Evaluation of Attributional and Consequential Approaches for A Holistic Life Cycle Assessment

Dilara Nur Keskin[1], Mohammad Sakikhales[2]
[1-2] University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS

Keywords: Life Cycle Assessment, Attributional LCA, Consequential LCA, Sustainable construction

Abstract

Buildings are responsible for a large portion of resource consumption and CO_2 emissions, so the construction industry is one of those where rapid action is required. At this point, Life Cycle Assessment (LCA), a tool to evaluate the buildings' environmental impacts, is playing an increasingly important role in sustainable building design. There are two LCA approaches: Attributional Life Cycle Assessment (ALCA) and Consequential Life Cycle Assessment (CLCA). ALCA represents the potential environmental impacts linked to the life cycle of the assessed buildings, while CLCA examines the environmental consequences of the decisions. Although the attributional approach is widely used, there are limited studies explaining how to apply consequential LCA in the construction industry. While some studies identify differences between ALCA and CLCA, the methodological features of the consequential approach have not been discussed in detail. Nowadays, with the effects of climate change is becoming more distinct, detecting the environmental impact of a building over a certain period has highlighted. Therefore, a comprehensive approach to determining the future effects of our decisions is crucial for environmental sustainability. In this study, the existing literature on both approaches is critically analysed to explore the key characteristics of both approaches and evaluate the opportunities and challenges for a holistic life cycle assessment system that considers attributional and consequential approaches together. Furthermore, a theoretical approach to developing a holistic framework is introduced.

1. INTRODUCTION

Buildings and the construction industry have a significant impact on the environment. According to the Global Status Report, the sector was responsible for 36% of global final energy consumption and 37% of CO_2 emissions due to energy use in 2021 (United Nations Environment Programme, 2021). Furthermore, the industry entails substantial initial and ongoing costs, long life cycles, and uses a considerable amount of resources and energy (Nemry *et al.*, 2010). Building's life cycle energy consists of embodied and operational energy. Embodied energy is the sum of all the required energy for a product used in the buildings. According to BS EN 15978:2011 (European Committee for Standardization, 2011), the required energy is calculated by including the product stage, construction, usage, and end of life, as well as the benefits and loads beyond the product's life cycle, which is represented in Table 1.

Table 1: Life cycle stages from BS EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (European Committee for Standardization, 2011).

A1-A3 Product	A1	Raw material supply
	A2	Transport
	A3	Manufacturing
A4-A5 Construction Process	A4	Transport
	A5	Construction/Installation
B1-B7 Use	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Refurbishment
	B5	Replacement
		B6 Operational Energy Use
		B7 Operational Water Use
C1-C4 End of life	C1	Deconstruction/Demolition
	C2	Transport
	C3	Waste Processing
	C4	Disposal
D Benefits and loads beyond the life cycle		Reuse/Recovery/ Recycling potential

Meanwhile, operational energy is related to maintaining the indoor environment with heating, cooling, ventilation, lighting, or appliances (Dixit *et al.*, 2010). Although the focus is mainly on operational energy in practice and academia, embodied energy can reach up to 60% of the total energy used in buildings, especially if the operational energy requirement is low (Anderson *et al.*, 2022). While the construction industry has a considerable impact on the environment, it can also play a vital role in decreasing the environmental impacts. Life Cycle Assessment (LCA) is one option for measuring the embodied energy and environmental impacts of the buildings (Rocha, Antunes and Partidário, 2019). It assists in having a clear picture of all activities related to the planning, construction, usage, and demolition of a building (Fonseca i Casas and Fonseca i Casas, 2017). The first studies related to LCA were conducted in the late 1960s and early 1970s (Vigovskaya, Aleksandrova and Bulgakov, 2017) when environmental concerns about resource and energy efficiency, pollution, and waste management became widespread. However, there has been a lack of international scientific platforms to discuss LCA until the 1990s. Since the standardization of LCA methods by the International Organization for Standardization (ISO) in the late 1990s, there has been increasing attention to LCA (Guinée *et al.*, 2011) and since then, LCA's methodological development has continued to promote a streamlined approach (Amahmoud, El Attar and Meleishy, 2022).

There are two common approaches for LCA studies: attributional and consequential. The attributional approach provides information on the potential environmental impacts of the product at a certain point in time. However, the consequential approach which has gotten attention in recent years is more relevant to assessing the consequences of decisions (Fauzi *et al.*, 2021).

There are some studies on evaluating both Attributional Life Cycle Assessment (ALCA) and Consequential Life Cycle Assessment (CLCA) in buildings. Schaubroeck *et al.* (2021) worked on conceptual characteristics and modelling restrictions of these approaches. Their results pointed out three issues about considering the methods in the literature. First, they determined that there are some ambiguities about the meaning of the approaches and what they are used for. Second, LCA-related standard such as ISO 14040-14044 does not clearly define and distinguish between the ALCA and CLCA. Third, attributional and consequential approaches are neglected mainly by not stating what approach is used for LCA. In addition, Fauzi *et al.* (2021) performed an ALCA and CLCA on a hybrid wood multi-storey building and showed that CLCA could reveal potential unintended impacts. In another study, Bamber *et al.* (2020) analysed the uncertainty of ACLA and CLCA and concluded that while the multi-functionality causes a problem in ALCA, identification of marginal technologies and substitution are challenging in CLCA practices. Moreover, the research by Ekvall *et al.* (2016) demonstrated that the International Reference Life Cycle Data System (ILCD) Handbook, which is used as a guideline for LCA practitioners, is inconsistent with other research on ALCA and CLCA, so it needs to be revised.

Although there are some CLCA studies in the construction field (Buyle, Braet and Audenaert, 2014; Buyle *et al.*, 2018; M. Buyle *et al.*, 2019; Matthias Buyle *et al.*, 2019; Pedinotti-Castelle *et al.*, 2019; Cordier *et al.*, 2021; Fauzi *et al.*, 2021), CLCA practices on buildings are very limited (Earles and Halog, 2011; Buyle, Braet and Audenaert, 2014; Ghose, Pizzol and McLaren, 2017; Buyle *et al.*, 2018; Fauzi *et al.*, 2021). Additionally, while the ALCA is the commonly used approach, the method name is not specified in most research. The main identified problem in the literature is the lack of clarity on ALCA and CLCA. Therefore, this paper aims to explore the key characteristics of ACLA and CLCA to assess opportunities and challenges for a holistic LCA approach in the construction industry.

2. LITERATURE REVIEW

2.1. Aim of the approaches

There are different methods of LCA which are discussed in the literature. These methods focus on commercially available products/systems or new and unmarketed products. For commercially available products, there are two common systems including ALCA and CLCA (Guinée *et al.*, 2018). These two terms were first introduced at an international workshop on electricity data for Life Cycle Inventory (LCI) in 2001 (Curran, Mann and Norris, 2005).

ALCA aims to describe the environmentally relevant physical flows to and from a life cycle and its subsystems to determine the environmental impacts that are directly linked to a product's life cycle (Finnveden *et al.*, 2009). ALCA which was defined as traditional LCA by Cabeza *et al.* (2014) gives information on the current average environmental impact of a product or service. In other words, ALCA measures the share of the total burdens associated with the product or service by using inventory data from the suppliers or average data (Moretti *et al.*, 2022). ILCD (JRC, 2010) described ALCA with the words "accounting", "book-keeping", "retrospective", and "descriptive" because it demonstrates possible environmental impacts of a product/system throughout its life cycle. This method is most relevant to the micro-level considerations such as comparisons and decisions on specific products or systems (Heimersson, Svanström and Ekvall, 2019). Currently, various databases could be used for ACLA, such as GaBi, Ecoinvent, Athena (US), ELCD (European) etc.

On the other hand, the CLCA aims to describe how environmentally relevant physical flows will change as a result of our decisions (Finnveden *et al.*, 2009). CLCA evaluates how the production and consumption of a product affect the global environmental impact (Ekvall, 2019). CLCA is assessing the environmental impact of future policies by taking into account the economic cause-effect chains resulting from changing production systems (Fauzi *et al.*, 2021). Marginal data, which reflects the effect of a change in the technologies and inputs, is used for this approach. The data should represent the consequences of a change in the analyzed system rather than the average environmental impact of manufacturing a product unit (Heimersson, Svanström and Ekvall, 2019). Therefore, ILCD defines CLCA as "change-oriented", "effect-oriented", "decision-based", and "market-based" since CLCA does not reflect a specific or average supply chain but rather a hypothetical general supply chain that is forecasted using market mechanisms and may include political interactions and changes in consumer preferences (JRC, 2010). One of the constraints of the CLCA applications is that there are only a few databases with marginal data such as Ecoinvent v3 (+ 2013) available at the moment.

Several authors pointed out how to decide which approach to follow (Mary Ann Curran, 2006; Brander *et al.*, 2008; Buyle, Braet and Audenaert, 2014; Agarski and Budak, 2019; Ekvall, 2019). The common idea is that we need to identify the question we aim to answer first. According to Curran et al. (2005), ALCA responds to “How are things (i.e. pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?” while CLCA answers the question “How will flows beyond the immediate system change in response to decisions?” Similarly, Ekvall (2019) stated that we need to use ALCA if we are looking for an answer to “What part of the global environmental burden should be assigned to the product?” and prefer CLCA when our aim is to respond “What is the impact of the product on the global environmental burdens?”. For instance, when we consider this for the construction industry, ALCA would examine what would be the environmental impacts of a specific building, whereas CLCA shows what would be the environmental consequences if we build more of this building in terms of new material implementations or construction systems in the upcoming years such as 10 or 20 years.

2.2. System boundary and assumption methods

The system boundary is the limits on which processes in the life cycle of the product are included in the LCA (International Standards Organisation., 2006). System boundaries differ in ALCA and CLCA practices. ALCA only considers direct effects, such as fossil fuel combustion from construction equipment, while both direct and indirect effects such as emissions caused by the change in the production are taken into consideration in CLCA (Brander *et al.*, 2008). While CLCA can cause complexity as it includes market effects outside of the product life cycle, the amount of knowledge obtained about the system increases significantly with CLCA (Buyle, 2018).

One of the most important problems discussed concerning the system boundary is multifunctionality. Multifunctionality is defined by Ekvall and Finnveden (2001) as an activity that performs various functions, such as a production process which includes more than one product or a waste management process with multiple waste flows. The issue here is how to decide how much of the environmental burden should be allocated to the process. Allocation and substitution methods have been suggested to handle the multifunctionality problem of LCA, which occurs when more than one product is used in the process, (Tillman, A.M.; Ekvall, T.; Baumann, H.; Rydberg, 1993; Weidema, 2014; Majeau-Bettez *et al.*, 2018; Moretti *et al.*, 2020).

ISO 14044:2006 (International Standards Organisation., 2006) defines the allocation as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems". Different allocation approaches are discussed in the literature, such as the cut-off, the 50:50, the Circular Footprint Formula (CFF), the linearly degressive (LD) approach, and the product environmental footprint (PEF) (Nicholson *et al.*, 2009; Gaudreault, Samson and Stuart, 2010; Eberhardt *et al.*, 2020; Obrecht *et al.*, 2021). It is believed that cut-off, which is also called the 100:0 or the recycled content, is the most appropriate approach for ALCA in terms of reducing uncertainty since we do not know how many times the materials are recycled in the process (Gaudreault, Samson and Stuart, 2010). The cut-off method assumes that the environmental impacts of a product's manufacturing are attributed to the product's initial usage and adopt the "polluter pays" principle. It means the environmental loads of the production are allocated to first use. Consequently, only the environmental effects of product collection and preparation for further use are considered for the second usage, not the impact from the production stage (Obrecht *et al.*, 2021). For instance, if recycled material is used in the system, this material does not bring any burden from the raw material production in the cut-off method. The use of this method for life cycle analysis is controversial. Eberhardt *et al.* (2020) agreed that the cut-off approach could be used for cradle-to-grave LCA. Häfliger *et al.* (2017) have also reported that cradle-to-grave analysis is based on a cut-off approach while system expansion should be used for cradle-to-cradle LCA and suggested further research is needed on the approaches for cradle-to-cradle LCA.

The other method used for multifunctionality problems is substitution. Substitution solves this problem by removing the avoided burden associated with co-products that are not part of the functional unit. Tillman et al. (1993) and Weidema (2014) advocate the idea that substitution is preferred in CLCA. In addition, although Brander and Wylie (2011) used the substitution method in ALCA, they concluded that this method could create a problem in understanding how ALCA results should be used, and it is more suitable for CLCA since the goal of CLCA is to quantify the total change in emissions caused by a change in a product's output level, including changes in emissions depending on the life cycle of other products.

Additionally, ISO 14044:2006 (International Standards Organisation., 2006) suggests system expansion to avoid multifunctionality problems. In system expansion which is also called "avoided burden", additional functions related to the co-products are included by expanding the system. For instance, when the energy is produced as output by waste incineration, this energy can be considered as an input to another product system (Weidema, 2014). Weidema (2014) also claims that substitution and system expansion are synonymous and used for the same aims. Furthermore, Moretti *et al.* (2020) argue that ISO does not give a clear explanation of the differences between system expansion and substitution, and how to apply these methods to ALCA or CLCA.

2.3. Steps and methods of conducting analysis

ISO 14044:2006 (International Standards Organisation., 2006) defines the framework of the LCA in four steps:

1. goal and scope definition,
2. life cycle inventory analysis,
3. life cycle impact assessment,
4. and interpretation of the results.

Goal and scope definition include determination of reasons for applying LCA, functional unit selection, system boundary, determining data requirements, allocation methods, etc. In the first step of all LCA studies, the methods should be identified for the goal and scope definition. There are three LCA methods for ALCA studies; process LCA, Economic Input-Output (EIO) and hybrid LCA. Process LCA demonstrates how the unit processes of a system are related to the product stream by using detailed process-level information. Therefore, it demonstrates all relations between the product/system and the environment. In contrast, EIO analyses aggregate sector-level data to determine how much environmental affect each sector of the economy has and how much each industry consumes from others. In this way, it is witnessed how a change in one component of an economic system affects other parts of the system. In addition, process and EIO LCA are combined in hybrid LCA to take advantage of the strength of both methods (Yang, Heijungs and Brandão, 2017).

Data collection and calculation procedures are incorporated in inventory analysis. In order to understand the environmental impacts, the inventory data is associated with specific environmental impact categories and category indicators. This framework is applied to all LCA studies since there is no distinction between ALCA and CLCA in ISO 14044:2006.

Until 1999, there was no specific methodology followed for the CLCA. As highlighted in the section above, marginal data is used for CLCA. Weidema (2003) introduced another framework for CLCA which has been followed by most CLCA research (Ghose, Pizzol and McLaren, 2017; M. Buyle *et al.*, 2019; Matthias Buyle *et al.*, 2019; Fauzi *et al.*, 2021) and can be considered in conjunction with these four steps of the ISO standard.

This framework which is called the “five-step procedure” follows these steps:

1. What time horizon does the study apply to?
2. Do the changes in production volume only affect specific processes or is a market affected?
3. What is the trend in the volume of the affected market?

4. Does this technology have a potential to provide the desired capacity adjustment?
5. Is this technology the preferred object of the desired capacity adjustment?

The five-step procedure aims to determine the situation in which the examined demand change occurred and analyses which technology is affected by the change in the detected condition by answering these questions.

Process LCA, Economic Input-Output (EIO) and hybrid LCA methods which are explained before can also be used in CLCA. However, an additional model would be required for CLCA to identify marginal technology. As highlighted in the section above, marginal data is used for CLCA. Since the technology has an impact on marginal data, which also influences marginal environmental load, identifying marginal technology is one of the crucial steps of CLCA. For instance, Yang and Heijungs (2018) reported that linear production models (process and EIO LCA) ignore market dynamics such as substitution, price impacts, and supply and demand variability, so they suggested using these methods along with more sophisticated models such as general or partial equilibrium analysis. Fauzi *et al.* (2021) summarized the models of identifying marginal technology used in the literature as follows:

- Partial and general equilibrium models
- Trade network analysis
- Causal descriptive
- Agent-based modelling
- Game theory
- Experience curves

It is seen that the studies that used these models are mainly on the energy and agricultural sector. While equilibrium models are generally preferred in energy studies, causal descriptive and agent-based models are used for agricultural, and land-use change research (Luu *et al.*, 2020). Although some CLCA studies include these models, there is no step-by-step approach for explaining how to conduct the analysis clearly.

Although there is no other framework used in CLCA research, there are studies in which this approach is modified (M. Buyle *et al.*, 2019; Fauzi *et al.*, 2021). For instance, Fauzi *et al.* (2021) explained steps four and five more clearly by asking "if there is a potential to provide an increase or decrease in production capacity". In addition, Pizzol and Scotti (2017) proposed two approaches, bottom-up and top-down, for identifying the geographical market boundaries required for steps two and three. With the bottom-up approach, the traded volume of a product is compared with the total production volume of a market. In the end, if it is observed that the traded volume is smaller than the market volume, this country is not considered within the geographical market boundary. Additionally, global trade data and network analysis, where the clusters represent geographical markets, are used for the top-down technique.

Details of the review show that there are limited studies on how to apply CLCA to buildings and the application of the approach is not clear for practitioners. In addition, although the use of ALCA in the construction industry is increasing day by day, this approach is not differentiated from CLCA by not explaining the method. Furthermore, there is no holistic LCA approach in which these two methodologies that support each other can be evaluated together.

3. RESEARCH DESIGN AND METHODOLOGY

To evaluate current comments, suggestions, best practices, and limitations, a wide range of relevant theoretical literature focused on ALCA and CLCA was reviewed. These steps are followed for the review: (1) formulating the research problem; (2) developing and validating the review protocol; (3) searching the literature; (4) screening for inclusion; (5) assessing quality; (6) extracting data; (7) analysing and synthesizing data; and (8) reporting the findings.

1. Formulating the research problem: First, Building LCA was identified as a broad field of interest and background information was gathered with the literature review. After narrowing the scope and focus of the research, the gap in knowledge and the problem were specified.
2. Developing and validating the review protocol: A plan was created by deciding the methods to be used in the study. According to the identified problem, the research objective was determined. Web of Science was used for identifying relevant studies.
3. Searching the literature: Publications on ALCA and CLCA methods were identified by using the Web of Science in April 2022. The search was conducted on topics and titles of the publications and characterized by the keywords: “Consequential LCA”, “Attributional LCA”, “Attributional AND Consequential”, “Building Life Cycle Assessment AND Consequential”, “Building Life Cycle Assessment AND Attributional”. Five hundred forty-six documents were compiled in terms of the keyword search on the topics, and seventy-one papers were gathered with the search on titles. In addition, Google Scholar was used for snowballing during the reading.
4. Screening for inclusion: After screening all titles and the keywords, the papers unrelated to this research were excluded. Followingly, abstracts were read, and the studies which do not provide any contribution to this research were not considered. It was determined that the research areas differ for this topic such as food production, energy fuels, construction, waste management, and material science. Therefore, studies were selected based on their relation to the research's aim in terms of the research area, sources, analysis, and implementation of practices in ALCA and/or CLCA.
5. Assessing quality : Eighty-five papers were selected for final read and they were examined in terms of the contribution on this research. Moreover, while reading some references were discovered and searched by Google Scholar as mentioned in searching the literature phase.

6. Extracting data: Key characteristics of the studies were captured for data extraction. Items extracted from each reference were listed for analysing. In terms of the reference journals, most of the papers used for this research were published in The International Journal of Life Cycle Assessment, Sustainability, Renewable and Sustainable Energy Reviews, Journal of Cleaner Production, and Journal of Environmental Management.
7. Analysing and synthesizing data from both methods: Following the collection of data, the analysis was applied to explain the key characteristics of ALCA and CLCA. After the analysis, the synthesis made up the result section of the review by combining the data.
8. Reporting the findings: A table which explains key characteristics of ALCA and CLCA and a narrative synthesis of our findings were presented.

4. RESULTS AND DISCUSSION

It was observed that although the first LCA works started in the late 1960s, there was no significant improvement until the 90s, the standardization time of LCA. In addition, while the formation of a standard contributed to the spread of LCA studies in general, attributional and consequential methods were not defined until the International Workshop on Electricity Data for Life Cycle Inventories in 2001. Although 20 years have passed since this definition, most of the LCA studies only use the attributional approach and do not even mention the name of the approach.

Attributional and consequential LCA have different aims and frameworks. Therefore, Table 2 displays the summary of key characteristics of ALCA and CLCA. It is seen that the question to be answered, data requirements, timescales, boundaries and databases are differentiated for the approaches. Moreover, while there are some similarities on conducting LCA, CLCA needs more methods to identify geographical market boundaries and marginal technology for calculating the environmental effects of the chance in the market based on our decisions.

In addition, there are some studies in which we can understand the process, EIO and hybrid methods in detail for conducting analysis (Säynäjoki *et al.*, 2017; Ghosh and Bakshi, 2020). However, there is limited information on clearly integrating the methods of identifying marginal technology into the process. Although there are uncertainties in ALCA because of the assumptions, CLCA outcomes could be more sensitive to uncertainties than ALCA due to the inclusion of market trends and the identification of marginal technology. In addition to uncertainty issues, multifunctionality is the other problem that needs to be considered. System boundaries should be identified at the beginning of the LCA study according to the aim so that the best method for avoiding multifunctionality problems can be evaluated.

In terms of the ALCA and CLCA applications on buildings, data acquisition is easier for ALCA than for CLCA. Therefore, building-specific ALCA software, which has average data, makes it more straightforward to conduct analysis, but there is no CLCA software for buildings. However, some product LCA software with Ecoinvent v3 data could be used for Building CLCA.

Table 2: Key characteristic of ALCA and CLCA

LCA Approach	Attributional LCA	Consequential LCA
Description	"accounting”, “book-keeping”, “retrospective”, “descriptive” (JRC, 2010)	“change-oriented”, "effect-oriented", "decision-based", “market-based”(JRC, 2010)
Aim of the approach	To describe the environmentally relevant physical flows to and from a life cycle and its subsystems so it is used to determine the environmental impacts that are directly linked to a product's life cycle.	To evaluate how the production and consumption of a product affect the global environmental impact.
Question to be answered (For example)	What would be the environmental impacts of a specific building?	What would be the environmental consequences if we built more of these buildings in the upcoming years?
System boundary	Direct effects in the life cycle are considered.	Both direct and indirect effects such as market effects outside of the product life cycle are considered.
Assumption methods	Allocation	System expansion / Substitution / Avoided Burden
Required data	Specific or Average data	Marginal data
Database	GaBi, Ecoinvent, Athena (US), ELCD (European) etc.	Ecoinvent v3 (+ 2013)
Time scales	Specific time (It can be for the past, today or future)	Depends on the timeframe of the change
Methods of conducting LCA	Process, Economic Input-Output, Hybrid methods	Equilibrium, input-output, or process model using dynamic models. Equilibrium is the most frequently used.
Methods of Identifying geographical market boundaries	Not required	Bottom-up approach Top-down approach (Pizzol and Scotti, 2017)
Identify marginal technology	Not required	1. Partial and general equilibrium models 2. Trade network analysis 3. Causal descriptive models 4. Agent modelling 5. Game theory 6. Experience curves (Fauzi *et al.*, 2021)

Table 2: Key characteristics of ALCA and CLCA (Continued)

Steps	The steps in general LCA 1. Goal and scope definition 2. Life cycle inventory analysis 3. Life cycle impact assessment 4. Interpretation of the results (International Standards Organisation., 2006)	1. Time horizon identification 2. Market delimitation 3. Identification of the trend in the volume of the affected market 4. Identification of whether the technology has a potential for a production capacity increase 5. Which of the suppliers/technologies are the most or least preferred (Weidema, 2003)

The most obvious finding to emerge from the study is that ALCA is more straightforward for practitioners than CLCA because of its standardisation, identified steps, data acquisition and available software variety to make the process easier. However, despite all these works cited in the literature, it has been found that even ALCA is a complex process for non-experts. Thus, it needs to be simplified for non-experts. Moreover, due to the rise in the demand for buildings due to the rapid population growth and urbanisation the impact of the built environment on climate change has increased and it is not sufficient to only analyse the environmental footprint of buildings. Consequently, it is important to consider the CLCA approach to determine the future impacts of the decisions being made by professionals in the construction sector.

Some challenges were determined for CLCA. First, different methods can be used to identify marginal technology. However, it is quite challenging to understand which way is the best for building LCA research and how to implement it due to the limited studies. ISO ISO 14044:2006 is using ALCA even though the name of the LCA approach is not specified. However, no specific standard explains CLCA methodology clearly except Weidema's five-step approach, which has been followed for CLCA studies since 2003. Nevertheless, this method has not been developed after the publication, and no other method was proposed for CLCA. Therefore, there is a need for a clear framework to show how these applications can be integrated.

The proposed framework is developed for providing a holistic LCA approach. To successfully implement the framework, it is key to start by defining the aim as it forms the basis of the analysis, and the results are finally interpreted according to the aim of the study. In the second phase, the scope including life cycle boundary, functional unit, timeframe, impact category selections, and assumption should be described. Then, according to the scope of work, the calculation method will be chosen. Collecting information about the building materials is the first step of the data collection phase. It is also required to have average and marginal data of the selected materials as well as marginal technology and geographical market boundary identification to conduct the analysis. Moreover, operational energy and water consumption values should be input for the analysis. Finally, the results per material option and the total environmental effect of the building are combined and interpreted to select the most environmentally friendly options.

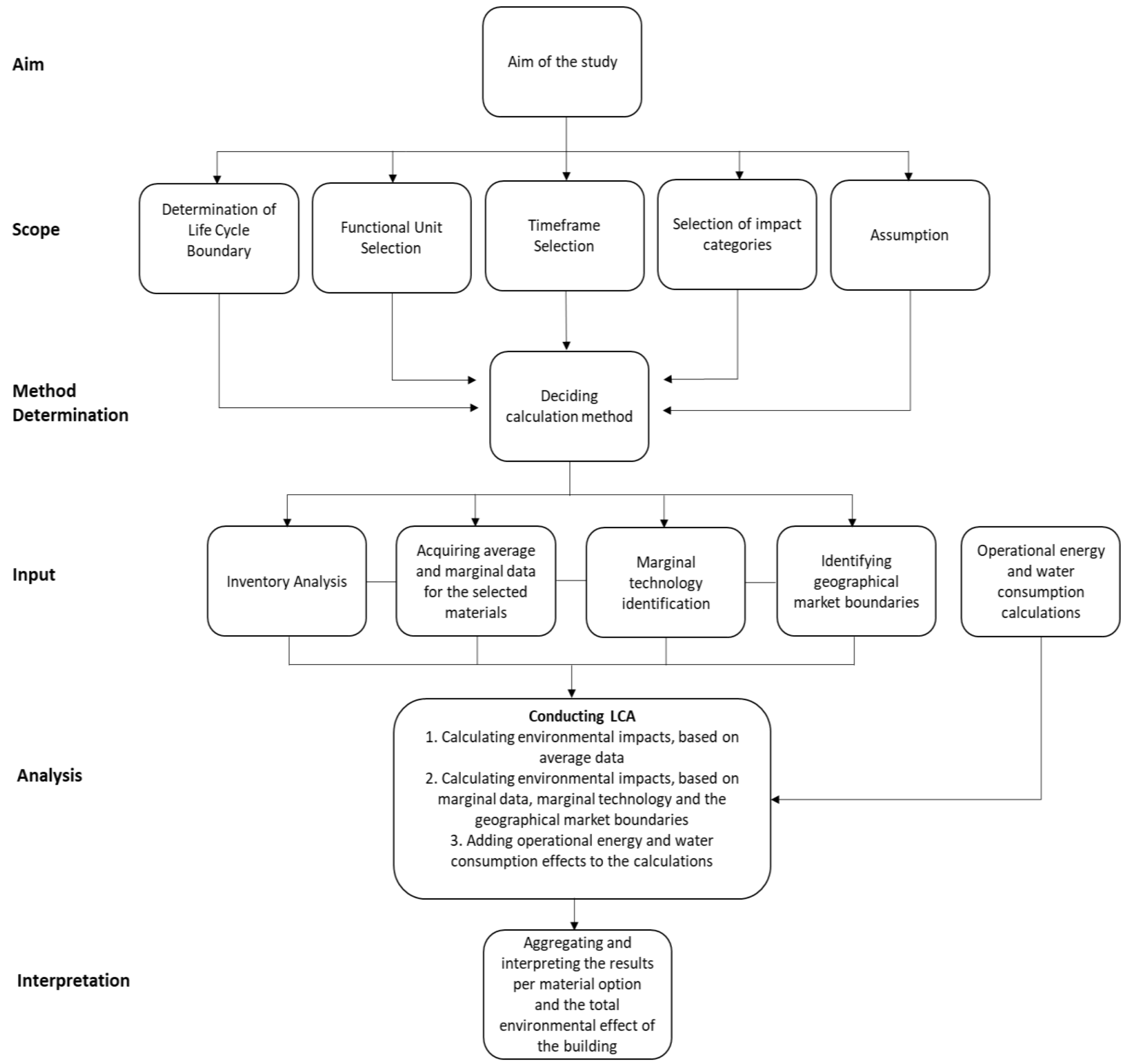

Figure 1: A framework for providing a holistic LCA approach.

This framework will be used to decide the most sustainable solutions for building design by measuring the environmental impacts of a building at a specific time and also considering the future effects of material selections. Since the effects of climate change are increasing daily, it is crucial to evaluate our decisions by considering both their current and future impacts,

5. CONCLUSION

This paper evaluated the opportunities and challenges of attributional and consequential LCA approaches by identifying their key characteristics. The differences and similarities between the approaches include system boundary and required data classified to develop a holistic framework. It is important to consider attributional and consequential LCA approaches together in the construction industry to evaluate how design affects the environment at a specific time and what will be the consequences of the design choices on the environment. In this way, the environmental impacts that are directly related to the life cycle of a building and the consequences of the decisions could be interpreted together by using the proposed framework.

Further development would be useful to describe how to identify marginal technology with the given different methods and integrate these methods into the process. This study draws our attention to the importance of having a simple guideline for CLCA and ALCA to understand the purposes and the application steps clearly for the practitioners to have a holistic LCA approach and spread the applications. Therefore, ISO and ILCD should be revised following the updated knowledge of these two approaches. Moreover, a new set of ISO standards or ILCD guidelines would be beneficial to present a step-by-step approach for CLCA implications on buildings.

REFERENCES

Agarski, B. and Budak, I. (2019) 'Attributional Versus Consequentional Life Cycle Assessment Modelling in Metalworking Production System', *Mašinstvo*, 1–2(16), pp. 37–42. Available at: https://mf.unze.ba/wp-content/uploads/2019/06/Masinstvo-1-2.pdf#page=38.

Amahmoud, A., El Attar, M. M. and Meleishy, A. (2022) 'The Evolution of Life Cycle Assessment Approach: A Review of Past and Future Prospects', *IOP Conference Series: Earth and Environmental Science*, 992(1), p. 012002. doi: 10.1088/1755-1315/992/1/012002.

Anderson, N. *et al.* (2022) 'Embodied Energy Consumption in the Residential Sector : A Case Study of Affordable Housing', pp. 1–18.

Bamber, N. *et al.* (2020) 'Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations', *International Journal of Life Cycle Assessment*, 25(1), pp. 168–180. doi: 10.1007/s11367-019-01663-1.

Brander, M. *et al.* (2008) 'Consequential and Attributional Approaches to LCA', *Ecometrica Press*, (April). Available at: https://uu.blackboard.com/bbcswebdav/pid-2938200-dt-content-rid-18783033_2/courses/GEO-2018-2-GEO4-2602-V/GEO-2018-2-GEO4-2602-V_ImportedContent_20180628010821/0804_Ecometrica_-_Consequential_and_attributional_approaches_to_LCA.pdf.

Brander, M. and Wylie, C. (2011) 'The use of substitution in attributional life cycle assessment', *Greenhouse Gas Measurement and Management*, 1(3–4), pp. 161–166. doi: 10.1080/20430779.2011.637670.

Buyle, M. *et al.* (2018) 'Strategies for optimizing the environmental profile of dwellings in a Belgian context: A consequential versus an attributional approach', *Journal of Cleaner Production*, 173(2018), pp. 235–244. doi: 10.1016/j.jclepro.2016.08.114.

Buyle, M. (2018) 'Towards a structured consequential modelling approach for the construction sector: the Belgian case. A fairy tale on methodological choices in LCA', (May), p. 230. doi: 10.13140/RG.2.2.25673.65129.

Buyle, M. *et al.* (2019) 'Consequential LCA of demountable and reusable internal wall assemblies: A case study in a Belgian context', *IOP Conference Series: Earth and Environmental Science*, 323(1), pp. 0–9. doi: 10.1088/1755-1315/323/1/012057.

Buyle, Matthias *et al.* (2019) 'Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context', *Journal of Cleaner Production*, 218(2019), pp. 141–156. doi: 10.1016/j.jclepro.2019.01.306.

Buyle, M., Braet, J. and Audenaert, A. (2014) 'Life cycle assessment of an apartment building: Comparison of an attributional and consequential approach', *Energy Procedia*, 62, pp. 132–140. doi: 10.1016/j.egypro.2014.12.374.

Cabeza, L. F. *et al.* (2014) 'Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review', *Renewable and Sustainable Energy Reviews*, 29, pp. 394–416. doi: 10.1016/j.rser.2013.08.037.

Cordier, S. *et al.* (2021) 'Regional environmental life cycle consequences of material substitutions: The case of increasing wood structures for non-residential buildings', *Journal of Cleaner Production*, 328(October), p. 129671. doi: 10.1016/j.jclepro.2021.129671.

Curran, M. A., Mann, M. and Norris, G. (2005) 'The international workshop on electricity data for life cycle inventories', *Journal of Cleaner Production*, 13(8), pp. 853–862. doi: 10.1016/j.jclepro.2002.03.001.

Dixit, M. K. *et al.* (2010) ‘Identification of parameters for embodied energy measurement: A literature review’, *Energy and Buildings*, 42(8), pp. 1238–1247. doi: 10.1016/j.enbuild.2010.02.016.
Earles, J. M. and Halog, A. (2011) ‘Consequential life cycle assessment: A review’, *International Journal of Life Cycle Assessment*, 16(5), pp. 445–453. doi: 10.1007/s11367-011-0275-9.
Eberhardt, L. C. M. *et al.* (2020) ‘Development of a life cycle assessment allocation approach for circular economy in the built environment’, *Sustainability (Switzerland)*, 12(22), pp. 1–16. doi: 10.3390/su12229579.
Ekvall, T. *et al.* (2016) ‘Attributional and consequential LCA in the ILCD handbook’, *International Journal of Life Cycle Assessment*, 21(3), pp. 293–296. doi: 10.1007/s11367-015-1026-0.
Ekvall, T. (2019) ‘Attributional and Consequential Life Cycle Assessment’, in *Sustainability Assessment at the 21st Century*, p. 13. Available at: http://dx.doi.org/10.1039/C7RA00172J%0Ahttps://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics%0Ahttp://dx.doi.org/10.1016/j.colsurfa.2011.12.014.
Ekvall, T. and Finnveden, G. (2001) ‘Allocation in ISO 14041 - a critical review’, *Journal of Cleaner Production*, 9(3), pp. 197–208. doi: 10.1016/S0959-6526(00)00052-4.
European Committee for Standardization (2011) ‘UNE-EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method’, *International Standard*, (November).
Fauzi, R. T. *et al.* (2021) ‘Life cycle assessment and life cycle costing of multistorey building: Attributional and consequential perspectives’, *Building and Environment*, 197(December 2020), p. 107836. doi: 10.1016/j.buildenv.2021.107836.
Finnveden, G. *et al.* (2009) ‘Recent developments in Life Cycle Assessment’, *Journal of Environmental Management*, 91(1), pp. 1–21. doi: 10.1016/j.jenvman.2009.06.018.
Fonseca i Casas, P. and Fonseca i Casas, A. (2017) ‘Using Specification and Description Language for Life Cycle Assesment in buildings’, *Sustainability (Switzerland)*, 9(6). doi: 10.3390/su9061004.
Gaudreault, C., Samson, R. and Stuart, P. R. (2010) ‘Energy decision making in a pulp and paper mill: Selection of LCA system boundary’, *International Journal of Life Cycle Assessment*, 15(2), pp. 198–211. doi: 10.1007/s11367-009-0125-1.
Ghose, A., Pizzol, M. and McLaren, S. J. (2017) ‘Consequential LCA modelling of building refurbishment in New Zealand- an evaluation of resource and waste management scenarios’, *Journal of Cleaner Production*, 165(2017), pp. 119–133. doi: 10.1016/j.jclepro.2017.07.099.
Ghosh, T. and Bakshi, B. R. (2020) ‘Designing hybrid life cycle assessment models based on uncertainty and complexity’, *International Journal of Life Cycle Assessment*, 25(11), pp. 2290–2308. doi: 10.1007/s11367-020-01826-5.
Guinée, J. B. *et al.* (2011) ‘Life Cycle Assessment: Past, Present, and Future’, *Environmental Science & Technology*, 45(1), pp. 90–96. doi: 10.1021/es101316v.
Guinée, J. B. *et al.* (2018) ‘Digesting the alphabet soup of LCA’, *International Journal of Life Cycle Assessment*, 23(7), pp. 1507–1511. doi: 10.1007/s11367-018-1478-0.
Häfliger, I. F. *et al.* (2017) ‘Buildings environmental impacts’ sensitivity related to LCA modelling choices of construction materials’, *Journal of Cleaner Production*, 156, pp. 805–816. doi: 10.1016/j.jclepro.2017.04.052.
Heimersson, S., Svanström, M. and Ekvall, T. (2019) ‘Opportunities of consequential and attributional modelling in life cycle assessment of wastewater and sludge management’, *Journal of Cleaner Production*, 222, pp. 242–251. doi: 10.1016/j.jclepro.2019.02.248.
International Standards Organisation. (2006) ‘ISO 14040: 2006. Environmental management–Life cycle assessment–Principles and framework.’, *The International Journal of Life Cycle Assessment*, 2006(7), pp. 652–668.
JRC, E. (2010) *ILCD handbook: general guide for Life Cycle Assessment: detailed guidance*, *Publications Office of the European Union: Luxembourg*. doi: 10.2788/38479.
Luu, Q. Le *et al.* (2020) ‘A conceptual review on using consequential life cycle assessment methodology for the energy sector’, *Energies*, 13(12). doi: 10.3390/en13123076.
Majeau-Bettez, G. *et al.* (2018) ‘Choice of allocations and constructs for attributional or consequential life cycle assessment and input-output analysis’, *Journal of Industrial Ecology*, 22(4), pp. 656–670. doi: 10.1111/jiec.12604.
Mary Ann Curran (2006) *Life Cycle Assessment: Principles and Practice*. Cincinnati.
Moretti, C. *et al.* (2020) ‘Reviewing ISO compliant multifunctionality practices in environmental life cycle modeling’, *Energies*, 13(14), pp. 1–24. doi: 10.3390/en13143579.
Moretti, C. *et al.* (2022) ‘Attributional and consequential LCAs of a novel bio-jet fuel from Dutch potato by-products’, *Science of the Total Environment*, 813. doi: 10.1016/j.scitotenv.2021.152505.
Nemry, F. *et al.* (2010) ‘Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs’, *Energy and Buildings*, 42(7), pp. 976–984. doi: 10.1016/j.enbuild.2010.01.009.
Nicholson, A. L. *et al.* (2009) ‘End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions’, *2009 IEEE International Symposium on Sustainable Systems and Technology, ISSST ’09 in Cooperation with 2009 IEEE International Symposium on Technology and Society, ISTAS*. doi: 10.1109/ISSST.2009.5156769.
Obrecht, T. P. *et al.* (2021) ‘An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment’, *Journal of Cleaner Production*, 327(September). doi: 10.1016/j.jclepro.2021.129527.
Pedinotti-Castelle, M. *et al.* (2019) ‘Is the environmental opportunity of retrofitting the residential sector worth the life cycle

cost? A consequential assessment of a typical house in Quebec', *Renewable and Sustainable Energy Reviews*, 101(November 2018), pp. 428–439. doi: 10.1016/j.rser.2018.11.021.
Pizzol, M. and Scotti, M. (2017) 'Identifying marginal supplying countries of wood products via trade network analysis', *International Journal of Life Cycle Assessment*, 22(7), pp. 1146–1158. doi: 10.1007/s11367-016-1222-6.
Rocha, C. S., Antunes, P. and Partidário, P. (2019) 'Design for sustainability models: A multiperspective review', *Journal of Cleaner Production*, 234, pp. 1428–1445. doi: 10.1016/j.jclepro.2019.06.108.
Säynäjoki, A. *et al.* (2017) 'Input–output and process LCAs in the building sector: are the results compatible with each other?', *Carbon Management*, 8(2), pp. 155–166. doi: 10.1080/17583004.2017.1309200.
Schaubroeck, T. *et al.* (2021) 'Attributional & consequential life cycle assessment: Definitions, conceptual characteristics and modelling restrictions', *Sustainability (Switzerland)*, 13(13), pp. 1–47. doi: 10.3390/su13137386.
Tillman, A.M.; Ekvall, T.; Baumann, H.; Rydberg, T. (1993) 'Choice of system boundaries in life cycle assessment', *Journal of Cleaner Production*, 2(1), pp. 21–29. doi: 10.1109/WCNCW.2016.7552692.
United Nations Environment Programme (2021) *2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Nairobi.
Vigovskaya, A., Aleksandrova, O. and Bulgakov, B. (2017) 'Life Cycle Assessment (LCA) in building materials industry', *MATEC Web of Conferences*, 106, pp. 0–4. doi: 10.1051/matecconf/201710608059.
Weidema, B. (2003) 'Market information in life cycle assessment', *Danish Environmental Protection Agency Environmental Project*, 863(863), p. 147. Available at: http://www.norlca.org/resources/780.pdf.
Weidema, B. (2014) 'ISO system expansion = substitution', *2.0 Consultants*, p. 1. Available at: https://lca-net.com/blog/iso-system-expansion-substitution/.
Yang, Y. and Heijungs, R. (2018) 'On the use of different models for consequential life cycle assessment', *International Journal of Life Cycle Assessment*, 23(4), pp. 751–758. doi: 10.1007/s11367-017-1337-4.
Yang, Y., Heijungs, R. and Brandão, M. (2017) 'Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA', *Journal of Cleaner Production*, 150, pp. 237–242. doi: 10.1016/j.jclepro.2017.03.006.