PAPER • OPEN ACCESS

The challenge of integrating Life Cycle Assessment in the building design process – a systematic literature review of BIM-LCA workflows

To cite this article: Tajda Potrč Obrecht *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 032024

View the article online for updates and enhancements.

The challenge of integrating Life Cycle Assessment in the building design process – a systematic literature review of BIM-LCA workflows

Tajda Potrč Obrecht [1,*]**, Martin Röck** [2]**, Endrit Hoxha** [2] **and Alexander Passer**[2]

[1] Department of Building Physics, Slovenian National Building and Civil Engineering Institute, Ljubljana, 1000, Slovenia
[2]Working Group Sustainable Construction, Institute of Technology and Testing of Construction Materials, TU Graz, 8010 Graz

Corresponding author: tajda.obrecht@zag.si

Abstract. To foster sustainable development in construction sectors, environmental impacts need to be reduced dramatically. The Life Cycle Assessment (LCA) technique is the most firmly established methodology used to quantify these environmental impacts and, therefore, has been applied with increasing frequency to assess the environmental performance of buildings. To effectively improve a building's environmental performance, an integration of LCA in the design process is required. This can be achieved by coupling LCA with digital design tools, e.g., Building Information Modelling (BIM). To identify the pro and cons of streamlining the integration of LCA and BIM, a comprehensive Systematic Literature Review (SLR) was performed. We identified more than 50 relevant BIM-LCA case studies and analyzed the applied BIM-LCA workflows in detail. In most of the studies reviewed, the LCA has been applied in an early design stage. The authors primarily used LCA tools and manual or semi-automatic methods to exchange data between BIM models. In most cases, contemporary BIM-LCA workflows utilized conventional spreadsheets (e.g., Excel worksheets). However, the results of the analysis show that an automated link between LCA and BIM can be achieved if certain challenges are overcome. By automating exchange of information between BIM and LCA tools and improving the reliability of this process, the LCA application can be streamlined in design practice and, hence, the necessary improvements of the environmental performance of buildings can be supported.

1. Introduction
The construction and maintenance of buildings have a significant influence on total amount of resources consumed and emissions released into the environment. To sustainably develop the building stock, a multi-disciplinary approach must be adopted that covers a number of aspects, such as energy efficiency, the intelligent use of materials, including water, the reuse and recycling of materials and emissions control throughout the whole life cycle of the building [1–3].

The Life Cycle Assessment (LCA) technique is a method used to systematically analyze the environmental performance of products over their entire life cycle, encompassing the production (including the raw material extraction), use and end-of-life phases [1,4,5]. The method involves a process, whereby the material and energy flows are evaluated. Subsequently, the global and/or regional impacts (e.g., global warming potential, acidification) are calculated based on the input and

output flows determined. In recent times, this method has been widely applied in the construction sector, as well as other sectors, for the assessment of the environmental flows of building products and buildings [6]. In order to perform an LCA study, detailed data must be gathered about the building, including information about the building materials used, the building process, the use phase of the building and the predicted end-of-life scenarios. According to practitioners, carrying out an LCA its complex and time-consuming due to the amount of data needed for the assessment. Building Information Modelling (BIM) tools can be used to integrate various information into the building model; therefore, these are helpful in that they reduce the efforts and time required when performing an LCA [7].

Researchers take different approaches when integrating BIM and LCA tools. Several researchers have tried to classify the integration approaches. Nizam et al. [8] classified the studies into four groups. The first group contained studies that address projects-based outcomes but lack a general framework that could be extended to other projects. The second group contained studies that used BIM merely as a quantity take-off toll and exported these quantities into other tools. The third group contained studies that ignored the construction phase during the estimation of embodied energy and were limited to the cradle-to-site phase. The fourth group contained studies that provided rigorous and complex methods that might not seem practical for adoption in further studies.

Soust-Verdaguer et al. [7] classified the integration of BIM and LCA into three groups. The first group described the case in which the BIM tool were used during the Life Cycle Inventory (LCI) stage to generate the Bill of Quantities (BoQ). The second group included the studies in which the environmental information was integrated into BIM software. The third group encompassed studies in which BIM and LCA tools were combined in an automatic process.

The most comprehensive classification was proposed by Wastiels and Decuypere [9]. They divided the possible BIM-LCA integration methods into five groups. The first method involved the integration of the tool by exporting the BoQ from the BIM environment into other tools. The second approach taken was the import of surfaces using the Industry Foundation Classes (IFC) data models, which were then aligned by an LCA practitioner to fit predefined LCA profiles. The third method involved an approach in which information from a BIM tool was further processed in a BIM viewer tool and then transferred into dedicated LCA software. The fourth approach required the use of specially developed plug-ins that enabled the LCA analysis to be performed using the BIM tool. Examples of such plug-ins include Tally, One Click LCA and CAALA. The fifth method involved an approach in which the LCA information was included in BIM objects that were used in the BIM model, instead of being attributed to the building materials at a later stage and using a separate tool. The five different methods of integration described by Wastiels and Decuypere are illustrated in Fig 1.
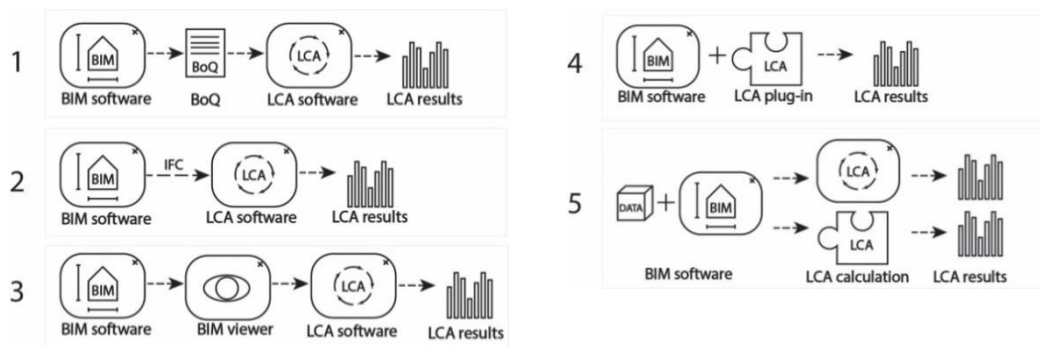

Figure 1. The classification of BIM-LCA integration adopted after Wastiels and Decuypere [9]

2. Systematic literature review

In order to identify BIM-LCA approaches in the current scientific literature, we performed a Systematic Literature Review (SLR). SLR is a systematic, structured procedure used to identify relevant sources and obtain a comprehensive overview of the published literature, in order to answer a specific research question. Based on the research question, relevant keywords are identified, and the search is performed in previously defined databases. In our case, the keywords chosen were "life cycle assessment" OR "LCA" AND "building information modelling" OR "BIM," and the chosen databases were Science Direct, Scopus, Web of Science and Springer. The results were limited to papers published in the English language. The search criteria were also defined to exclude gray literature (e.g., conference proceedings, master's and/or doctoral theses, books/chapters) and no time boundaries were set.

The results obtained as a result of the literature review were obtained in three phases: a search was conducted (1) based on the title, (2) based on the abstract and (3) after reading the full paper. The data used for the analysis presented in this study were extracted from full papers that were identified as relevant. We also collected additional relevant literature by applying the "snowball" approach, checking the references cited in the paper initially identified as relevant and then interviewing selected experts in this field. The entire process is presented in Fig 2.
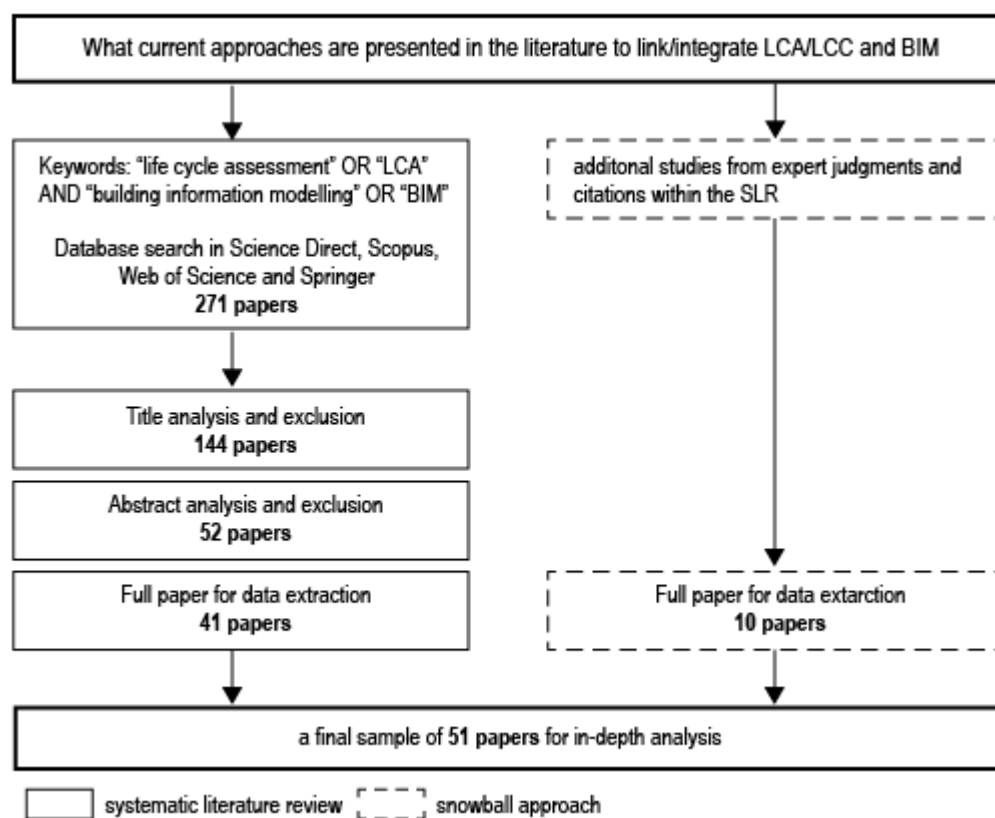

Figure 2. The process used to collect relevant papers

Fifty-one papers were identified as relevant [7,8,17–26,9,27–36,10,37–46,11,47–56,12–16]. Using a structured table, we organized information about the BIM-LCA integration workflows, the tools used for BIM, LCA and energy calculation, the data granularity, the LCA methodology (e.g., scope of the study, databases, indicators standards and life cycle stages) and metadata. In order to compare the different approaches taken in the literature, we classified the existing studies that were identified as relevant using the method cited in [9].

3. Results and discussion

The most common link between BIM and LCA tools is the exchange of integration via BoQ, as shown in Fig 3. The data from the BIM model is exported as a schedule which contains information about the materials used and their quantities. This data is than imported into an LCA tool manually or automatically. If the import of data into the LCA tool is done manually, which is the most adopted approach, this procedure is very time consuming and bares the risk of errors. There are proposals how to automate the exchange process [12,13,51,53,55,57–63,18,19,22,40,41,43,44,49]. Two studies established a fully automatic exchange of data between BIM and LCA. Abanda et al. combined a BIM tool with the –NET framework Environment to import the information to the Excel tool [64]. Kumanayake and Luo [65] established an automatic information exchange from BIM to Excel by combining Visual Studio C# Object Oriented Programming language in the .NET framework integrated with a Structured Query Language containing information from the Bath ICE database. On the other hand, several studies tried to facilitate the integration of BIM at LCA to some degree. We have identified two general approaches. The first approach tries to integrate various additional information into the BIM model [8,17,23,28,66,67]. This can be done by adding additional parameters directly to BIM model [17,66] or by using tools that enable the import of this information like Dynamo or similar [23,28,67]. The second approach combines the studies where extraction of data in BIM and its import to LCA tools is semi-automated [8,29,47,68].

The second most adopted approach of integration was the use of the LCA plug-in tools. The plug-in enable fast results but have the limitation that in most of the cases they use generic data. Therefore they are often used in early design stages to identify the most important impacts. Most of the identified studied, that used the plug-in approach for the calculation, were using the Tally tool [15,38,69,70]. Tally is a Revit plug-in and enables the LCA analysis by the use of the Gabi database. If the impacts of the operational phase are also assessed, Tally can be combined with Green Build Designer, which is also a Revit plug-in. On the other hand, Hollberg and Ruth used the eLCA tool as a plug-in and coupled it with Grashopper 3D tool within Rhino to optimize the design [71]. Lee et al. developed an own plug-in for Revit that is able to generate results for 6 impact categories [72]. Jalalei et al. [73] developed a plug in that serves as a link between BIM, LCA, energy analysis and lightning simulation.

We identified only one study that used the IFC format to facilitate the data exchange between BIM and LCA tools. Two studies also coupled information relevant for the LCA in the BIM environment. The calculation and analysis can either be performed with a plug-in or can be exported to dedicated LCA software.
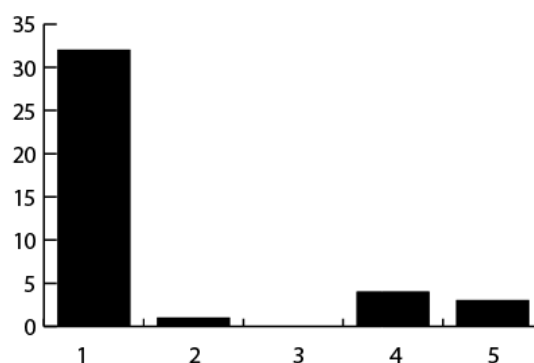

Figure 3. The workflow classification of the relevant papers

Furthermore, we divided the studies based on the degree of automatization of the BIM-LCA integration. In some cases, the integration was performed manually. This means that the data were transferred by copying and pasting them from one file to another. In most of the cases, LCA practitioners needed to assign the data appropriately. The second approach taken was a semi-automated integration. In this approach, the data were exchanged and filled into the file automatically, but some level of user interaction was required for the export and import steps. The third approach taken was the so-called "one click" integration method. In this approach, the data exchange process was fully automated. The results are presented in Fig 4.
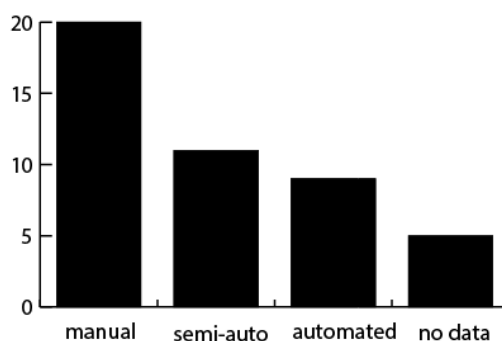

Figure 4. The link between BIM and LCA

Most of the data exchange performed between BIM and LCA tools was performed manually in the identified studies. Most studies used a BIM tool to generate a BoQ. The information collected in the BoQ was then used in a separate tool, applied to perform the LCA. This approach is highly time consuming, errors can occur. The semi-automated approach was also commonly used in the identified studies. Part of the information was exported from BIM tools into LCA tools, but this information then needed to be further processed. In most of the cases, supplementary information was required that was not available within the BIM environment. The automated approach was most frequently applied when LCA plug-in tools were used, but we also identified some examples where the authors developed scripts by integrating different tools. The use of a plug-in generates results rapidly, but these tools were recognized to have certain limitations. For example, sometimes they could only be applied to generic data or no possibility was available to adjust the scenarios in the LCA study. The latter approach required the user to have certain programming skills. The developed scripts enabled users to couple different tools, supporting the development of new LCA tools or plug-ins.

We evaluated the reproducibility of the process used to integrate BIM and LCA. We divided the studies into four groups, namely, into groups of studies in which the reproducibility of the integration was "high", "medium", "low", or "not reproducible." The studies with a high degree reproducibility were identified as studies that provided exact procedures, clear information about the tools and a large amount of supplementary data for the integration. The process of integration was described completely clearly in these papers. The studies that were classified with a medium level of reproducibility were the studies in which basic information about the tools and integration workflows were given. The studies identified as having a low level of reproducibility provided basic information about the tools that were used but did not describe the workflow. The studies that were classified as not reproducible are those in which the information about certain tools or the workflow is missing, but the data were obtained from a BIM model.

In most of the studied papers, the studies offered detailed insights into the process used to facilitate data exchange between BIM and LCA tools and into the tools and information that were used in this process. It appeared as though certain cases were completely reproducible because all data required were provided in the paper. In some cases, certain pertinent information seemed to be missing, but the process used to integrate the BIM and LCA tools was clear, so these studies were classified as having

a medium level of reproducibility. Some studies only list the tools used, which provided us with basic information about the integration but not enough to reproduce the workflow. In some studies, the authors only stated that the data for the LCA study were obtained from BIM; no further explanations were offered. These results are presented in Fig 5.
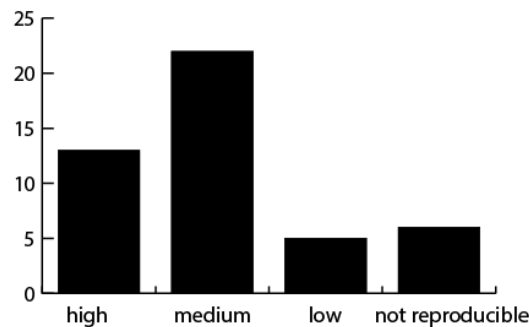

Figure 5. The reproducibility of the workflows

4. Conclusions

By conducting a thorough SLR and taking the "snowball" approach, we revealed that methods used to integrate LCA and BIM tools are still at early stages of development. In the majority of studies identified as relevant, the researchers were still using the BIM to obtain information about the quantity of the materials (i.e., BoQ), although BIM is a powerful environment and is able to provide much more information for LCA. Currently, analyses of the majority of applied workflows show that data are exchanged via spreadsheets and that the data extraction is performed manually. The automatized integration of BIM and LCA was most often achieved by the use of LCA plug-ins or by integrating tools via a script.

The aim of this study was to provide a critical overview of the BIM-LCA integration workflows and, hereby, enhance the further development of the integration process used by LCA practitioners and software developers. However, more reliably integrating BIM and LCA would foster the optimization of the environmental performance of the building during the design process, supporting the improvement of the quality of future building stock.

References

[1]   Ramesh T, Prakash R and Shukla K K 2010 Life cycle energy analysis of buildings: An overview *Energy Build.* **42** 1592–600
[2]   Röck M, Ruschi Mendes Saade M, Balouktsi M, Nygaard F, Birgisdottir H, Frischknecht R, Habert G and Lützkendorf T 2019 Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation *Appl. Energy* **258** 114107
[3]   Wohlin C 2014 Guidelines for snowballing in systematic literature studies and a replication in software engineering *ACM Int. Conf. Proceeding Ser.*
[4]   Cabeza L F, Rincón L, Vilariño V, Pérez G and Castell A 2014 Life cycle assessment (LCA)

and life cycle energy analysis (LCEA) of buildings and the building sector: A review *Renew. Sustain. Energy Rev.* **29** 394–416

[5]   Buyle M, Braet J and Audenaert A 2013 Life cycle assessment in the construction sector: A review *Renew. Sustain. Energy Rev.* **26** 379–88

[6]   Passer A, Lasvaux S, Allacker K, De Lathauwer D, Spirinckx C, Wittstock B, Kellenberger D, Gschösser F, Wall J and Wallbaum H 2015 Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries *Int. J. Life Cycle Assess.* **20** 1199–212

[7]   Soust-Verdaguer B, Llatas C and García-Martínez A 2017 Critical review of bim-based LCA method to buildings *Energy Build.* **136** 110–20

[8]   Nizam R S, Zhang C and Tian L 2018 A BIM based tool for assessing embodied energy for buildings *Energy Build.* **170** 1–14

[9]   Wastiels L and Decuypere R 2019 Identification and comparison of LCA-BIM integration strategies *IOP Conf. Ser. Earth Environ. Sci.* **323**

[10]   Anon 2011 Copyright ASCE 2011 Computing in Civil Engineering 2011 Copyright ASCE 2011 Computing in Civil Engineering 2011 194–201

[11]   Abanda F H, Oti A H and Tah J H M 2017 Integrating BIM and new rules of measurement for embodied energy and CO2 assessment *J. Build. Eng.* **12** 288–305

[12]   Ajayi S O, Oyedele L O, Ceranic B, Gallanagh M and Kadiri K O 2015 Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment *Int. J. Sustain. Build. Technol. Urban Dev.* **6** 14–24

[13]   Alireza A F F, Rashidi T H, Akbarnezhad A and Waller S T 2017 BIM-enabled sustainability assessment of material supply decisions *Eng. Constr. Archit. Manag.* **24** 668–95

[14]   Basbagill J, Flager F, Lepech M and Fischer M 2013 Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts *Build. Environ.* **60** 81–92

[15]   Bueno C and Fabricio M M 2018 Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in *Autom. Constr.* **90** 188–200

[16]   Bueno C, Pereira L M and Fabricio M M 2018 Life cycle assessment and environmental-based choices at the early design stages: an application using building information modelling *Archit. Eng. Des. Manag.* **14** 332–46

[17]   Cavalliere C, Dell'Osso G R, Pierucci A and Iannone F 2018 Life cycle assessment data structure for building information modelling *J. Clean. Prod.* **199** 193–204

[18]   Cavalliere C, Habert G, Dell'Osso G R and Hollberg A 2019 Continuous BIM-based assessment of embodied environmental impacts throughout the design process *J. Clean. Prod.* **211** 941–52

[19]   Eleftheriadis S, Duffour P and Mumovic D 2018 BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives *Energy Build.* **173** 587–600

[20]   Gantner J, Lenz K, Horn R, von Both P and Ebertshäuser S 2018 Ökobau.dat 3.0-Quo vadis? *Buildings* **8** 1–33

[21]   Gardezi S S S, Shafiq N, Zawawi N A W A, Khamidi M F and Farhan S A 2016 A multivariable regression tool for embodied carbon footprint prediction in housing habitat *Habitat Int.* **53** 292–300

[22]   Georges L, Haase M, Houlihan Wiberg A, Kristjansdottir T and Risholt B 2015 Life cycle emissions analysis of two nZEB concepts *Build. Res. Inf.* **43** 82–93

[23]   Hollberg A, Genova G and Habert G 2020 Evaluation of BIM-based LCA results for building design *Autom. Constr.* **109** 102972

[24]   Hollberg A and Ruth J 2016 LCA in architectural design—a parametric approach *Int. J. Life Cycle Assess.* **21** 943–60

[25]   Houlihan Wiberg A, Georges L, Dokka T H, Haase M, Time B, Lien A G, Mellegård S and Maltha M 2014 A net zero emission concept analysis of a single-family house *Energy Build.* **74**

        101–10

[26]   Iddon C R and Firth S K 2013 Embodied and operational energy for new-build housing: A case study of construction methods in the UK *Energy Build.* **67** 479–88

[27]   Jalaei F and Jrade A 2014 Integrating Building Information Modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings *J. Inf. Technol. Constr.* **19** 494–519

[28]   Jalaei F and Jrade A 2014 An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess Sustainable Building Projects *J. Constr. Eng.* **2014** 1–21

[29]   Jiang S and Lei W 2014 The application of BIM in green building energy saving: Take Helsinki Music Center as an example *Adv. Mater. Res.* **935** 3–7

[30]   Kulahcioglu T, Dang J and Toklu C 2012 A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole process of construction *HVAC R Res.* **18** 283–93

[31]   Kumanayake R and Luo H 2017 Development of an Automated Tool for Buildings' Sustainability Assessment in Early Design Stage *Procedia Eng.* **196** 903–10

[32]   Kylili A, Fokaides P A, Vaiciunas J and Seduikyte L 2016 Integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for sustainable constructions *J. Sustain. Archit. Civ. Eng.* **13**

[33]   Lee S, Tae S, Roh S and Kim T 2015 Green template for life cycle assessment of buildings based on building information modeling: Focus on embodied environmental impact *Sustain.* **7** 16498–512

[34]   Liu S, Meng X and Tam C 2015 Building information modeling based building design optimization for sustainability *Energy Build.* **105** 139–53

[35]   Lu Y, Le V H and Song X 2017 Beyond Boundaries: A Global Use of Life Cycle Inventories for Construction Materials *J. Clean. Prod.* **156** 876–87

[36]   Marzouk M, Abdelkader E M and Al-Gahtani K 2017 Building information modeling-based model for calculating direct and indirect emissions in construction projects *J. Clean. Prod.* **152** 351–63

[37]   Meex E, Hollberg A, Knapen E, Hildebrand L and Verbeeck G 2018 Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design *Build. Environ.* **133** 228–36

[38]   Najjar M, Figueiredo K, Hammad A W A and Haddad A 2019 Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings *Appl. Energy* **250** 1366–82

[39]   Najjar M, Figueiredo K, Palumbo M and Haddad A 2017 Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building *J. Build. Eng.* **14** 115–26

[40]   Oh M S and Na S 2017 Building information modelling (BIM) based CO2emissions assessment in the early design stage *Int. J. Civ. Eng. Technol.* **8** 1411–25

[41]   Panteli C, Kylili A, Stasiuliene L, Seduikyte L and Fokaides P A 2018 A framework for building overhang design using Building Information Modeling and Life Cycle Assessment *J. Build. Eng.* **20** 248–55

[42]   Peng C 2016 Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling *J. Clean. Prod.* **112** 453–65

[43]   Peng C and Wu X 2015 Case study of carbon emissions from a building's life cycle based on BIM and Ecotect *Adv. Mater. Sci. Eng.* **2015**

[44]   Rezaei F, Bulle C and Lesage P 2019 Integrating building information modeling and life cycle assessment in the early and detailed building design stages *Build. Environ.* **153** 158–67

[45]   Santos R, Costa A A, Silvestre J D and Pyl L 2019 Integration of LCA and LCC analysis within a BIM-based environment *Autom. Constr.* **103** 127–49

[46]   Santos R, Costa A A, Silvestre J D, Vandenbergh T and Pyl L 2019 BIM-based life cycle assessment and life cycle costing of an office building in Western Europe *Build. Environ.* **169**

106568

[47]   Shadram F, Johansson T D, Lu W, Schade J and Olofsson T 2016 An integrated BIM-based framework for minimizing embodied energy during building design *Energy Build.* **128** 592–604

[48]   Shadram F and Mukkavaara J 2018 An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy *Energy Build.* **158** 1189–205

[49]   Shafiq N, Nurrudin M F, Gardezi S S S and Kamaruzzaman A Bin 2015 Carbon footprint assessment of a typical low rise office building in Malaysia using building information modelling (BIM) *Int. J. Sustain. Build. Technol. Urban Dev.* **6** 157–72

[50]   Shin Y S and Cho K 2015 BIM application to select appropriate design alternative with consideration of LCA and LCCA *Math. Probl. Eng.* **2015**

[51]   Soust-Verdaguer B, Llatas C, García-Martínez A and Gómez De Cózar J C 2018 BIM-Based LCA Method to Analyze Envelope Alternatives of Single-Family Houses: Case Study in Uruguay *J. Archit. Eng.* **24** 1–15

[52]   Trigaux D, Oosterbosch B, De Troyer F and Allacker K 2017 A design tool to assess the heating energy demand and the associated financial and environmental impact in neighbourhoods *ENERGY Build.* **152** 516–23

[53]   Wang J, Wu H, Duan H, Zillante G, Zuo J and Yuan H 2016 Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study *J. Clean. Prod.* **172** 3154–66

[54]   Xu J, Shi Y, Xie Y and Zhao S 2019 A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction *J. Clean. Prod.* **229** 308–24

[55]   Yang X, Hu M, Wu J and Zhao B 2018 Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China *J. Clean. Prod.* **183** 729–43

[56]   Yung P and Wang X 2014 A 6D CAD model for the automatic assessment of building sustainability *Int. J. Adv. Robot. Syst.* **11** 1–8

[57]   Liu S, Meng X and Tam C 2015 Building information modeling based building design optimization for sustainability *Energy Build.* **105** 139–53

[58]   Jrade A and Jalaei F 2013 Integrating building information modelling with sustainability to design building projects at the conceptual stage *Build. Simul.* **6** 429–44

[59]   Basbagill J, Flager F, Lepech M and Fischer M 2013 Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts *Build. Environ.* **60** 81–92

[60]   Peng C 2016 Calculation of a building ' s life cycle carbon emissions based on Ecotect and building information modeling *J. Clean. Prod.* **112** 453–65

[61]   Feng H, Liyanage D R, Karunathilake H, Sadiq R and Hewage K 2020 BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia *J. Clean. Prod.* **250** 119543

[62]   Lu K, Jiang X, Tam V W Y, Li M, Wang H, Xia B and Chen Q 2019 Development of a carbon emissions analysis framework using building information modeling and life cycle assessment for the construction of hospital projects *Sustain.* **11** 1–18

[63]   Sartori T and Calmon J L 2019 Analysis of the impacts of retrofit actions on the life cycle energy consumption of typical neighbourhood dwellings *J. Build. Eng.* **21** 158–72

[64]   Abanda F H, Oti A H and Tah J H M 2017 Integrating {BIM} and new rules of measurement for embodied energy and {CO2} assessment *J. Build. Eng.* **12** 288–305

[65]   Kumanayake R and Luo H 2017 Development of an Automated Tool for Buildings' Sustainability Assessment in Early Design Stage *Procedia Eng.* **196** 903–10

[66]   Bueno C, Pereira L M and Fabricio M M 2018 Life cycle assessment and environmental-based choices at the early design stages: an application using building information modelling *Archit.*

Eng. Des. Manag. **14** 332–46

[67] Crippa J, Boeing L C, Caparelli A P A, da Costa M do R de M M, Scheer S, Araujo A M F and Bem D 2018 A BIM–LCA integration technique to embodied carbon estimation applied on wall systems in Brazil *Built Environ. Proj. Asset Manag.* **8** 491–503

[68] Marzouk M, Azab S and Metawie M 2016 Framework for sustainable low-income housing projects using building information modeling *J. Environ. Informatics* **28** 25–38

[69] Najjar M, Figueiredo K, Palumbo M and Haddad A 2017 Integration of {BIM} and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building *J. Build. Eng.* **14** 115–26

[70] Raposo C, Rodrigues F and Rodrigues H 2019 BIM-based LCA assessment of seismic strengthening solutions for reinforced concrete precast industrial buildings *Innov. Infrastruct. Solut.* **4** 1–10

[71] Hollberg A and Ruth J 2016 LCA in architectural design—a parametric approach *Int. J. Life Cycle Assess.* **21** 943–60

[72] Lee S, Tae S, Roh S and Kim T 2015 Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact *SUSTAINABILITY* **7** 16498–512

[73] Jalaei F, Zoghi M and Khoshand A 2019 Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM) *Int. J. Constr. Manag.* **0** 1–18