Canadian Journal of Civil Engineering

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Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2020-0284.R3
Manuscript Type:	Review
Date Submitted by the Author:	16-Mar-2021
Complete List of Authors:	Feng, Haibo; The University of British Columbia Okanagan, Civil Engineering Hewage, Kasun; University of British Columbia Sadiq, Rehan; University of British Columbia Okanagan, School of Engineering
Keyword:	Environmental product declaration, whole building life cycle assessment, Building Information Modelling, Building LCA challenges, LEED
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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Exploring the current challenges and emerging approaches in whole building life cycle assessment

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Abstract

The environmental impacts of building stock has received significant attention as buildings release one third of total greenhouse gas emissions. Whole-building life cycle assessment (WBLCA) has become a trend to address this limitation by ensuring best environmental performance of a building. However, the current WBLCA development faces many challenges which makes it hard to create reliable and comparable results.

The study aims to conduct a critical literature review to summarize the current challenges on WBLCA applications, and the emerging approaches that might address these challenges. Three main challenges are listed: variances on goal and scope definition, building structure complexity, and varieties on LCA database and methods. Emerging approaches are also presented to address

these challenges including integration of BIM into WBLCA and EPD applications in impact assessments. Findings of this study could support researchers and decision makers with the most popular approaches to conduct WBLCA and achieve reliable outputs.

Keywords:

Whole building LCA, Environmental product declaration, Building information modeling, Building LCA challenges, LEED

1 Introduction

The world is currently facing major environmental problems associated with climate change, such as more frequent extreme heat events, rising sea levels, and changes to precipitation patterns. The built environment have a substantial impact on the national environment due to the emissions attributed to embodied and operational energy use (U.S. Energy Information Agency 2013). In Canada, 33% of the energy use and 50% of the extracted natural resources are consumed by the construction and operation of commercial and residential buildings, which generates 25% of landfill waste and 35% of the country's greenhouse gas emissions (Innovation Science and Economic Development Canada 2015; Gelowitz and McArthur 2017). In the United States (US), buildings' embodied energy accounts for 10% of primary energy consumption, and the operation of buildings consumes about 40% of primary energy use (Cao et al. 2016; Schenck 2009). The upward trend in building energy demand will continue in the future due to the population growth, longer times spent inside buildings, and increasing demand for building services and comfort (Pérez-Lombard et al. 2008). Therefore, there is a pressing demand to reduce the environmental

impacts resulting from building construction and operation and improve the building performance (BPIE 2011).

In response to these challenges, ideas like green buildings, sustainable buildings, net-zero energy buildings have been widely adopted to improve building performance and reduce negative environmental impacts (Maslesa et al. 2018). Different types of building rating systems, such as Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) system, have been developed and adopted by countries to optimize building design and reduce energy consumption and emissions (Scofield 2013). For example, the concept of a net-zero building requires that the energy use of a building equals its energy generation (Wells et al. 2018), and the LEED rating system requires a building to achieve credits in six categories, such as location and site selection, water and energy efficiency, materials, and resources (Wu et al. 2016). The ultimate target is to develop high performance sustainable buildings from different aspects throughout their life cycle (Lewis et al. 2010). However, most of these sustainable building designs or green building rating systems only consider one or a few aspects of building performance. There is a need to develop a comprehensive method to evaluate the overall performance of a building by including its environmental impacts from cradle to grave.

The whole-building life cycle assessment (WBLCA) has become a popular method to analyze the overall performance of a building (Weißenberger et al. 2014; Minter 2014). Under this method, the environmental impacts of a building are considered throughout its life cycle phases to avoid passing the environmental load from one life cycle phase to another in the decision making process. Since not only the environmental impacts during the operational stage are considered, also the product stage, maintenance stage, and disposal stage are monitored in WBLCA. However, due to

the complexity of LCA development processes, the variability in building structures and material lifespans, and design quality, current studies usually face challenges when applying the LCA for a whole building (Khasreen et al. 2009; Abd Rashid and Yusoff 2015). With the importance of WBLCA in improving the building environmental performance, it is significant to understand the challenges of applying WBLCA method and the emerging approaches globally to improve the practicality of WBLCA method in building sector.

The objective of this study is to critically review the challenges of WBLCA development, and summarize the emerging approaches that could be used to address these challenges. Based on the limited information collected through literature reviews, the current status of WBLCA development is explored. The challenges are presented from three perspectives: the LCA development process, data variances, and building structures, and the associated approaches to address these challenges are summarized from the literature. In the end, the potential development opportunities of WBLCA are discussed. The compilation of information will be a useful reference for industry, practitioners and academics that are interested in applying WBLCA method to improve building performance.

2 Methodology

To achieve the research goal, the literature search was conducted through academic search engine web of science. The web of science is a multiple-database platform that includes Science Citation Index Expanded, Social Science Citation Index, etc., which provides a function of advanced search that allows users to customize their search preferences (Nwodo and Anumba 2019; Hong et al. 2020). In the first search, the advanced search function of Web of Science with the title “building life cycle assessment” was created to find all the related articles for this study. In the second search,

the same title “building life cycle assessment” with the topic “challenge” was created to narrow down the search boundary and focus on the WBLCA challenges. Table 1 lists the summary of search data for this study.

As shown in Figure 1, 427 papers were found with the first search. It is shown from the figure that the publications related to WBCLA are gradually increased in the last 20 years. In the second search, 40 paper were found that are related to the challenges of WBLCA. There are many articles from the Web of Science searches that only focus on LCA of specific building assemblies, materials or appliances. Therefore, a few criteria were applied to further narrow down the selected papers for in-depth review:

- Papers that only consider buildings as a functional unit for LCA were selected.
- Recent papers were more favored than the old papers.
- Peer reviewed articles are reviewed first over conference papers or reports.

Based on the above criteria, the selected papers from the two searches were evaluated by screening the titles and abstracts first. The papers that are more relevant to the objectives are selected for in-depth review. Based on the overview of the selected articles, the status and challenges of WBLCA were summarized and presented in the following section.

3 The challenges of WBCLA

Researchers and practitioners are applying WBLCA into their studies while they are pursuing more accurate building performance. However, the LCA development methodologies are different among these studies. The state-of-the-art literature review was conducted to understand the background and challenges of WBLCA.

3.1 Current status of WBLCA

WBLCA's are becoming increasingly popular in building construction-related decision making due to the comprehensive and systematic approach of LCA to environmental evaluation (Al-Ghamdi and Bilec 2017; Zabalza Bribián et al. 2009). Researchers have already commenced the application of WBLCA concept into studies. Kylili et al. (2017) conducted a WBLCA for a passive house located in Cyprus to assess the environmental performance. The parametric analysis has been performed to optimize the passive house design without increasing the total environmental emissions. Kristjansdottir et al. (2018) also conducted a LCA for eight different single-family houses in Norway, and the results demonstrated the relationships between the operational and the embodied environmental impacts. Atmaca and Atmaca (2015) analyzed the life cycle carbon and energy emissions of two residential buildings from the construction phase to the demolition phase. The results show that the emissions in the operation phase is much higher than the embodied emissions. Evangelista et al. (2018) presented a “cradle to grave” LCA analysis for four typical Brazilian residential buildings under eight impact categories. The building operational phase and material production phase contribute the largest portion to the total environmental impacts, and the foundation creates the greatest fraction of environmental impacts in terms of materials. Wang et al. (2018) also studied the life cycle energy performance of ten high-rise office buildings in Hong Kong. The results show that around 80% of the life cycle energy was consumed during the operational phase. The studies listed above show that WBLCA methods are widely used in the analysis of different type of buildings worldwide. The building performance in each life cycle stage were calculated and compared with different impact factors and building components.

WBLCA is also part of the overall assessment process in the existing green building certification schemes. Table 2 lists a few popular building rating schemes around the world that adopt WBLCA

into the assessment criteria. Most of these rating schemes analyze all the materials that form the building structure and enclosure, and a whole-building life cycle is included from material production, building construction, to building operation and demolition.

The adoption of WBLCA in the academic research and in the green building rating schemes help the public understand the carbon emissions and other environmental impacts, it also helps the government to fulfill the legislative requirement and achieve the environmental targets. However, the current development of WBLCA encounters many challenges due to the complexity of LCA development. Table 3 lists the WBLCA studies summarized from the selected literature in second search. The results show that the WBLCA development methods are inconsistent at the current stage with various LCA structures, which makes the LCA results unreliable. Based on the information in Table 3, three main challenges were observed that impact the LCA applications to improve the building sustainability performance: the variances on LCA goal and scope development, the complexity of building structures, and the database variance in impact assessment.

3.2 Challenges on variances of LCA goal and scope development

Based on the descriptions on ISO 14040 standard, basic information needs to be provided in general LCA goal and scope definition phase, such as functional unit, system boundary and data quality requirements (ISO14040 2006). While ISO 14040 standard is suitable for any LCA development, there are no specific requirements for each component of goal and scope definition.

In the current literature, the researchers define the goal and scope based on the specific needs and data availabilities in individual studies, which usually have different assumptions, cut-off rules, and limitations. Therefore, it is challenging to compare building level LCA results due to the variances on functional unit setup, system boundaries, reference study period, etc. For example,

due to the data availability, the system boundary could be different between case studies, which leads to the differences in calculation results and sensitivity increase (Häfliger et al. 2017; Oregi et al. 2017). Citherlet and Defaux conducted a WBLCA for three home designs in Switzerland. However, the system boundary of this study was not complete and additional material losses were considered in the LCA (Citherlet and Defaux 2007). On the other hand, the reference service life of the building could also result in a variation of the LCA results. As shown in Table 3, the reference service life of buildings varies from 20 years to 75 years. One study states that the annual energy demand could decrease approximately 14% when the building service life changes from 50 years to 75 years (Rauf and Crawford 2015).

The green building rating schemes that conduct WBLCA also define different goal and scopes. As shown in Table 2, all the rating schemes have the same system boundary from cradle to grave. However, they are aligned with different standards. ISO 14044 was referenced in Green Globes and LEED V4, while internal rules were developed for the system boundaries of BREEAM and CASBEE. The general requirements from international standards cited by different rating systems would create unreliability and variable results when applied by different building designers. In order to promote the application of WBLCA method to improve the building environmental performance, it is not enough by just following the general LCA guidelines, such as ISO 14000 Series and ISO 21930. More specific rules should be developed globally to regulate the LCA goal and scope development rules.

3.3 Challenges on building structure complexity

The variances in building structures between different case studies also create uncertainty for the LCA results. It was stated that the concrete structure has a higher impact than wood structure in residential buildings (Skullestad et al. 2016). There are possibly more than 60 materials and 1000

products in a single building. The variances in materials and cut-off rules in different case studies make the LCA results difficult for comparison (Chastas et al. 2018).

Based on the summary from the searched literature, the building elements considered might include or exclude any part of the buildings. For example, Bastos et al. (2014) only considered seven building materials from original drawings and Gómez de Cózar et al. (2018) only analyzed five main materials for the building LCA. Kylili et al. (2017) considered the building materials in the ground and first floor, while Proietti et al. (2013) considered the entrance ramp and exterior stairs in addition to the ground and first floor materials. Some research, such as the one conducted by Thiel et al. (2013), even included the duct work for the HVAC system and the PV panels on the roof. Therefore, it is urgent to set up a boundary for building level LCA studies to have a uniformed declaration format at the building element level.

On the other hand, the building elements that are included in LCA are also defined in a diverse way by different rating schemes. For example, in Green Globes, the whole building structure including envelope, foundation and footings, below grade or an attached parking garage are considered in the assessment. In LEED V4, the building elements are not described in the rating guide, which only requires the data set to be compliant with ISO 14040. In Green Star, the EN 15978 section 7.5 “The building model” is clearly cited to guide the building elements development. DGNB, BREEAM, and CASBEE all developed a detailed list of building elements that must be included in WBLCA. The boundary variances on building element declarations among different building rating systems also create barriers to share the WBLCA results, which slows down the WBLCA comparisons and building performance baseline developments.

3.4 Challenges on database and assessment method variances

There are many LCA database developed by different organizations, such as Ecoinvent, ELCD and USLCI. Ecoinvent v3 database is a popular one developed in Switzerland, which consists of

over 10,000 interlinked datasets and each dataset describes a life cycle inventory on a process level (Wernet et al. 2016). ELCD represents European life cycle database, which was developed by European Commission's Joint Research Centre (JRC). The ELCD is suitable for cradle-to-grave studies, and all the dataset are carefully selected to emphasize quality and consistency (SimaPro 2016). The USLCI represents U.S. Life Cycle Inventory Database, which was developed by National Renewable Energy Laboratory in US. USLCI database allow users to review and compare analysis results objectively based on similar data collection and analysis methods (National Renewable Energy Laboratory 2015).

Every LCA database has its strength and weakness. Due to the variances of development methods on these popular LCA database, the results from one LCA database could not be compared with the other database. On the other hand, each LCA database has its conditions and limitations for application, which is not easily noticed by the users while conducting WBLCA studies. For example, the USLCI database contains dummy processes, which use proxy data from other sources to bridge the gaps. The Ecoinvent database was established based on the specific industry in Switzerland or Europe for different datasets. The database are used globally to assess the environmental impacts of different products/processes that are happening in different countries, although they could easily be misused. One study indicates that the embodied CO₂e results could be over 50% different between Ecoinvent database and ICE database for different building designs (Chastas et al. 2017). Therefore, a lot of uncertainties/errors are embedded in the LCA studies. Furthermore, the applicants that are using these database usually don't have a strong knowledge on how these database, provided in commercial software such as SimaPro and OpenLCA, were developed, which further exaggerate the impact variances. Therefore, the issue on LCA database is a big challenge in front of WBLCA applications.

There are also many LCA methods that were developed globally, such as TRACI method developed by US Environmental Protection Agency (EPA), ReCiPe method created by different parties together in Europe, and EDIP 2003 method presented by the Technical University of Denmark (Goedkoop et al. 2016). The use of different LCA methods could lead to totally different LCA results. By selecting different LCA methods, the impact categories are different. For example, ReCiPe method has 18 impact categories, while TRACI 2.1 has 10 impact categories. As shown in Table 2, the impact categories adopted by each rating scheme are not the same as well. Most of these rating schemes have six impact factors, such as Green Globes, LEED, and Green Star. DGNB has five impact factors and CASBEE only has CO₂ as its impact factor. BREEAM is unique as it developed its own impact factor EcoPoints. Different LCA methods make it challenging to evaluate and compare the environmental performances among buildings. The literature summary in Table 3 shows that the WBLCA methods are inconsistent at the current stage, and the results comparisons between case studies are not very applicable. It is therefore necessary to address this challenge to further promote the application of WBLCA.

4 Approaches to address WBLCA challenges

With the increasing popularity of applying WBLCA to reduce environmental impacts on building sector, there are emerging approaches globally that are working on addressing the WBLCA challenges mentioned in section 3 by releasing advanced LCA standards, integrating new technologies, and improving the data accuracies.

4.1 Approaches to specify goal and scope definition

The goal and scope definition contains most of the instructions that are needed to conduct the LCA studies. If the goal and scope does not set up right, the WBLCA results might not be reliable or

comparable. Based on the searched literature review, many of the building LCA studies still follow the ISO 14040 series standards which was developed near 15 years ago. There are, in fact, many recent international standards that could support the WBLCA development with more specific details on goal and scope definition. For example, the EN 15978 standard, developed by European Union in 2011, shows a good calculation method for building level environmental performance (CEN 2011). In EN 15978 standard, the purpose of the assessment, the functional equivalent and reference study period were clearly explained and more specific steps were involved to start the WBLCA. As shown in Table 4, the detailed information modules that should be considered in each life cycle stage were listed. Another standard EN 15643, developed by European Union in 2011, also applies to all types of buildings to assess the environmental performance throughout the life cycle (European Committee for Standardization 2012). These two standards are good approaches that would promote the application of WBLCA development and further improve the building environmental performance. Therefore, it is recommended that EN 15978 and EN 15643 should be followed for WBLCA studies in the future.

There are also further approaches globally based on the standards mentioned above. The International Environmental Product Declaration (EPD) System, founded in Sweden, developed the building assessment schemes with EPD. EPD for a whole building is a transparent declaration of the building LCA with the Product Category Rule (PCR) 2014:02 Buildings, which was based on EN 15978 calculation method. The Athena Sustainable Materials Institute also published the first North American building level environmental declaration to the EN 15978 standard in order to meet the growing interest in WBLCA in North America. The main purpose is to ensure quality, consistency, and comparability of the WBLCA results. In the future, the WBLCA developments

should be further divided into different building categories based on the functional equivalent, such as residential buildings, commercial buildings, offices, industrial buildings.

4.2 Approaches to simplify building structure declaration

As mentioned above, there are different types of buildings with various building elements. Building elements that are included in WBLCA studies are totally based on the data availability or casual selections by authors. Besides the recommendations to develop WBLCA standards for different building categories, there is a need to standardize and simplify the building elements/calculation method.

In order to address this challenge, evaluating the environmental performance of a building using simulation is becoming a popular approach. BIM tools, such as Revit, have the potential to clearly cover the building level environmental impacts with standardized setup and efficient processes (Sharif and Hammad 2019). Nowadays, BIM has become the foundation for digitalisation of the construction industry. The UniFormat system, a uniform definition of construction assemblies and systems developed by Construction Specification Canada to promote the BIM application, is able to provide standardized declaration boundaries for building structure (CSI 2010). As shown in Table 5, these three main categories, including substructure, shell, and interior, could be used as a baseline to calculate building structure in future WBLCA studies.

Integrating BIM into WBLCA is also an ideal solution for addressing the challenges that are associated with the complexity of building structure. BIM model strictly follows the building plans, which is hard to miss any building-related data. Once the BIM model is established, the material quantities can be automatically generated, which improves the LCA development efficiency. On the other hand, when design revision happens, the material quantities of the revised portion could be exported simultaneously (Santos et al. 2019, Feng et al. 2020). Currently, there are three main

approaches to BIM integration with LCA and LCC. The first approach uses a range of tools for project modelling to conduct LCA analysis. The second approach generates a quantity take-off from a BIM model with LCA databases to obtain building level environmental impacts. The third approach incorporates sustainability-related information from BIM models to promote automatic simulations and improve information exchanges (Santos et al. 2020).

The first approach was started a while ago. Wang et al. explored the BIM-LCA potential to assess building environmental impacts, and the most sustainable solutions were identified using Ecotect (Wang et al. 2011). Basbagil et al. presented a method to apply LCA to the early stage of a project, to inform building designers of the relevant environmental impact importance of building component materials and dimensioning choices (Basbagill et al. 2013). Jalaei and Jrade proposed an automated model link green building certification system with BIM, LCA, energy analysis, and lighting simulations, which will provide a new way for designers to identify potential energy changes at the building level (Jalaei and Jrade 2014). Jrade and Abdulla also developed a prototype to link the Athena EcoCalculator with a BIM model to perform an LCA on a simple 3D object-oriented model using Industry Foundation Classes (IFC) as the data exchange standard (Jrade and Abdulla 2012).

The second approach is more recent due to advances in BIM technology and market demand for more automatic analysis. Jrade and Jalaei developed an integrated framework to assess the environmental performance of buildings. BIM was used to generate a quantity take-off, which is linked with external environmental and cost data for building components (Jrade and Jalaei 2013). Oti and Tizani also created a tool that extracts the materials' bill of quantity from the BIM model, and connected it with an external database to perform LCC, CO₂ emissions, and ecological footprint analysis (Oti and Tizani 2015). Shin and Cho proposed a framework that integrates LCA

with BIM tools. The building quantity information was exported from BIM and fed into an Excel spreadsheet that conducts WBLCA analysis (Shin and Cho 2015). Similar research conducted by Kreiner et al. used the bill of quantities from the BIM model to optimize building sustainability performance (Kreiner et al. 2015). Yung and Wang also used BIM to evaluate building sustainability with an external database. The BIM 4th dimension was used for schedule management and employee arrangement (Yung and Wang 2014).

The third approach has just started recently. For example, Santos et al. proposed a BIM-based WBLCA tool to improve the integration and tested it with a pilot case study. This work is expected to contribute to the development of automatic sustainability simulations (Santos et al. 2020). The main advantage of the third approach is that BIM is treated as a data exchange platform between users and tools, which allows the information stored in BIM to be easily edited and quickly updated by other users for WBLCA studies. With the growing popularity of integrating BIM into WBLCA, further studies are required to strengthen the knowledge of BIM platform, and develop BIM add-ins to simplify the WBLCA development processes while maintaining the WBLCA result accuracy and calculation flexibility among different building categories.

4.3 Approaches to reduce uncertainty from LCA database and methods

Based on literature, it is common that WBLCA studies use the background data from popular LCA database, such as Ecoinvent and USLCI, to evaluate the building environmental performance. However, the varieties of LCA database and methods dramatically increase the results reliability which was clearly explained in section 3 as a WBLCA challenge.

One popular approach to address this challenge is to promote EPD applications into LCA material impacts calculations. EPD is one of the most recommended methods for reporting the overall performance of building materials in terms of environment, resource use, and waste disposal

(Kuittinen and Linkosalmi 2015; BSI EN 15804 2014). EPD reports for building materials are developed by strictly following the EN 15804 standard, which have clear and uniformed requirements for all the LCA processes (Ibáñez-Forés et al. 2016). An EPD report is developed based on the involved processes, inputs and outputs that are associated with specific material productions in a region and verified by a third party that has qualifications in LCA knowledge (The International EPD System 2017; Rocha and Caldeira-Pires 2019). Therefore, the environmental impacts of a building material from a local EPD report are not background data anymore since it is developed based on the local industrial condition. Applying EPD reports into WBLCA would dramatically increase the accuracy of impact results for specific case studies. The EPD results among the same material categories could also be compared since all the LCA details are declared in the report (Del Borghi et al. 2014, Wiklund 2016). Since all the EPD reports were created with the same standard, the challenges on database variances could be addressed strategically.

EPD method also sets up strict rules on LCA impact assessment methods. As shown in Table 6, four main categories are required to report, including environmental impacts, resources use, waste to disposal, and other output flows. Each main category has different impact indicators (BSI EN 15804 2014). With the required impact assessment method, EPD reports would have all these impact results calculated and verified by LCA experts. The application of EPD results into WBLCA studies would significantly reduce the data uncertainties and address the associated challenge.

EPD has already become popular in the industrial world. The international EPD system, launched in 1999, was the first EPD program developed on a worldwide scale, and the most commonly implemented system in Europe (UNSD 2008). In 2000, Earthsure was founded by the Institute for

Environmental Research and Education in the US, which became the first EPD program in North America (Gelowitz and McArthur 2016). As more EPD programs are established, systems for EPDs are gradually becoming more popular and practical in the industry due to its ability to provide credible and comparable information regarding the environmental performance of services and products (Strazza et al. 2010). An EPD is a verified data source for a designer to select building materials while conducting WBLCA, and for end-users to select building materials with least environmental impacts. EPD is also a reliable and transparent way to communicate the environmental performance of building materials for different manufacturers (Pacheco-Torgal et al. 2013).

EPDs have been well developed in Europe, especially in Sweden, France, Germany, Italy, and United Kingdom. In 2004, ECO platform was established as an umbrella organization of various national EPD program holders in Europe to generate cross-border recognition of European Core EPD based on the EN 15804 standard and their implementation (IBU 2016). With the approach, the EPD database would be expanded and shared among different countries in Europe, which would dramatically improve the WBLCA database as well the building material performance. EPDs are also getting popular in Asia and North America. In Canada, FP Innovations became the first program operator to develop PCRs and EPDs for wood products in North America (FPInnovations 2017). EPDs are also well adopted in popular building rating schemes, such as LEED, BREEAM, and Green Globes, that assign credits to EPD reports in the applications. With the international trend in EPD, Canada should also spend more resources on its own EPD database development to bring the building material LCA into a new level.

Another approach to address the uncertainties that are associated with WBLCA developments, especially the challenge on LCA database and impact method variances, is to conduct uncertainty

analysis. There are two main directions to conduct uncertainty analysis: The first one is to conduct sensitivity analysis, and the second one is to conduct uncertainty assessment through mathematical methods (Dai et al. 2020; Harter et al. 2020). Sensitivity analysis is to monitor the changes of total WBLCA results while revising single or limited LCA input parameters by certain percentage (Morales et al. 2020). Uncertainty assessment could be conducted by Monte Carlo simulation manually through Excel or through commercial software such as @Risk, Crystal ball and SimaPro (Feng and Hewage 2014, Favi et al. 2018). Uncertainty assessment could also be conducted through fuzzy logic approach (Gumus et al. 2016; Kaziolas et al. 2017) and Pedigree matrix approach in OpenLCA software (Ciroth et al. 2014). With these mathematical methods, the LCA uncertainty challenges laying among the LCA database and methods would be mitigated although not eliminated.

5 Discussion

The fundamental purpose of the WBLCA method, which is to monitor and improve the overall performance of buildings by highlighting the main environmental impacts contributors, was not well practiced by the LCA society in general, especially in the industrial field. It is also important to compare the unit WBLCA results with other buildings under the same category and provide alternative solutions to improve the building life cycle performance, which has not been paid enough attention in WBLCA. One of the main reasons is the challenge on WBLCA developments. Therefore, it is significant to study the WBLCA development methods, regulate the development processes, and promote the WBLCA applications. The outputs of this review study could be used to address the difficulties on finding environmental impact hotspots, developing building level LCA performance benchmark, and promoting WBLCA results comparison under the same building category.

With the popularity of using WBLCA method to improve building level sustainability performance, the challenges that slow down the applications of WBLCA results in decision making could be overcome with time. The emerging approaches that were presented above to address the associated challenges have been started applying in some WBLCA studies. The literature review shows that developing and applying more specific WBLCA method, such as EN 15978/15643, instead of using general LCA standards, such as ISO 14040/21930, would support the WBLCA application on building performance. Furthermore, the approach to integrate BIM and EPD with WBLCA would regulate the LCA development processes and improve the results accuracy. In future studies, the specific methods to explore the BIM-EPD integration with WBLCA would be encouraged to verify how much is the accuracy of WBLCA results improved because of EPD or BIM. The decision makers and LCA researchers need to be aware of these newer approaches and potential research directions and apply them into future WBLCA studies.

There are a lot more approaches that are pushing the WBLCA developments into next level. For example, the new version of LEED building rating system assigned 3 credits to encourage projects to make early design decisions to reduce environmental impact through WBLCA (LeadingGreen 2019). BREEAM also set up standards to conduct building LCA in the building ratings since 2011 with 2 credits. However, the building level LCA has been too comprehensive for most building design teams when the concept was initially brought up to different commercial rating systems. With the growth of LCA community and the sustainability concepts in the building sector, more and more WBLCA studies have been conducted by building designers or LCA consultants. It is predictable that the WBLCA approach will soon become a necessary part of the initial design in building sector.

With the promotions in building rating systems, more and more commercial software are developed to simplify the WBLCA assessment process since manually conducting a detailed WBLCA study would be complex and time-consuming. For example, the Athena Institute software: Athena Impact Estimator for Building is able to conduct a quick and rough WBLCA with the major building assemblies, as well as conduct a detailed and accurate WBLCA if the material bill of quantity is attached (Athena 2014). Another popular one, called One Click LCA, is emerging quickly for WBLCA. With the biggest LCA database of building materials, One Click LCA is recognized globally by over 20 green building rating schemes and green building experts, which can calculate WBLCA in minutes without much of the LCA knowledge needed (One Click LCA 2020). The BIM add-in Tally is also getting popular since it can be directly used with the building design tool, such as Revit and ArchiCAD. The designers can check the building environmental impacts while conducting the building design without much effort (Tally 2014).

With the widespread of WBLCA requirements in different rating systems and municipality bylaws, these commercial WBLCA software would become more efficient and less comprehensive for users. One concern is the simplified WBLCA results from commercial products might lose the accuracy of building performance. The initial target of WBLCA is to evaluate the environmental impacts throughout the life cycle stages and point out the emission “hotspots”, and further improve the performance by reducing the emissions from the hotspots. With the full package of WBLCA calculations offered by different software, it would be harder to understand what is really going on behind the scenes. Therefore, future WBLCA approaches should focus on maintaining the results accuracy while improving the development efficiency.

6 Conclusions

In order to reduce environmental impacts in the building sector, WBLCA becomes a popular method by measuring the environmental performance of buildings throughout the life cycle. However, due to the complexity of WBLCA, challenges occur among the WBLCA development processes. This research conducted a comprehensive review of WBLCA studies based on Web of Science Core Collection database with the title search of “building life cycle assessment” to summarize the current challenges and emerging approaches in WBLCA developments.

Based on the searched literature, three main challenges were summarized that would impact the reliability and accuracy of WBLCA results. The first challenge is the variances on current goal and scope definitions due to the limited descriptions on system boundary, functional unit, reference service life, etc. The second challenge is due to the complexity of building structures, and the third challenge is the varieties on LCA database and impact methods.

Emerging approaches were discussed that would help address these three main challenges. The first challenge can be addressed by applying more recent building standards such as EN 15978 and EN 15643, as well as following the standardized WBLCA development approaches initiated by the International EPD system and Athena Sustainable Material Institute. The second challenge can be addressed by integrating BIM platform into WBLCA development to simplify building structure declarations. The third challenge can be addressed by promoting EPD into WBLCA to reduce the uncertainties from LCA database and method variances, since EPD provides standardized and verified environmental impacts for building materials with localized environmental data and specific impact method. The mathematical methods, such as Monte Carlo simulation, fuzzy logic and pedigree matrix approaches were introduced to further mitigate the challenges.

In the end, the review summarized the emerging commercial software, such as Athena Impact Estimator for Building, One Click LCA, and BIM-Tally, which are widely used in the building industry to quickly calculate WBLCA results. At the same time, this trend brought concerns to the WBLCA results accuracy. Future approach should focus on improving the efficiency of WBLCA calculation while maintaining the results accuracy.

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Figure 1: First literature search results

Draft

Exploring the current challenges and emerging approaches in whole building life cycle assessment

Table 1: Summary of search data for articles on WBLCA

Parameter	Setting
Title keyword	Building(s); Life cycle assessment(s); Challenge(s)
Type	Article or Review
Time Span	1990-2020 (August)
Selected database	Web of Science Core Collection
Language	English

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Table 2: WBLCA methods applied in green building certification schemes.

Certification	Boundary	Details
BREEAM	Cradle to grave	All building materials used in construction included in the LCA, BREEAM LCA tools and benchmark established for credit calculation, and EcoPoints indicator introduced.
DGNB	Cradle to grave	Building elements clearly described with exclusions, environmental values of the reference building established for credit calculation, and five impact factors included.
LEED v4	Cradle to grave	Materials of building's structure and enclosure included in LCA, design building should achieve min. 10% reduction from reference building, and six impact factors included.
Green Globes	Cradle to grave	Building elements clearly described with exclusions, building final design achieves 10-20% reductions for different indicators in comparison with the reference buildings, and six impact indicators included.
CASBEE	Cradle to grave	Building elements defined, building final design reaches different level based on the reference building which is developed from historical data, life cycle CO ₂ calculated.
Green Star	Cradle to grave	Building elements clearly defined, building final design achieves points by comparing with reference building (two options), and seven impact indicators included.

Table 3: The inconsistency of WBLCA methods in different case studies.

Reference	Type	Goal and scope			LCI	LCIA
		Boundary	Building elements	Life (yr)	Scenario development	Database/Method
Kylili et al., (2017)	Passive house	Cradle to site	Ground and first floor bill of quantity (BoQ)	50	External drainage, sewage, excavation not included	EcoHestia/ CML2001
Thiel et al., (2013)	Net-zero energy building	Product stage	Major components from structure to interior as well as ductwork, PV panel	50	Landscaping, interior finishes not included	Franklin USA98/ CED
Atmaca and Atmaca, (2015)	Resident building	Cradle to gate	Major building structures, material replacement factor considered	50	Energy consumption and CO ₂ emission in different stages accumulated	ICE database
Cuéllar-Franca and Azapagic, (2012)	Resident houses	Cradle to grave	BoQ from construction guides and material specifications	50	Energy and water in usage stage assumed	Ecoinvent/Gabi V4.3
Asdrubali et al., (2013)	Three types of buildings	Cradle to grave	Envelope and equipment system classified based on UNI 8290	50	Transport distance assumed, MC4 software for usage stage	Ecoindicator 99, IPCC 2007, CED
Proietti et al., (2013)	Passive house	Cradle to grave	Ground and first floor, entrance ramp and two exterior stairs, detailed end-of-life recycling stage	70	Life cycle improvement stage included, construction waste considered	Ecoinvent/ EPD 2007 Ecoindicator 99
Karami et al., (2015)	Three hypothetical buildings	Cradle to gate	Building components built in Revit, VIP insulation material studied	50	Material transport not included	International, German and Norwegian EPD system
Bastos et al., (2014)	Three residential buildings	End-of-life stage not included	Seven building elements info obtained from original drawings.	75	Retrofit phase included, Only energy and GHG impact considered	ICE 2.0
Wan Omar, (2018)	10 case studies	Product stage	Material quantities from standard BoQ in public works department	n/a	Only embodied energy and carbon calculated	ICE 2.0/I-O LCA
Wu et al., (2017)	26 buildings	Cradle to grave	BoQ not clearly presented, building floor area included	50	Life cycle CO ₂ calculated only, retrofit phase not included	BELES database
Gómez de Cózar et al., (2018)	Heritage theatre	Cradle to grave	Five main materials analyzed	n/a	Usage stage excluded, only GWP and CED calculated	Ecoinvent 2.0
Tulevech et al., (2018)	Industrial building	Cradle to grave	Equipment not analyzed, electrical & mechanical components included	20	Designer builder applied in usage stage, Retrofit not studied	Ecoinvent 3.0 & ESUCO
Wrålsen et al., (2018)	Apartment building	Cradle to grave	Major renovation materials exterior walls, doors, windows, balcony	30	Retrofit not considered	Ecoinvent 3.1/ReCiPe
Evangelista et al., (2018)	Four Brazilian dwellings	Cradle to grave	BoQ of main construction materials listed	50	water, energy use, waste during construction considered	Ecoinvent 3.01/CED 1.08 & ILCD 2011

Table 4: System boundary for a WBLCA according to EN 15978.

Stage	Information Module	Name
Product Stage	A1	Raw material supply
	A2	Transport
	A3	Manufacturing
Construction Stage	A4	Transport
	A5	Construction
Use Stage	B1	Usage
	B2	Maintenance
	B3	Repair
	B4	Replacement
	B5	Refurbishment
	B6	Operational energy use
	B7	Operational water use
End of Life Stage	C1	Demolition
	C2	Transport
	C3	Waste processing
	C4	Disposal

Table 5: Building elements that are included in WBLCA based on the UniFormat system.

A: Substructure	A1010	Standard foundation
	A1020	Special foundation
	A1030	Slab on grade
	A2020	Basement walls
B: Shell	B1010	Floor construction
	B1020	Roof construction
	B2010	Exterior walls
	B2020	Exterior windows
	B2030	Exterior doors
	B3010	Roofing
	B3020	Roof openings
C: Interior	C1010	Interior partitions
	C1020	Interior doors
	C2010	Stair construction
	C2020	Stair finishes
	C3010	Wall finishes
	C3020	Floor finishes
	C3030	Ceiling finishes

Table 6: Impact categories reported in EPD report according to EN 15978.

Indicator	Impact Category	Unit
Environmental impacts		
GWP	Global warming potential	kg CO ₂ eq.
ODP	Depletion potential of the stratospheric ozone layer	kg CFC 11 eq.
AP	Acidification potential of soil and water	kg SO ₂ eq.
EP	Eutrophication potential	kg (PO ₄) ³⁻ eq.
POCP	Formation potential of tropospheric ozone	kg C ₂ H ₄ eq.
ADP-elements	Abiotic depletion potential for non-fossil resources	kg Sb eq.
ADP-fossil fuels	Abiotic depletion potential for fossil resources	MJ, net calorific value
Resource use		
PERE	Use of renewable primary energy excluding renewable primary energy resources used as raw materials	MJ, net calorific value
PERM	Use of renewable primary energy resources used as raw materials	MJ, net calorific value
PERT	Total use of renewable primary energy resources	MJ, net calorific value
PENRE	Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	MJ, net calorific value
PENRM	Use of non-renewable primary energy resources used as raw materials	MJ, net calorific value
PENRT	Total use of non-renewable primary energy resources	MJ, net calorific value
SM	Use of secondary material	kg
RSF	Use of renewable secondary fuels	MJ, net calorific value
NRSF	Use of non-renewable secondary fuels	MJ, net calorific value
FW	Net use of fresh water	m ³
Waste to disposal		
HWD	Hazardous waste	kg
NHWD	Non-hazardous waste	kg
RWD	Radioactive waste disposed (total low, intermediate and high level waste)	kg
RW	Radioactive waste (high level waste)	kg
Other output flows		
CRU	Components for reuse	kg
MFR	Materials for recycling	kg
MER	Materials for energy recovery	kg
EE	Export energy	MJ per energy carrier

Exploring the current challenges and emerging approaches in whole building life cycle assessment

Figure 1: First literature search results