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A Review of Life Cycle Assessment Tools for Measuring the Environmental Impact of Building and a Decision Support Framework for Choosing Among Them

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Abstract: The increased environmental concerns in recent decades have resulted in examining waste emissions, resource utilization, and resource depletion. A holistic environmental assessment should consider all these factors. Researchers, policymakers, and companies are paying more attention to environmental management. As a result, organizations are developing their environmental practices to enhance environmental management throughout the building life cycle. Contemporary life cycle assessment (LCA) stands out as a reliable and comprehensive method that effectively communicates such benefits to stakeholders and offers them more leverage. LCA is increasingly being used to assess how construction processes affect the environment and minimize these impacts. There is a need for research on the use of LCA tools in buildings, which is a key point and a solution to facilitate environmental management practices and transform the construction industry. Based on a literature review, the research studies LCA tools for quantifying buildings' environmental impact and provides a decision support framework for choosing LCA tools. The paper aims to analyze the current uses of LCA in construction, present LCA tools, compare applied tools in buildings, and explore three commonly used LCA tools for building studies. Moreover, this research explores that managing the database is one of the most significant issues with current LCA tools. It suggests that building information modeling (BIM) and LCA integration is an approach that might facilitate and simplify data management for LCA analysis throughout all building life cycles. This study's results will assist project stakeholders in choosing the appropriate tools and selecting the most environmentally friendly products at different building life cycle stages (i.e., design, construction, and maintenance) for the project's success.

Key words: Life cycle assessment tools, LCA applications, building, construction, environmental impact of buildings, life-cycle analysis.

Introduction

Today, built environments consume large amounts of energy and resources, harming human health and the natural ecosystem (Ansah et al., 2021). As stated in *Architecture2030* (2022), greenhouse gas emissions (GHGs) come mainly from the built environment, which is responsible for up to 50% of all carbon dioxide (CO2) emissions globally. Buildings caused the most significant impacts, primarily due to the massive amounts of raw materials consumed by construction activity. The building industry uses about 40% of the world's materials annually (Ansah et al., 2021). Therefore, the industry must find environmentally friendly answers to environmental problems that also enable decreased material and energy usage throughout a building's life cycle. As a result, evaluations and analyses of a building's energy and environmental performance need to evaluate its entire life cycle using internationally accepted methods such as the life cycle assessment (Ansah et al., 2021). Life cycle assessment is an analytical methodology for quantifying the environmental impact of processes and products over their life cycle. (Dalla Mora et al., 2020). This method is getting more attention through construction technology advancements and integrated design processes (Srinivasan et al., 2014). In the opinion of studies, at the product level, LCA can quantify the product's energy consumption and environmental impacts from the cradle to the grave. At the building level, it can be used to compare the environmental impacts of different building designs and choose the alternative with the least impact. Corresponding to ISO 14040 (2006), LCA analyses potential environmental impacts from the procurement of raw materials through production, use, and disposal. It also evaluates the construction, ownership, and disposal costs involved with building systems (Han & Srebric, 2011). Accordingly, both academia and the construction industry have been developing approaches to apply LCA to buildings. In conducting this review, this research attempts to answer the following key questions: (RQ1) What is the current state of LCA? (RQ2) What research on LCA tools is available? and (RQ3) What are the best LCA tools used in buildings?

Background

Life cycle assessment studies the overall environmental impacts of buildings across their life cycles. Chau et al. (2015) describe LCA as an objective approach for analyzing the environmental burdens associated with recognizing and measuring the impact of a product, process, or activity on the environment in terms of energy, materials, and emissions; and, finally, developing and implementing measures to reduce or eliminate these impacts. The International Organization for Standardization (ISO) has advanced LCA standards to address a project's technical and administrative concerns. The LCA general methodology follows the four-stage framework recommended by ISO 14040 (2006) and ISO 14044 (2006). The four stages are (1) goals and scope definition, (2) life cycle inventory (LCI), (3) life cycle assessment (LCA), and (4) interpretation. In particular, standard EN 15978 (2011) is a reference for calculating the environmental impacts of buildings and evaluating the flow of materials, resources, energy consumption, and emissions that are released into the environment. It is organized according to the building's life cycle, which includes production, construction, usage, and end-of-life phases. LCA is a reliable environmental management technique, and it has the potential to evaluate alternatives (Abd Rashid & Yusoff, 2015). Databases, methodologies, and impact assessment models have been created and implemented in specialized software tools that contribute to the LCA results. In the existing literature, only a limited number of studies have tried to compare outcomes using several LCA software tools in buildings. It is essential to choose suitable LCA tools since they can affect results and decisions during the building life cycle (Silva, Nunes et al., 2019).

Methodology

This study's methodology provided a set of data analyses to present the qualitative approach through concepts and experiences, as well as insight into scholarly publications. Initially, data was gathered from a variety of sources. The original search keywords were "life cycle assessment tools, LCA applications, building, construction, the environmental impact of buildings, and life cycle analysis." The initial literature review identified research gaps and emerging trends in relevant LCA topics within the construction industry. This step helped the researcher become familiar with the current state of knowledge and the constraints of a particular topic. Second, this extensive literature review attempted to answer the research questions raised above about the concept of LCA and discussed the similarities and differences between these tools. The study provided a basic knowledge of LCA tools and suggested eight criteria for the LCA analysis. These criteria were used as a filter in the decision support framework, which will assist stakeholders in deciding LCA tools for buildings. Lastly, the research applied the proposed criteria to compare three examples of digital LCA tools, including the Athena Impact Estimator, EC3, and Tally. The study delivered a roadmap for academic researchers who will continue analyzing and comparing LCA tools using the suggested methodology.

Review of Life Cycle Assessment tools in construction

The first review of notes in this area was by Al-Ghamdi & Bilec (2016). The research included a comparative analysis to evaluate the commercial LCA tools. These tools were accessible to designers throughout various phases of the design process, and they could be used to meet the requirements of multiple green building rating systems (GBRS). Global warming potential is a required category in comparison to a baseline building. The impact category and material takeoff accuracy influence the LCA software effect. Given the same building, the LCA results produced by the three different software tools varied in both the embedded impacts (such as metal, concrete, masonry, etc.) and the operational impacts (for example, area lights, exterior loads, heat rejection, etc.). The paper recommended refining LCA methodologies for GBRS and obtaining more comprehensive data sets for building systems and products. Similarly, Jrade & Abdulla (2012) reviewed the LCA, BIM, and data exchange standards that could facilitate integrating them. The paper chose the EcoCalculator as a tool and Autodesk Revit as BIM software because of their widespread use by architectural engineering and construction (AEC) professionals, which enables them to reduce learning and development costs, especially in the early planning stages. As a result, the authors recommend dividing LCA tools into three categories: (1) product comparison tools for LCA and non-LCA practitioners; (2) whole process construction tools; and (3) comprehensive assessment and rating frameworks. According to the study, future LCA implementation should consider significant factors such as building type, geographic location, and data source.

Nine out of the 15 papers mentioned literature review as a research methodology. One study chose to use the experimentation and case study methods. Through a literature review, Bueno & Fabricio (2016) suggested adding LCA databases to the Building Information Modeling (BIM) platform, which is used in the design process. The research considered the plug-in Tally as the simplification and friendly use, which included identifying the most prominent environmental impacts and how impacts can be compared among the different materials options concerning energy consumption operations. By doing that, the result was the LCA on demand and an environmental information layer for decision-making in the same building design software. In agreement with Antón (2013), the study introduced the integration of BIM and LCA as tools to achieve sustainable construction. The research presented potential solutions, focusing on their contribution to sustainability to understand the construction industry and building sector's main features and existing problems. The investigation focused on the design phase since it may have the greatest impact. The research recommended criteria for assessing the cases studied based on the analysis with LCA software developers. The author also concluded that the availability of databases is one of the main difficulties when developing an LCA of buildings. Similarly, Dalla Mora et al. (2020) reviewed the state of the art of research published in the past ten years on integrating BIM-LCA as a method whereby the BIM approach might facilitate and simplify data management for LCA analysis. Based on their specific objectives and the available data, the research established a framework of all available adopted methodologies in the science community to assist designers in making appropriate decisions. In the future, researchers will find a way to link the BIM integration of impact data with the requirements for building labels or rating systems that are either required or optional. Complex workflows will be one of the most developed scenarios in future research regarding the interoperability of BIM, especially in developing tools and methodologies to enable automatic quantity takeoff. Dalla Mora et al. (2020) successfully presented evidence of a general heterogeneous framework to define the common and widespread approaches to identifying building factors that were considered in applying the BIM-LCA integration.

Rossi et al. (2012), Han & Srebric (2011), Lopes Silva et al. (2019), and Srinivasan et al. (2014) used case studies as research methodology and reviewed different LCA software tools. Rossi et al. (2012) described and applied some LCA tools to achieve the complete LCA of residential buildings in three European towns. Rossi et al. (2012) also identified some building characteristics to consider when choosing an LCA. Concurrently, Han & Srebric (2011) introduced different LCA tools: BEES, Athena Eco Calculator, Athena Impact Estimator, and SimaPro. The paper discussed these tools in terms of performance and environmental impact analysis to help users choose appropriate tools for project analysis. Lopes Silva et al. (2019) presented the differences in LCA results due to using various LCA software tools for the same product system. After performing a cause-effect analysis of the problem, the authors found two root causes: (1) the import process for background datasets and (2) the lack of rules for implementing life cycle inventory analysis (LCIA) methods in the software tools. The main findings of this work uncover different numbers of characterization factors and sub-compartments in each software tool for each impact category that can generate different LCA results. Srinivasan et al. (2014) conducted a case study that applied two existing LCA tools: an economic input output-based (EIO LCA) model and a process-based model (as Athena), to estimate life-cycle energy use in an example building. The comparison was centered on the energy-based indicators used. The authors explored whether these LCA tools could help enrich sustainability-related decision-making in building design, construction, operation, and decommissioning. Future researchers should put more effort into tracking data at all stages of the building life cycle, including the end-of-life stage, which currently needs more research.

Each project is unique, and every building project has different characteristics to consider when implementing a life cycle assessment (Rossi et al., 2012). Consequently, the paper discussed each section, highlighting how previous researchers developed the life cycle assessment concept while identifying objectives, methods, challenges, and findings, thus supporting future work. As a result, the current state of LCA tools was analyzed, synthesized, and summarized from the reviewed literature. All the tools can be helpful for their particular purpose, provided the user understands their potential limitations. The suitability of one software program relative to another depends on the user's scope or objectives, system level, and building location, and the database of each program could be different (Ormazabal et al., 2014). Accordingly, given that different projects have various objectives, stakeholders should define the expected results and details of interest for each project before starting life cycle analyses to choose the right tool (Han & Srebric, 2011). Completing an LCA at different system levels (i.e., materials, components, structures, portions, or the entire building), especially a whole building analysis, is time and resource-intensive. The above papers have touched on key areas relating to data resources and associated LCA digital methods in the building life cycle.

Comparative analysis of selected LCA tools

This study chose digital methods (including tools, applications, and software) to advance the LCA in buildings. The concept of digital technology is to build a three-dimensional (3D) virtual representation of a building; thus, building components can be planned and evaluated before actual construction. The 3D virtual model helps improve documentation quality, increases productivity, and improves visibility while minimizing adverse environmental impact. BIM is the best choice for stimulating LCA, as BIM is one of the options for calculating life-cycle assessment and energy consumption (Jrade & Abdulla, 2012). The BIM model contains geometric and functional properties of intelligent objects for visualization and simulation to facilitate the interdisciplinary flow of information and data for building projects over their life cycle. The researchers selected three examples of digital LCA tools: the Athena Impact Estimator, EC3, and Tally. These tools are intended to assess buildings and other elements that form part of the built environment. They generally focus on energy and emissions. In addition, they considered the depletion of natural resources, waste production, water consumption, the release of pollutants, and human health impacts. They are three of the most prominent applications, giving the program high visibility and reliability, thereby enhancing its chances of distribution. As shown in Table 1, different parameters were adopted to evaluate the state of the art regarding selected LCA tools. The direct comparison of these tools includes their tool description, purposes, license cost, pros, and cons. This approach also adds a basic understanding of LCA tools to help facilitate decision-making.

Table 1.
Basic Comparison of selected LCA Tools

#	Parameters	EC3 tool (Embodied Carbon)	Tally (App in Revit)	Athena Impact Estimator
1	Description	An open-access tool by Skanska (US) and Change Labs in partnership with Microsoft, Autodesk	Revit Plugin LCA Tool developed by Kieran Timberlake (US) in partnership with Sphera and Autodesk (2014)	Desktop LCA Tool developed by Athena Sustainable Materials Institute (Canada, 2002)
2	Purposes	Allows benchmarking, assessment & reductions in embodied carbon CO2 Used for supply chain emissions of materials	Quantifies the environmental impact of building materials for whole building analysis and comparative design options.	Explores the environmental impact of different material choices and core-and-shell system options.
3	Cost	Free Software	Not free (requires Revit)	Free Software
4	Pros	Simple visualization of a project's potential and realized embodied carbon impacts.	Easy to use Requires no special expertise The result is on demand Allows designers to evaluate various design options	Allows users to include energy simulation results to calculate operating energy effects alongside the effects of embodied energy
5	Cons	Works best in the design stage and construction stage only.	Interprets difficulty the LCA results	Technical knowledge of the building construction is required for data input.

*The information in the table is from each tool's technical documentation, which was based on the authors' insights gained from reviewing the developers' technical reports.

Criteria Proposal

Each building has different characteristics that could influence the selection of appropriate LCA tools. By conducting a literature review of published studies and expanding upon the framework proposed by Dalla Mora et al. (2020), this research suggested eight criteria regarding the LCA analysis, as shown in Table 2. Selection criteria added a filter for study characteristics that helped determine whether they should be included, allowing researchers to better analyze the data. These criteria served as the attributes in the decision support framework, which thereafter will support stakeholders in making transparent decisions on selecting LCA tools in a construction project.

A description of eight criteria:
1. Design stage: refers to the five phases of a design project, which are schematic design, design development, construction documents, bidding, and construction administration.
2. Development Level: This specifies the degree of the building component's specifications, the geometry of its attached information, and (2) the level of frequency of update.
3. Integration Tools: integrate with other standard design software to create a building model, a quantity take-off, a bill of materials, and data exchange.
4. Impacts category (or environmental impact categories): shows the potential impact of a given life cycle impact assessment (LCIA) methodology.
5. Learning curve: (1) time required to develop the LCA model, analyze alternate design options, and update the LCA results; and (2) ease of use of the software.

6. Database: digital data includes environmental information for building materials. It determines the LCA analysis and the evaluation of each building component.
7. LCA Phase: describes the different building life cycles in the analysis as defined by EN 15978.
8. Reporting results: can be (1) extracted as an LCA report for reporting purposes by illustrating results, or (2) produced as design option comparisons within the software.

Table 2.
Analysis Criteria for choosing LCA tools

	Propose the Criteria n literature review of related topic	Al-Ghamdi & Bilec (2016)	Ansah et al. (2021)	Antón (2013)	Battisti et al. (2019)	Bueno & Fabricio (2016)	Chau et al. (2015)	Dalla Mora et al. (2020)	Han & Srebric (2011)	Lopes Silva et al. (2019)	Jrade & Abdulla (2012)	Rossi et al. (2012)	Singh et al. (2011)	Silva et al. (2009)	Srinivasan et al. (2014)	Ormazabal et al. (2014)
1	Design Stage	✓		✓	✓	✓	✓	✓			✓	✓			✓	
2	Level of Development	✓	✓			✓		✓	✓					✓	✓	
3	Integration Tools	✓	✓			✓	✓	✓	✓	✓	✓			✓		✓
4	Impact Category	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓			✓
5	Learning Curve	✓	✓	✓	✓	✓		✓	✓	✓	✓			✓		✓
6	Database	✓	✓	✓	✓	✓		✓		✓		✓	✓			✓
7	LCA Phase	✓	✓				✓				✓	✓				
8	Reporting Results	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Summary	8	7	4	5	7	5	6	5	5	6	5	3	4	3	5

*The number of ticks for each LCA publication shows their contributions in terms of the study's proposed criteria.

Our research has applied the proposed criteria, expanding upon the framework suggested by Anthony Pak & Farzad Jalalei (2019), to compare the three most widely used LCA tools, including EC3, Tally, and Athena. The comparison results are shown in Table 3.

Table 3.
Comparison of selected LCA Tools based on the proposed Criteria

#	Analysis Criteria	EC3 tool (Embodied Carbon)	Tally (App in Revit)	Athena Impact Estimator

1	Design Stage	Construction documents. Bidding. Construction admin.	Schematic design. Design development. Construction documents.	Schematic design, Design development, Construction documents, Bidding & Construction admin.
2	Level of Development	The EC3 tool uses third-party verified EPD entries. The number of product categories have limited. Provide inaccurate estimates for materials.	Updates annually. Develops new features. Mapping from Revit elements. Need to model design options in Revit software.	Updates data annually. Not provide new features or user interface. Develops alternatives of material or assembly options.
3	Integration Tools	Integrates with Revit, Excel, etc. Automatically takeoffs from Revit model Use generic product category EPD (before products are specified)	Integrates with EC3 tool to compare manufacturer specific EPDs. No spreadsheet import of material quantities.	No Revit/BIM plugin is available Manual takeoffs from drawings and updating takeoffs Excel for importing material quantities.
4	Impact Category	Embodied Carbon for Global Warming Potential	Global Warming Potential Acidification Potential Eutrophication Potential Ozone Depletion Potential Smog Formation Potential Primary Energy Demand Non-renewable Energy	Global Warming Acidification Human Health Respiratory Effects Ozone Depletion Photochemical Smog Eutrophication Fossil Fuel Consumption
5	Learning curve	Users can quickly provide owners with the information they need to set embodied carbon performance targets.	Easy to learn mapping functionality. Requires Revit knowledge Define relationships between BIM elements and construction materials from the Tally database.	Easy to learn the basics Extensive help file documentation. Customize the model of assemblies and envelope Provides flexibility for design options .
6	Database	Bases on EPD data. Data entry without BIM import is heavy. Materials must be entered by weight and volume, not length or surface area.	Relies on GaBi background Mostly industry average data manufacturer specific EPD Has no regionalization data assumptions for the U.S.	Relies on Ecoinvent background. Mostly industry average data. Limited manufacturer data. Regionalized assumptions for Canadian and the U.S.
7	LCA Phase	Production	Production, Construction, Use & End of life	Production, Construction, Use & End of life
8	Reporting Results	Enables the visualization of a project's potential. Realizes embodied carbon impacts. Understand the baselines. Sets reduction targets. Provides several carbon benchmarks for a project on the same design.	Provides detailed report generated for LEED submission, which includes graphs and an excel sheet. Has a detailed estimation of material quantities. Challenging to model option material/ assembly options .	Generates LEED results reports with basic graphs and Excel exports. Results are aggregated by element and cannot be disaggregated to show the contribution of individual materials or assemblies.

*EPD - Environmental Product Declarations; *LEED - Leadership in Energy and Environmental Design.
The data information is collected to identify these technologies based on the authors' insights gained from reviewing the developers' technical reports and personal practice experiences.

Results and Discussions

The study investigated common challenges encountered while implementing the LCA framework based on a thorough literature review. Subsequently, managing the database is one of the most significant issues with current LCA tools. The database needs reliability, completeness, and consistency associated with the software outputs. The database includes the volume, quality, accuracy, and relevance of data available to the user in the software (Ormazabal et al., 2014). EPD's limitations provide environmental information that does not allow direct comparison or choice of construction products. Thus, the insertion of LCA data into models developed in the BIM platform would facilitate the implementation of such a quantitative environmental assessment methodology in the construction field (Bueno & Fabricio, 2016). Another challenge was that data for various geographical areas or building locations are needed to achieve global practical tools (Antón, 2013). Most existing LCA tools contained data or parameters that restricted the tool's use to a particular geographic or regional location (Han & Srebric, 2011). Using data not representative of the analyzed product could be challenging because the impacts of similar products in different countries can differ significantly. It was due to different production processes, transportation distances, and the source of raw materials. For some tools, it was possible to link to additional databases more representative of locations, processes, or other characteristics of the product being analyzed. The selection of commercially available tools was an additional obstacle for designers.

The tools vary systematically in how they are built, the user skills required, and the design stage at which they can be used (Al-Ghamdi & Bilec, 2016). Necessarily, the industry needs to take an active interest in developing common databases, and research is needed to develop and implement protocols for collecting, verifying, gathering, synthesizing, updating, and summarizing this data into a usable form (Singh et al., 2011). Respectively, the four objectives were achieved, including (1) analyzing the current uses of LCA in construction, (2) presenting LCA tools, (3) comparing applied tools in buildings, and (4) exploring three commonly used LCA tools for building studies. Three questions were addressed: the current state of LCA, the available research on LCA tools, and the best suitable LCA tools used in buildings. In this paper's scope, the research methodology's design did not cover all aspects of LCA methodologies, thus, it left some trails around the topic. A complete building LCA of future research will include an evaluation of the impacts of all resource needs, inputs, and outputs at each stage of the building life cycle. Also, time and resources limited the number of related publications and articles. LCA wasn't readily implemented because of several limitations such as system boundaries, selection availability, quality data sources, and geographic data. The assessment was as data-based as possible and relied on hypotheses and estimates, which should be studied further in future research.

Conclusions

This research contributes to the body of knowledge by examining LCA methodologies and developing the criteria for choosing appropriate LCA methods, including the design stage, level of development, integration tools, impact category, learning curve, database, LCA phase, and reporting results. The study adopted and built upon the framework developed by Dalla Mora et al. (2020). Most significantly, the framework proposed in our research advanced the prior works by adding the following three criteria: learning curve, integration, and reporting results. In addition, this research applied our proposed framework to compare the three most widely used LCA tools, including EC3, Tally, and Athena. This research benefits practitioners and researchers by providing a road map to continue analyzing and comparing different LCA tools (e.g., OneClick LCA, SimaPro, or BEES) using the proposed framework. Additionally, this research concluded that the current BIM and LCA integration is limited to the design and construction phases due to their generic data. Future research is needed to expand further and enhance the integration of BIM and LCA throughout all building life cycles, including operation, maintenance, demolition, and recycling or reuse. Meeting sustainability standards in design is a common source of difficulty for experts (Dalla Mora et al., 2020). New buildings should be designed with environmental friendliness and energy efficiency in mind. LCA is among the different methods developed to assess environmental performance and reduce its impacts. Ultimately, several studies have emphasized incorporating LCA into the building design process as early as possible (Battisti et al.,

2019) using adaptable, user-friendly technologies connected to current digital data databases.

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