOD 200 or below, the LCA information for phase A was relevant to define the workflow of the building design. In the case of detailed design, or in the case of LOD 300 or above, the evaluation of phase B should be absolutely considered for an accurate LCA assessment of the whole building. This point was supported by Stevanovic et al. [82]: the case study revealed that the environmental impact was primarily caused by electricity use for the appliances and lighting, cleaning processes and material production.

Globally the most used databases were Ecoinvent and Athena, for different reasons. On the one hand, Ecoinvent is widely available on most of the platforms and tools, such as SimaPro, One Click LCA, and Open LCA. On the other hand, Athena is largely adopted for its exhaustive databases and calculation tool for the American building sector.

The widespread adoption of EPDs is relevant due to the specific implication of datasets strictly related to country production and markets and also because the user can select EPD data sources relevant to the actual material properties. The trend in the recent research was to adopt a commercial database, improving the dataset with national ones, such as Belgian [79], Norway [74], China [75], Switzerland [57], UK [109] and Brazil [77].

BIM-LCA software must have more databases. In accordance with Cavalliere [57], in order to carry out LCA analysis in all phases of the design, databases should be added with information at various levels of detail to allow a quick and agile adoption during the design stages to obtain the best solution.

Finally, the review underlines that BIM-LCA integration needs future developments in order to standardize processes and to allow the end user to easy manage environmental data; in fact the complex workflows, that combine BIM models for the quantification of building materials, environmental databases and LCA tools, have the advantage of including more environmental impact categories but still have the disadvantage of requiring more manual editing.

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

Appendix A

This section contains, in detail, the collected data in the analysis phase and study of the selected papers according to the declared parameters (Table A1).

Table A1. Collected data according to the analysis parameters.

Reference	Early or Detailed Design Stage	LOD	Tool	Impact	Functional Unit	Database	LCA Phase
Seo et al., 2007 [41]	Early	n/a	Graphisoft Archicad, Eco-indicator 99 tool	Human Health, Ecosystem Quality, Resourse Use	Complete Building	Australian LCID	n/a
Wang et al, 2011 [98]	n/a	n/a	Autodesk Revit, Autodesk Ecotect	COE, EE, PEC, PED	Complete Building	BEDEC database	A1–A3, B1, B6–B7
Jrade and Abdulla, 2012 [117]	Early	n/a	Autodesk Revit, IFC analyser, MS Excel, Athena EcoCalculator, Athena IE	GWP, AP, HH, EP, ODP, S	Wall, Door	Athena IE LCID	n/a
Shrivastava and Chini, 2012 [118]	Early	n/a	Autodesk Revit	EE	Complete Building	Canadian Architect Database	A1–A3
Jrade and Jalaei, 2013 [119]	Early	n/a	Autodesk Revit, MS Excel, Athena IE	AP, EP, GWP, HH, ODP, PEC, PCSP, REP, WRRU	Complete Building	Athena IE LCID	A1–A3, B6–B7
Basbagill et al., 2013 [64]	Early	n/a	DProfiler, eQuest, SimaPro, RSMeans, Athena EcoCalculator	GWP, NREC, HT, AP, EP, EE	Complete Building	Athena IE LCID	A1–A3, B1–B5, B6–B7
Iddon and Firth, 2013 [106]	Early	n/a	Other BIM Tool, MS Excel	ECOE, OCOE	Complete Building	ICE	A1–A3, B6
Abanda et al., 2014 [120]	Detailed	n/a	Autodesk Revit, MS Excel	ECOE, EE	Complete Building	ICE	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, D
Antón and Díaz, 2014 [66]	Early	n/a	DProfiler, SimaPro, Athena EcoCalculator	EIF	Complete Building	Athena IE LCID	A1–A3, B1–B5, B6–B7,
Houlihan Wiberg et al., 2014 [58]	Detailed	n/a	Autodesk Revit, MS Excel, SIMIEN, SimaPro 7.3	ECOE, OCOE	1Mq of heated floor area	Ecoinvent 2.2	A1–A3, B4, B6,

Table A1. *Cont.*

Reference	Early or Detailed Design Stage	LOD	Tool	Impact	Functional Unit	Database	LCA Phase
Jalaei and Jrade, 2014 [121]	Early	n/a	Autodesk Revit, Autodesk Ecotect, IESVE, MS Excel, Athena IE	AP, EP, GWP, HH, ODP, PEC, PCSP, REP, WRRU	Complete Building	Athena IE LCID	A1–A3, B6,
Ajayi et al., 2015 [63]	Early	200	Autodesk Revit, GBS, MS Excel, Athena IE	GWP, HH	Complete Building	Athena IE LCID	A1–A3, B1–B5, B6–B7
Lee et al., 2015 [71]	Detailed	300	Autodesk Revit	ADP, AP, EP, GWP, ODP, POCP	Complete Building	Korea LCI	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4
Shafiq et al., 2015 [107]	Early	n/a	Autodesk Revit, MS Excel	ECOE, EE	Complete Building	ICE	A1–A3, A4
Shin and Cho, 2015 [89]	Early	n/a	Graphisoft Archicad, MS Excel	COE	Complete Building	Korea LCI	A1–A3, A4–A5, B1–B5, B6
Georges et al., 2015 [62]	Detailed	n/a	Autodesk Revit, MS Excel, SIMIEN, SimaPro 7.3	ECOE, EE, OCOE	1mq of HFA	Ecoinvent 2.2	A1–A3, B1, B4, B6
Peng, 2016 [96]	Detailed	n/a	Autodesk Revit, Autodesk Ecotect	COE	Complete Building	ICE	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4
Shadram et al., 2016 [122]	Detailed	n/a	Autodesk Revit, Power Pivot, FME, Google Maps API	ECOE, EE	Complete Building	EPD inventory	A1–A3, A4
Schultz et al., 2016 [47]	Early	n/a	Autodesk Revit, Tally, Athena IE	GWP, ODP, AP, EP, PEC, SMP, PENRT	Wall	Australian LCID Athena IE LCID GaBi	n/a
Abanda et al., 2017 [61]	Detailed	n/a	Autodesk Revit, Navisworks, MS Excel, Autodesk API	ECOE, EE	Complete Building	ICE	n/a
Basbagill et al., 2017 [90]	Early	n/a	DProfiler, Cost lab, eQUEST, SimaPro, Athena EcoCalculator, MS Excel	EE, EIF	Complete Building	Athena IE LCID	A1–A3, B1–B5, B6–B7

Table A1. *Cont.*

Reference	Early or Detailed Design Stage	LOD	Tool	Impact	Functional Unit	Database	LCA Phase
Marzouk et al., 2017 [97]	Detailed	n/a	Autodesk Revit, SQL, DB link for MS access, Athena IE, MS Excel, Visual Studio	COE, AP, PM, EM, ODP, S, PSP	Complete Building	Athena IE LCID	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4
Najjar et al., 2017 [100]	Early	n/a	Autodesk Revit, Tally, GBS	AP, EP, GWP, ODP, SMP, PET, PERT, PENRT	Complete Building	GaBi	A1–A3, B1–B5, B6–B7, C1–C4
Bueno and Fabricio, 2018 [39]	Early	n/a	Autodesk Revit, Autodesk Dynamo, Tally	AP, EP, GWP, ODP, PED, RED	Wall	Ecoinvent GaBi	n/a
Santos et al., 2018 [24]	Detailed	n/a	Autodesk Revit, Autodesk Dynamo, MS Excel, Tally	AP, EP, GWP, ODP, PED, PER-NRE, ADPele	Wall	GaBi EPD	A1–A3
Soust-Verdaguer et al., 2018 [40]	Detailed	300	Graphisoft Archicad, MS Excel	GWP, ODP, FAETP, HTTP		Ecoinvent 2.0	A1–A3, A4–A5, B2–B4, B6, C1, C2, C4
Cavalliere et al., 2018 [31]	Detailed	n/a	Autodesk Revit, SimaPro	AP, EP, GWP, HH, ODP, PEC, PCSP, REP, WRRU	whole external wall	Ecoinvent 3	n/a
Röck et al., 2018 Rock [72]	Early	200	Autodesk Revit, Autodesk Dynamo, MS Excel	GWP	Complete Building	SIA MB 2032 database	n/a
Shadram and Mukkavaara 2018, [99]	Detailed	n/a	Autodesk Revit, Autodesk Dynamo, MySQL, Grasshopper, Slingshot, Archsim, Octopus, Energy plus	EE, OE	Complete Building	ICE	A1–A3, B1, B4, B6–B7
Bueno et al., 2018 [65]	Early	n/a	Autodesk Revit, Autodesk Dynamo, MS Excel	ReciPe midpoit indicators	Wall and Roofing system	Ecoinvent	n/a
Eleftheriadis et al., 2018 [93]	Early	n/a	Autodesk Revit, MS Excel	ECE, ECOE	1mq of GFA	EPD	A1–A3

Table A1. *Cont.*

Reference	Early or Detailed Design Stage	LOD	Tool	Impact	Functional Unit	Database	LCA Phase
Nizam et al., 2018 [108]	Early	n/a	Autodesk Revit, External Database	EE	Complete Building	ICE Chinese Handbook	A1–A3, A4–A5
Panteli et al., 2018 [33]	Early	n/a	Autodesk Revit, Insight	GWP, AP, EP, ODP, ADPele, ADPfoss, TETP, FAETP, HTTP, MAETP, POCP	Complete Building	EcoHestia LCID	A1–A3, A4–A5
Dalla Mora et al., 2018 [48]	Early	200	Autodesk Revit, OneClick LCA, Tally	GWP, PED	Complete Building	Ecoinvent 2.2 GaBi	A1–A3, A5, B2–B4, C1–C4,
Santos et al., 2019 [73]	Detailed	300	Autodesk Revit, LCA/LCC prototype tool	ADPE, ADPM, AP, EP, GWP, ODP, POCP, PE-NRE, PE-RE, PED	Complete Building, m^2 for building components, m^3 for reinforced concrete	EPD-Belgium Ecoinvent	A1–A3, A4–A5, B2–B4, B6–B7, C2–C4, D
Nilsen and Bohne, 2019 [74]	Early	200–300–350	Autodesk Revit, OneClick LCA	GWP	m^3 for building materials	EPD-Norway	A1–A3
Lu et al., 2019 [75]	Early	300	Autodesk Revit, spreadsheet, Glodon GTJ2018	COE	n/a	China Carbon Emission Estimator for Residential Buildings (CEERB), carbon emission coefficient (CEC) database	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, D
Lu and Wang, 2019 [76]	Early	300	Autodesk Revit, spreadsheet, Glodon GTJ2018	COE	n/a	China Carbon Emission Estimator for Residential Buildings (CEERB), carbon emission coefficient (CEC) database	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, D
Rezaei et al., 2019 [59]	Early and Detailed	100, 300	Autodesk Revit, OpenLCA	Impact by Impact 2002+ method	Complete building	Ecoinvent 3.3 for Québec or North America	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, D

Table A1. *Cont.*

Reference	Early or Detailed Design Stage	LOD	Tool	Impact	Functional Unit	Database	LCA Phase
Cavalliere et al., 2019 [57]	Early and Detailed	100–200 –300–400	other BIM tool, 3D Rhinoceros, MS Excel	GWP	m2 of heated floor area	Swiss Buildings Database, KBOB and Bauteilkatalog, based on Ecoinvent 3.3 background data s	A1–A3, B4, C3–C4
Kim, 2019 [109]	Detailed	n/a	Autodesk Revit 2016, LCA LCC IES IMPACT	ECOE	Complete building	UK IES IMPACT dataset provided by BRE, ICE	A (cradle-to-site) and B (cradle-to-grave)
Di Bari et al., 2019 [68]	Early	n/a	other BIM tool, SBS-online tool, MS Excel	GWP	Complete building	GaBi 3	n/a
Stevanovic et al., 2019 [82]	Detailed	n/a	Autodesk Revit, Autodesk Design Review 2013, MS Excel, Belgian MMG+_KULeuven tool, SimaPro 8.3	CEN and CEN+ categories (mainly GWP, PE, AP, HTP, PM)	€/unit	Ecoinvent 2.2	A1–A3, A4–A5, B2, B4, B5, B6–B7, C1–C3.
Gomes et al., 2019 [77]	Detailed	300	Autodesk Revit Architecture 2016		Complete building	EPD-Brasil	A1–A3, A4–A5, B1–B5, C1–C2
Galiano-Garrigós et al., 2019 [60]	Early and Detailed	n/a	Autodesk Revit, MS Excel	EE, EC	Complete	ICE	n/a
Hasik et al., 2019 [110]	Detailed	n/a	Autodesk Revit, Tally	AP, EP, GWP, ODP, SMP, NRED	Complete	GaBi	A1–A3, A4, B2–B5, C2–C4, D
Sharif and Hammad, 2019 [78]	Detailed	300	Autodesk Revit, Design Builder, Athena IE	GWP, EE, OE	Complete	ICE Athena IE LCID	A1–A3, A5, B1–B5, B6–B7, C1, C3–C4
M. K. Najjar et al., 2019 [87]	Early	n/a	Autodesk Revit, Open LCA 1.5.0	Impact 2002+, ILCD 2011 methods	Complete	Ecoinvent 3	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4
Jalaei et al., 2019 [113]	Detailed	n/a	Autodesk Revit, Navisworks, Athena IE	GWP, AP, HH, EP, ODP, SMP	Complete	Athena IE LCID	A4–A5, B1–B5, B6–B7, C1–C4

Table A1. *Cont.*

Reference	Early or Detailed Design Stage	LOD	Tool	Impact	Functional Unit	Database	LCA Phase
M. Najjar et al., 2019 [111]	Early	n/a	Autodesk Revit, GBS, Open LCA 1.5.0	Impact 2002+, ILCD 2011 methods	Complete	Ecoinvent 3	A1–A3, A4–A5, B1–B5, B6–B7, C1–C4

Abbreviations: ADP, Abiotic Depletion Potential; ADPele, Abiotic Depletion Potential—elements; ADPfoss, Abiotic Depletion Potential—fossil; AP, Acidification Potential; COE, CO2 Emissions; ECE, Embodied Carbon Emission; ECOE, Embodied CO2 Emissions; EE, Embodied Energy; EFP, Effects Potential; EIF, Embodied Impact Factor; EP, Eutrophication Potential; FAETP, Fresh water Aquatic Ecotoxicity Potential; GHG, Greenhouse Gases; GWP, Global Warming Potential; HH, Human Health; HTP, Human toxicity potential; MAETP, Marine Aquatic Ecotoxicity Potential; NRED, Non-Renewable Energy Demand; OCOE, Operative CO2 Emissions; ODP, Ozone Depletion Potential; OE, Operational Energy; PED, Primary Energy Delivery; PET, Total Primary Energy; PCSP, Photo-chemical Smog Potential; PEC, Primary Energy Consumption; PERT, Total renewable primary energy; PENRT, Total Non-Renewable Primary Energy; PM, Particular Matter; POCP, Photochemical Ozone Creation Potential; REP, Respiratory Effects Potential; S, Smog; SMP, Smog Formation Potential; WRRU, Weighted Raw Resource Use; FEW, freshwater aquatic ecotoxicity; HT, human toxicity; GBS, Green Building Studio; Athena IE, Athena Impact Estimator; EPD, Environmental Product Declaration.

References

1. Galán-Martín, A.; Pozo, C.; Azapagic, A.; Grossmann, I.E.; Mac Dowell, N.; Guillén-Gosálbez, G. Time for Global Action: An Optimised Cooperative Approach towards Effective Climate Change Mitigation. *Energy Environ. Sci.* **2018**, *11*, 572–581. [CrossRef]

2. European Commission. *A Clean Planet for All: A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; COM 773 Final; European Commission: Brussels, Belgium, 2018.

3. D'Agostino, D.; Parker, D.; Melià, P. Environmental and Economic Implications of Energy Efficiency in New Residential Buildings: A Multi-Criteria Selection Approach. *Energy Strategy Rev.* **2019**, *26*, 100412. [CrossRef]

4. Buyle, M.; Braet, J.; Audenaert, A. Life Cycle Assessment in the Construction Sector: A Review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 379–388. [CrossRef]

5. Grilo, A.; Jardim-Goncalves, R. Value Proposition on Interoperability of BIM and Collaborative Working Environments. *Autom. Constr.* **2010**, *19*, 522–530. [CrossRef]

6. Koeppel, S.; Ürge-Vorsatz, D. *Assessment of Policy Instruments for Reducing Greenhouse Gas Emissions from Buildings*; CEU: Budapest, Hungary, 2007.

7. Petersdorff, C.; Boermans, T.; Harnisch, J. Mitigation of CO_2 Emissions from the EU-15 Building Stock. Beyond the EU Directive on the Energy Performance of Buildings. *Environ. Sci. Pollut. Res.* **2006**, *13*, 350–358. [CrossRef] [PubMed]

8. European Commission. *Towards a Thematic Strategy on the Sustainable Use of Natural Resources*; European Commission: Brussels, Belgium, 2003.

9. EEA European Environment Agency. *Sustainability Transitions: Policy and Practice*; EEA Report No. 09/2019; EEA: Copenhagen, Denmark, 2019.

10. Bhatta, B. Causes and Consequences of Urban Growth and Sprawl. In *Analysis of Urban Growth and Sprawl from Remote Sensing Data*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 17–36. [CrossRef]

11. Zari, M.P. Regenerative Design for the Future. *Build* **2010**, *115*, 68–69.

12. Naneva, A.; Bonanomi, M.; Hollberg, A.; Habert, G.; Hall, D. Integrated BIM-Based LCA for the Entire Building Process Using an Existing Structure for Cost Estimation in the Swiss Context. *Sustainability* **2020**, *12*, 3748. [CrossRef]

13. Lasvaux, S.; Favre, D.; Périsset, B.; Bony, J.; Hildbrand, C.; Citherlet, S. Life Cycle Assessment of Energy Related Building Renovation: Methodology and Case Study. *Energy Procedia* **2015**, *78*, 3496–3501. [CrossRef]

14. BSI Standards Publication. *BS EN 15643-2, Sustainability of Construction Works-Assessment of Buildings-Part 2: Framework for the Assessment of Environmental Performance*; British Standards Institution: London, UK, 2012.

15. Cavalliere, C.; Brescia, L.; Maiorano, G.; Dalla Mora, T.; Dell'Osso, G.R.; Naboni, E. Towards an Accessible Life Cycle Assessment: A Literature Based Review of Current BIM and Parametric Based Tools. In Proceedings of the 16th IBPSA Conference, Rome, Italy, 2–4 September 2019; pp. 159–166. [CrossRef]

16. Succar, B. Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders. *Autom. Constr.* **2009**, *18*, 357–375. [CrossRef]

17. European Parliament; Council of the European Union. Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on Public Procurement and Repealing Directive 2004/18/EC (Text with EEA Relevance). In *Brussels Commentary on EU Public Procurement Law*; Hart/Nomos: Oxford, UK, 2018; Volume 2014, pp. 65–242. [CrossRef]

18. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Simplification in Life Cycle Assessment of Single-Family Houses: A Review of Recent Developments. *Build. Environ.* **2016**, *103*, 215–227. [CrossRef]

19. Ilhan, B.; Yaman, H. Green Building Assessment Tool (GBAT) for Integrated BIM-Based Design Decisions. *Autom. Constr.* **2016**, *70*, 26–37. [CrossRef]

20. Wong, J.K.W.; Zhou, J. Enhancing Environmental Sustainability over Building Life Cycles through Green BIM: A Review. *Autom. Constr.* **2015**, *57*, 156–165. [CrossRef]

21. CEN European Committee for Standardization. *ISO EN 14040: 2006: Environmental Management: Life Cycle Assessment; Principles Framework*; (ISO 14040 2006); CEN (European Committee for Standardization): Brussels, Belgium, 2006.

22. Kellenberger, D.; Althaus, H.-J. Relevance of Simplifications in LCA of Building Components. *Build. Environ.* **2009**, *44*, 818–825. [CrossRef]

23. Klöpffer, W.; Grahl, B. From LCA to Sustainability Assessment. *Life Cycle Assess.* **2014**, *756*. [CrossRef]

24. Santos, R.; Costa, A.; Silvestre, J.D.; Pyl, L. A Validation Study of a Semi-Automatic BIM-LCA Tool. In *2º Congresso Português de Building Information Modelling*; Instituto Superior Técnico Universidade de Lisboa: Lisbon, Portugal, 2018.

25. BSI Standards Publication. *BS EN 15978: 2011 Sustainability of Construction Works: Assessment of Environmental Performance of Buildings*; Calculation Method; BSI: London, UK, 2011.

26. Scherer, R.J.; Katranuschkov, P. BIMification: How to Create and Use BIM for Retrofitting. *Adv. Eng. Inform.* **2018**, *38*, 54–66. [CrossRef]

27. Borrmann, A.; König, M.; Koch, C.; Beetz, J. Einführung. In *Building Information Modeling*; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2015; pp. 1–21. [CrossRef]

28. Solnosky, R. Current Status of BIM Benefits, Challenges, and the Future Potential for the Structural Discipline. In *Structures Congress 2013*; American Society of Civil Engineers: Reston, VA, USA, 2013; pp. 849–859. [CrossRef]

29. Oti, A.H.; Tizani, W.; Abanda, H.; Jalyzada, A.J.; Tah, J.H.M. Structural Sustainability Appraisal in BIM. *Autom. Constr.* **2016**, *69*, 44–58. [CrossRef]

30. Eastman, C.M.; Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*; John Wiley & Sons: Hoboken, NJ, USA, 2011.

31. Cavalliere, C.; Dell'Osso, G.R.; Pierucci, A.; Iannone, F. Life Cycle Assessment Data Structure for Building Information Modelling. *J. Clean. Prod.* **2018**, *199*, 193–204. [CrossRef]

32. Gao, G.; Liu, Y.-S.; Wang, M.; Gu, M.; Yong, J.-H. A Query Expansion Method for Retrieving Online BIM Resources Based on Industry Foundation Classes. *Autom. Constr.* **2015**, *56*, 14–25. [CrossRef]

33. Panteli, C.; Kylili, A.; Stasiuliene, L.; Seduikyte, L.; Fokaides, P.A. A Framework for Building Overhang Design Using Building Information Modeling and Life Cycle Assessment. *J. Build. Eng.* **2018**, *20*, 248–255. [CrossRef]

34. Kylili, A.; Fokaides, P.A.; Vaiciunas, J.; Seduikyte, L. Integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for Sustainable Constructions. *J. Sustain. Archit. Civ. Eng.* **2016**, *13*, 28–38. [CrossRef]

35. Dautremont, C.; Jancart, S.; Dagnelie, C.; Stals, A. Parametric Design and BIM, Systemic Tools for Circular Architecture. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*. [CrossRef]

36. ISO International Organization for Standardization. *ISO 29481-1:2016: Building Information Models: Information Delivery Manual: Part. 1: Methodology and Format*; ISO: Geneva, Switzerland, 2016.

37. BRE Global. *BREEAM In-Use International, Technical Manual*; SD221-2.0:2015–Version: 2. BREEAM IN-USE Int. 2015- v.2; BRE Global: Dubai, UAE, 2016.

38. US Green Building Council. *Leadership in Energy and Environmental Design (LEED) V4*; US Green Building Council: Atlanta, GA, USA, 2019.

39. Bueno, C.; Fabricio, M.M. Comparative Analysis between a Complete LCA Study and Results from a BIM-LCA Plug-In. *Autom. Constr.* **2018**, *90*, 188–200. [CrossRef]

40. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A.; Gómez de Cózar, J.C. BIM-Based LCA Method to Analyze Envelope Alternatives of Single-Family Houses: Case Study in Uruguay. *J. Archit. Eng.* **2018**, *24*, 05018002. [CrossRef]

41. Seo, S.; Tucker, S.; Newton, P. Automated Material Selection and Environmental Assessment in the Context of 3D Building Modelling. *J. Green Build.* **2007**, *2*, 51–61. [CrossRef]

42. Giesekam, J.; Barrett, J.; Taylor, P.; Owen, A. The Greenhouse Gas Emissions and Mitigation Options for Materials Used in UK Construction. *Energy Build.* **2014**, *78*, 202–214. [CrossRef]

43. Yuan, Y.; Yuan, J. The Theory and Framework of Integration Design of Building Consumption Efficiency Based on BIM. *Procedia Eng.* **2011**, *15*, 5323–5327. [CrossRef]

44. GaBi. Available online: www.GaBi-software.com/italy/solutions/life-cycle-assessment (accessed on 25 May 2020).

45. Tally. Available online: www.choosetally.com/ (accessed on 25 May 2020).

46. Khemlani, L. *Autodesk Revit: Implementation in Practice*; White Paper; Autodesk: San Rafael, CA, USA, 2004.

47. Schultz, J.; Ku, K.; Gindlesparger, M.; Doerfler, J. A Benchmark Study of BIM-Based Whole-Building Life-Cycle Assessment Tools and Processes. *Int. J. Sustain. Build. Technol. Urban Dev.* **2016**, *7*, 219–229. [CrossRef]

48. Dalla Mora, T.; Bolzonello, E.; Peron, F.; Carbonari, A. PLEA 2018 Hong Kong Integration of LCA Tools in BIM toward a Regenerative Design. In Proceedings of the 34th International Conference on Passive and Low Energy Architecture, Hong Kong, China, 10–12 December 2018; TCU of Hong Kong, Ed.; Smart and Healthy within the Two-Degree Limit: Hong Kong, China, 2018; p. 6.

49. Timberlake, K. Tally LCA App for Autodesk Revit. Available online: http://choosetally.com (accessed on 25 May 2020).

50. OneClickLCA. *Life-Cycle Assessment Guide for Green Building Experts—Part 1*; OneClickLCA: Helsinki, Finland, 2018.

51. Chong, H.-Y.; Lee, C.-Y.; Wang, X. A Mixed Review of the Adoption of Building Information Modelling (BIM) for Sustainability. *J. Clean. Prod.* **2017**, *142*, 4114–4126. [CrossRef]

52. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical Review of Bim-Based LCA Method to Buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]

53. Potrč Obrecht, T.; Röck, M.; Hoxha, E.; Passer, A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability* **2020**, *12*, 5534. [CrossRef]

54. Soares, N.; Bastos, J.; Pereira, L.D.; Soares, A.; Amaral, A.R.; Asadi, E.; Rodrigues, E.; Lamas, F.B.; Monteiro, H.; Lopes, M.A.R.; et al. A Review on Current Advances in the Energy and Environmental Performance of Buildings towards a More Sustainable Built Environment. *Renew. Sustain. Energy Rev.* **2017**, *77*, 845–860. [CrossRef]

55. Eleftheriadis, S.; Mumovic, D.; Greening, P. Life Cycle Energy Efficiency in Building Structures: A Review of Current Developments and Future Outlooks Based on BIM Capabilities. *Renew. Sustain. Energy Rev.* **2017**, *67*, 811–825. [CrossRef]

56. Llatas, C.; Soust-Verdaguer, B.; Passer, A. Implementing Life Cycle Sustainability Assessment during Design Stages in Building Information Modelling: From Systematic Literature Review to a Methodological Approach. *Build. Environ.* **2020**, *182*, 107164. [CrossRef]

57. Cavalliere, C.; Habert, G.; Dell'Osso, G.R.; Hollberg, A. Continuous BIM-Based Assessment of Embodied Environmental Impacts throughout the Design Process. *J. Clean. Prod.* **2019**, *211*, 941–952. [CrossRef]

58. Houlihan Wiberg, A.; Georges, L.; Dokka, T.H.; Haase, M.; Time, B.; Lien, A.G.; Mellegård, S.; Maltha, M. A Net Zero Emission Concept Analysis of a Single-Family House. *Energy Build.* **2014**, *74*, 101–110. [CrossRef]

59. Rezaei, F.; Bulle, C.; Lesage, P. Integrating Building Information Modeling and Life Cycle Assessment in the Early and Detailed Building Design Stages. *Build. Environ.* **2019**, *153*, 158–167. [CrossRef]

60. Galiano-Garrigós, A.; García-Figueroa, A.; Rizo-Maestre, C.; González-Avilés, Á. Evaluation of BIM Energy Performance and CO2 Emissions Assessment Tools: A Case Study in Warm Weather. *Build. Res. Inf.* **2019**, *47*, 787–812. [CrossRef]

61. Abanda, H.; Oti, A.H. Integrating BIM and New Rules of Measurement for Embodied Energy and CO_2 Assessment. *J. Build. Eng.* **2017**, *12*, 288–305. [CrossRef]

62. Georges, L.; Haase, M.; Houlihan Wiberg, A.; Kristjansdottir, T.; Risholt, B. Life Cycle Emissions Analysis of Two NZEB Concepts. *Build. Res. Inf.* **2015**, *43*, 82–93. [CrossRef]

63. Ajayi, S.O.; Oyedele, L.O.; Ceranic, B.; Gallanagh, M.; Kadiri, K.O. Life Cycle Environmental Performance of Material Specification: A BIM-Enhanced Comparative Assessment. *Int. J. Sustain. Build. Technol. Urban Dev.* **2015**, *6*, 14–24. [CrossRef]

64. Basbagill, J.P.; Flager, F.; Lepech, M.; Fischer, M. Application of Life-Cycle Assessment to Early Stage Building Design for Reduced Embodied Environmental Impacts. *Build. Environ.* **2013**, *60*, 81–92. [CrossRef]

65. Bueno, C.; Pereira, L.M.; Fabricio, M.M. Life Cycle Assessment and Environmental-Based Choices at the Early Design Stages: An Application Using Building Information Modelling. *Archit. Eng. Des. Manag.* **2018**, *14*, 332–346. [CrossRef]

66. Antón, L.Á.; Díaz, J. Integration of Life Cycle Assessment in a BIM Environment. *Procedia Eng.* **2014**, *85*, 26–32. [CrossRef]

67. Brahme, R.; Mahdavi, A.; Lam, K.P.; Gupta, S. Complex Building Performance Analysis in Early Stages of Design: A Solution Based on Differential Modeling, Homology-Based Mapping, and Generative Design Agents. In Proceedings of the Seventh International IBPSA Conference, Rio de Janeiro, Brazil, 13–15 August 2001; Volume 2, pp. 661–668.

68. Di Bari, R.; Jorgji, O.; Horn, R.; Gantner, J.; Ebertshäuser, S. Step-by-Step Implementation of BIM-LCA: A Case Study Analysis Associating Defined Construction Phases with Their Respective Environmental Impacts. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012105. [CrossRef]

69. AIA American Institute of Architects. *G202-2013 Building Information Modelling Protocol Form*; AIA: Washington, DC, USA, 2013.

70. Dupuis, M.; April, A.; Lesage, P.; Forgues, D. Method to Enable LCA Analysis through Each Level of Development of a BIM Model. *Procedia Eng.* **2017**, *196*, 857–863. [CrossRef]

71. Lee, S.; Tae, S.; Roh, S.; Kim, T. Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact. *Sustainability* **2015**, *7*, 16498–16512. [CrossRef]

72. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of Environmental Potentials in Building Construction at Early Design Stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]

73. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Integration of LCA and LCC Analysis within a BIM-Based Environment. *Autom. Constr.* **2019**, *103*, 127–149. [CrossRef]

74. Nilsen, M.; Bohne, R.A. Evaluation of BIM Based LCA in Early Design Phase (Low LOD) of Buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012119. [CrossRef]

75. Lu, K.; Jiang, X.; Tam, V.W.Y.; Li, M.; Wang, H.; Xia, B.; Chen, Q. Development of a Carbon Emissions Analysis Framework Using Building Information Modeling and Life Cycle Assessment for the Construction of Hospital Projects. *Sustainability* **2019**, *11*, 6274. [CrossRef]

76. Lu, K.; Wang, H. Estimation of Building's Life Cycle Carbon Emissions Based on Life Cycle Assessment and Building Information Modeling: A Case Study of a Hospital Building in China. *J. Geosci. Environ. Prot.* **2019**, *7*, 147–165. [CrossRef]

77. Gomes, V.; Barros, N.N.; Ruschel, R.C. Building Information Modelling for Whole-Building LCA: BIM4LCA. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *290*, 012044. [CrossRef]

78. Sharif, S.A.; Hammad, A. Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment. *J. Build. Eng.* **2019**, *21*, 429–445. [CrossRef]

79. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Informetric Analysis and Review of Literature on the Role of BIM in Sustainable Construction. *Autom. Constr.* **2019**, *103*, 221–234. [CrossRef]

80. Japanese Ministry of Land Infrastructure and Transport. *Building Materials Environmental Information DB Final Report*; Japanese Ministry of Land Infrastructure and Transport: Tokyo, Japan, 2015.

81. BIM Forum. LOD Specification 2018 Part I: For Building Information Models and Data. 2018. Available online: https://bimforum.org/lod (accessed on 25 May 2020).

82. Stevanovic, M.; Allacker, K.; Vermeulen, S. Development of an Approach to Assess the Life Cycle Environmental Impacts and Costs of General Hospitals through the Analysis of a Belgian Case. *Sustainability* **2019**, *11*, 856. [CrossRef]

83. Goedkoop, M.; De Schryver, A.; Oele, M.; Durksz, S.; de Roest, D. *Introduction to LCA with SimaPro 7*; PRé Consultants: Amersfoort, The Netherlands, 2008.

84. SimaPro. Available online: www.simapro.com (accessed on 25 May 2020).

85. Suh, S.; Lippiatt, B.C. Framework for Hybrid Life Cycle Inventory Databases: A Case Study on the Building for Environmental and Economic Sustainability (BEES) Database. *Int. J. Life Cycle Assess.* **2012**, *17*, 604–612. [CrossRef]

86. Athena Impact Estimator. *Athena Impact Estimator for Buildings V 4.2 Software and Database Overview*; Retrieved; Athena Impact Estimator: Ottawa, ON, Canada, 2017; Volume 10.

87. Najjar, M.K.; Figueiredo, K.; Evangelista, A.C.J.; Hammad, A.W.A.; Tam, V.W.Y.; Haddad, A. Life Cycle Assessment Methodology Integrated with BIM as a Decision-Making Tool at Early-Stages of Building Design. *Int. J. Constr. Manag.* **2019**, 1–15. [CrossRef]

88. Athena Sustainable Materials Institute; Hershfield, M. *Maintenance, Repair and Replacement Effects for Building Envelope Materials*; ATHENA Sustainable Materials Institute: Reading, PA, USA, 2002.

89. Shin, Y.; Cho, K. BIM Application to Select Appropriate Design Alternative with Consideration of LCA and LCCA. *Math. Probl. Eng.* **2015**, *2015*, 281640. [CrossRef]

90. Basbagill, J.P.; Flager, F.; Lepech, M. Measuring the Impact of Dynamic Life Cycle Performance Feedback on Conceptual Building Design. *J. Clean. Prod.* **2017**, *164*, 726–735. [CrossRef]

91. Hildebrand, L. *Strategic Investment of Embodied Energy during the Architectural Planning Process*; TU Delft: Delft, The Netherlands, 2014.

92. ISO International Organization for Standardization. *ISO 14044:2006—Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; ISO: Geneva, Switzerland, 2006.

93. Eleftheriadis, S.; Duffour, P.; Mumovic, D. BIM-Embedded Life Cycle Carbon Assessment of RC Buildings Using Optimised Structural Design Alternatives. *Energy Build.* **2018**, *173*, 587–600. [CrossRef]

94. Passer, A.; Kreiner, H.; Maydl, P. Assessment of the Environmental Performance of Buildings: A Critical Evaluation of the Influence of Technical Building Equipment on Residential Buildings. *Int. J. Life Cycle Assess.* **2012**, *17*, 1116–1130. [CrossRef]

95. Moncaster, A.M.; Pomponi, F.; Symons, K.E.; Guthrie, P.M. Why Method Matters: Temporal, Spatial and Physical Variations in LCA and Their Impact on Choice of Structural System. *Energy Build.* **2018**, *173*, 389–398. [CrossRef]

96. Peng, C. Calculation of a Building's Life Cycle Carbon Emissions Based on Ecotect and Building Information Modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [CrossRef]

97. Marzouk, M.; Abdelkader, E.M.; Al-Gahtani, K. Building Information Modeling-Based Model for Calculating Direct and Indirect Emissions in Construction Projects. *J. Clean. Prod.* **2017**, *152*, 351–363. [CrossRef]

98. Wang, E.; Shen, Z.; Berryman, C. A Building LCA Case Study Using Autodesk Ecotect and BIM Model. In Proceedings of the 47th ASC Annual International Conference, Omaha, NE, USA, 6–9 April 2011.

99. Shadram, F.; Mukkavaara, J. An Integrated BIM-Based Framework for the Optimization of the Trade-off between Embodied and Operational Energy. *Energy Build.* **2018**, *158*, 1189–1205. [CrossRef]

100. Najjar, M.; Figueiredo, K.; Palumbo, M.; Haddad, A. 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.* **2017**, *14*, 115–126. [CrossRef]

101. Tsalidis, C.; Christodoulakis, D.; Maritsas, D. Athena: A Software Measurement and Metrics Environment. *J. Softw. Maint. Res. Pract.* **1992**, *4*, 61–81. [CrossRef]

102. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part I): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]

103. Moncaster, A.M.; Song, J.-Y. A Comparative Review of Existing Data and Methodologies for Calculating Embodied Energy and Carbon of Buildings. *Int. J. Sustain. Build. Technol. Urban Dev.* **2012**, *3*, 26–36. [CrossRef]

104. Takano, A.; Winter, S.; Hughes, M.; Linkosalmi, L. Comparison of Life Cycle Assessment Databases: A Case Study on Building Assessment. *Build. Environ.* **2014**, *79*, 20–30. [CrossRef]

105. Hammond, G.; Jones, C.; Lowrie, F.; Tse, P. *Inventory of Carbon & Energy: ICE v2.0*; University of Bath, Ed.; Sustainable Energy Research Team, Department of Mechanical Engineering: Bath, UK, 2011; Volume 5.

106. Iddon, C.R.; Firth, S.K. Embodied and Operational Energy for New-Build Housing: A Case Study of Construction Methods in the UK. *Energy Build.* **2013**, *67*, 479–488. [CrossRef]

107. Shafiq, N.; Nurrudin, M.F.; Gardezi, S.S.S.; Kamaruzzaman, A.B. Carbon Footprint Assessment of a Typical Low Rise Office Building in Malaysia Using Building Information Modelling (BIM). *Int. J. Sustain. Build. Technol. Urban Dev.* **2015**, *6*, 157–172. [CrossRef]

108. Nizam, R.S.; Zhang, C.; Tian, L. A BIM Based Tool for Assessing Embodied Energy for Buildings. *Energy Build.* **2018**, *170*, 1–14. [CrossRef]

109. Kim, K.P. Chapter 13—BIM-Enabled Sustainable Housing Refurbishment—LCA Case Study. In *Sustainable Construction Technologies*; Tam, V.W.Y., Le, K.N., Eds.; Butterworth-Heinemann: Oxford, UK, 2019; pp. 349–394. [CrossRef]

110. Hasik, V.; Escott, E.; Bates, R.; Carlisle, S.; Faircloth, B.; Bilec, M.M. Comparative Whole-Building Life Cycle Assessment of Renovation and New Construction. *Build. Environ.* **2019**, *161*, 106218. [CrossRef]

111. Najjar, M.; Haddad, A.; Figueiredo, K. Daylight Assessment and Energy Consumption Analysis at an Early Stage of Designing Residential Buildings Integrating BIM and LCA. In *Innovative Production and Construction*; World Scientific: Singapore, 2019; pp. 79–98. [CrossRef]

112. Bare, J. TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. *Clean Technol. Environ. Policy* **2011**, *13*, 687–696. [CrossRef]

113. Jalaei, F.; Zoghi, M.; Khoshand, A. Life Cycle Environmental Impact Assessment to Manage and Optimize Construction Waste Using Building Information Modeling (BIM). *Int. J. Constr. Manag.* **2019**, 1–18. [CrossRef]

114. Deutsche Gesellschaft Für Nachhaltiges Bauen DGNB. Kritienkatalog Gebäude Neubau—Ökologische Qualität. 2018. Available online: https://www.dgnb-system.de/de/gebaeude/neubau/kriterien/index.php/ (accessed on 25 May 2020).

115. Martins, C.; Dias, A.M.P.G.; Costa, R.; Santos, P. Environmentally Friendly High Performance Timber-Concrete Panel. *Constr. Build. Mater.* **2016**, *102*, 1060–1069. [CrossRef]

116. Hollberg, A.; Genova, G.; Habert, G. Evaluation of BIM-Based LCA Results for Building Design. *Autom. Constr.* **2020**, *109*, 102972. [CrossRef]

117. Jrade, A.; Abdulla, R. Integrating Building Information Modeling and Life Cycle Assessment Tools to Design Sustainable Buildings. In Proceedings of the 29th International Conference CIB W78, Beirut, Lebanon, 17–19 October 2012; pp. 173–182.

118. Shrivastava, S.; Chini, A. Using Building Information Modeling to Assess the Initial Embodied Energy of a Building. *Int. J. Constr. Manag.* **2012**, *12*, 51–63. [CrossRef]

119. Jrade, A.; Jalaei, F. Integrating Building Information Modelling with Sustainability to Design Building Projects at the Conceptual Stage. *Build. Simul.* **2013**, *6*, 429–444. [CrossRef]

120. Abanda, F.H.; Nkeng, G.E.; Tah, J.H.M.; Ohandja, E.N.F.; Manjia, M.B. Embodied Energy and CO_2 Analyses of Mud-Brick and Cement-Block Houses. *AIMS Energy* **2014**, *2*, 18–40. [CrossRef]

121. Jalaei, F.; Jrade, A. An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess Sustainable Building Projects. *J. Constr. Eng.* **2014**, *2014*, 672896. [CrossRef]

122. Shadram, F.; Johansson, T.D.; Lu, W.; Schade, J.; Olofsson, T. An Integrated BIM-Based Framework for Minimizing Embodied Energy during Building Design. *Energy Build.* **2016**, *128*, 592–604. [CrossRef]