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IMPROVING BUILDING LIFE CYCLE ASSESSMENT THROUGH INTEGRATED APPROACHES

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Abstract
Life Cycle Assessment (LCA) is a valuable method for enhancing the environmental sustainability of buildings. By considering the entire life cycle of a building, Life Cycle Assessment helps to make informed decisions by optimizing the use of materials and energy resources, reducing environmental impacts, and creating a more sustainable built environment. Based on a review of studies on the life cycle assessment of buildings, this article describes methods that aim to improve the quality of construction data, integrate environmental, social, and economic impacts, and utilize various models such as BIM, transportation, economic, and ecological modelling. Context-specific LCA can improve the quality of the results. Developing robust impact assessment methods can enhance the accuracy of environmental impact assessments. Integrating life cycle thinking into decision-making helps stakeholders to consider the environmental impacts of products or buildings. This is achieved through integrated methods that promote holistic approaches and improve green building practices.

Keywords: *Life Cycle Assessment, Green Building, Integrated Methods, Decision-Making*

1. Introduction

1.1. Green Building Life Cycle Assessment

Green buildings aim to reduce their environmental impact by integrating sustainable design, construction, and operational processes. The Life Cycle Assessment is a valuable tool in the field of green building, providing a comprehensive approach to assessing and enhancing the environmental sustainability of buildings. By considering the full life cycle of a building and its components, LCA helps make informed decisions, optimize material and energy resource use, reduce environmental impacts, and create more sustainable built environments. LCA can provide a comprehensive approach to assessing the environmental impacts of various building materials, energy use, waste generation, and emissions associated with the entire life cycle of a building, from its creation from cradle to grave. The life cycle of a building includes several stages, such as raw material extraction, manufacturing, transportation, construction, use, and end-of-life. A life cycle assessment considers all these stages and evaluates their environmental impacts, which include resource depletion, greenhouse gas emissions, land use, water use, and waste generation. The process of conducting a life cycle assessment involves collecting data about inputs and outputs at each stage of the life cycle, quantifying environmental impacts using standardized metrics, engaging stakeholders, interpreting results to identify areas for improvement, and developing more reliable methods for assessing the specific impact of a building. Life cycle assessment considers both direct impacts, such as energy use on a site, and indirect impacts, such as those associated with the production and transportation of building materials. By applying LCA to green building design and construction, architects, engineers, and construction professionals can make informed decisions to reduce a building's environmental footprint. It enables them to identify opportunities to improve material selection, enhance energy efficiency, promote water conservation, waste management, and implement other sustainable practice.

1.2. Reviewing Previous Studies

In this article, we reviewed numerous scientific studies conducted in the past decade that focused on enhancing the life cycle assessment of buildings. We also formulated the methods employed in these studies to improve the life cycle assessment. Improving the quality of construction data was one such avenue, as enhancing life cycle assessment relies on the availability of accurate and up-to-date data. This ensures the improvement of Environmental Impact Assessment (EIA) results for the different stages in the building life cycle (Francart et al., 2021). Another approach that has been used in numerous studies is to expand the life cycle assessment to incorporate additional environmental, social, and economic impacts that have not been traditionally evaluated. This can include the effects of climate change, social justice, human health, and the economic costs and benefits of different consumption and production patterns in buildings (Su et al., 2019). The life cycle of a building can be evaluated using various models, including Building Information Modelling (BIM), transportation modelling, economic modelling, and environmental modelling. Studies show that context-specific LCA provides decision-makers with more relevant and actionable insights (Veselka et al., 2020). Comparing life cycle assessments based on different databases, such as processes or inputs and outputs, improves the quality of assessment results (Vuarnoz et al., 2020). The development of more robust impact assessment methods can have a positive impact on life cycle assessment. By improving the methods used to assess the environmental impacts of different stages in the product life cycle, their accuracy and comprehensiveness can be enhanced (Lucchi et al., 2020).

1.3. Research aim

In this study, we conduct a comprehensive review of the latest studies that have addressed methods for enhancing the life cycle assessment of buildings. Our objective is to determine the most effective approach to improving the life cycle assessment of buildings.

2. Methods for enhancing Life Cycle Assessment

The methodology used in this study relies on reviewing previous studies, examining the methods employed in them, monitoring data, and extracting relevant and valuable information from these specific studies. This is supported by evidence that confirms the validity of the life cycle assessment. Based on this review, the methodologies used to comprehensively improve life cycle assessment will be summarized as follows. *Figure 1* illustrates various methods for enhancing LCA.

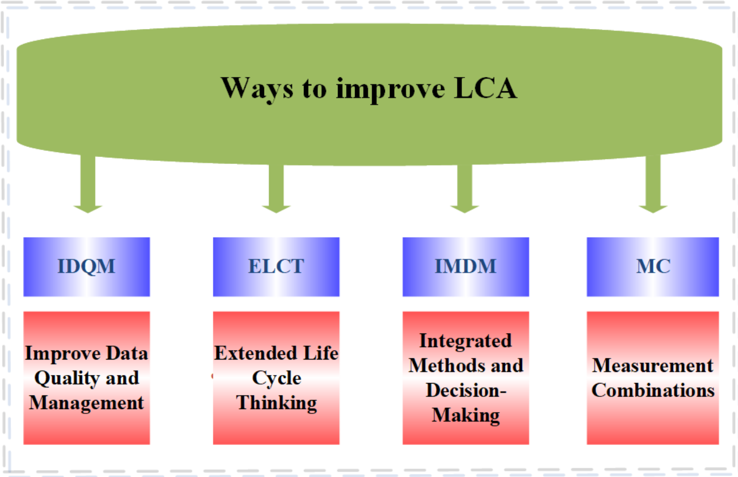

Figure 1. *Methods for enhancing Life Cycle Assessment*

2.1. Improved Data Quality and Management (IDQM)

Improving the quality and availability of data is crucial to ensure accurate and comprehensive life cycle assessments for green buildings. This approach is considered one of the most important ways to improve assessment, as it serves as the starting point for evaluating the life cycle of any building. Therefore, over the past few years, researchers have been focused on utilizing various methods to improve data quality. One such method is collecting primary data, which is considered more accurate than secondary data sources such as databases or industry averages. (Roberts et al., 2023). It is also essential to collect primary data at all stages of the building life cycle from construction to demolition (Lützkendorf, 2022). Normative data can also be obtained from product databases, industry associations, and government agencies. In addition to being recommended by numerous studies, promoting data sharing among stakeholders results in greater data availability and lower costs of data collection. Some of these studies also recommended the establishment of an information platform (Beemsterboer et al., 2020; Ye et al., 2023). Other studies have recommended the use of advanced technologies, such as sensors and automation, to improve data collection and analysis. For example, sensors can collect real-time data on energy consumption, water usage, and indoor air quality (Zimmermann et al, 2019; Theißen et al., 2020). A unified database is another way to enhance the quality and comparability of data across different buildings and projects (Francart et al., 2020). Collaborating with experts, such as architects, civil engineers, energy auditors, energy evaluators, and sustainability consultants, can enhance the quality and accessibility of data. Experts can provide valuable insights into building design, construction, and operation. They can also help identify data gaps and uncertainties (Goulouti et al., 2020). Data management is the next step in collecting high-quality data. This involves maintaining accurate records of data sources, ensuring data security and privacy, and implementing quality control measures. Additionally, it involves conducting a preliminary analysis of energy usage, which includes analysing billing data and final energy consumption during the use stage (Mastrucci et al., 2020).

2.2. Extended Life Cycle Thinking (ELCT)

Extended Life Cycle Thinking (ELCT) is an important and promising approach for green buildings. This expansion includes the studies of Primary Energy Assessment (PEA), Life Cycle Cost (LCC), and Social Impact Assessment (SIA) (van Stijn et al., 2021). *Figure 2* presents the expanding scope of the Life Cycle Assessment of buildings.

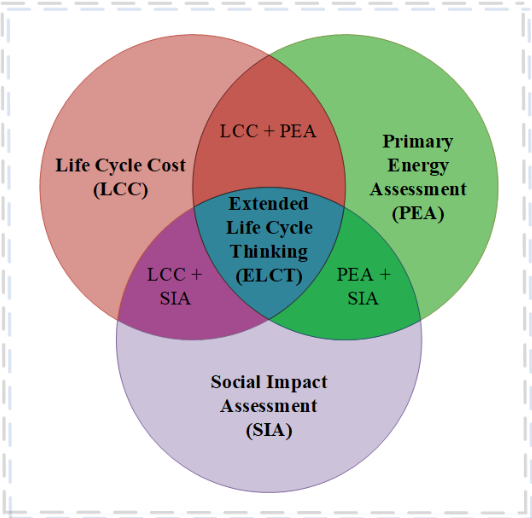

Figure 2. *Expanding the scope of the Life Cycle Assessment of buildings*

2.2.1. Primary Energy Assessment (PEA)

The concept of primary energy is essential for understanding the overall energy efficiency and environmental impact of a building. A building's primary energy refers to the total energy consumed from natural resources or raw energy sources to meet its energy requirements. It includes all the energy needed for heating, cooling, lighting, appliances, and other electrical and non-electrical requirements of a building. To calculate a building's primary energy consumption, both the direct energy consumed at the site (known as site energy) and the indirect energy required to distribute energy (referred to as source power) must be considered. The latter considers the energy losses during the extraction, transformation, and distribution of energy. Site energy is consumed directly within a building to meet its energy needs. (Usman et al., 2023). This includes electricity for lighting, appliances, and equipment, as well as energy for heating, cooling, and hot water production. Site energy is typically measured in kWh or British Thermal Units (BTUs). Source energy refers to the primary energy required to produce site energy and transport it to the building. It represents the energy losses that occur during the production, transmission, and distribution of electricity and other energy carriers. For example, when electricity is generated in a power plant, there are energy losses during fuel extraction, transformation, and transportation. Source power is usually measured by the quantity of primary energy sources (such as coal, natural gas, oil, nuclear, and renewables) required to generate power at a specific location. By assessing site and source energy, building professionals and policymakers can gain a better understanding of a building's actual energy consumption and its environmental impact. This information is crucial for making informed decisions regarding energy efficiency improvements, the integration of renewable energy sources, and overall sustainability efforts aimed at reducing a building's carbon footprint and contributing to global energy conservation goals (Usman et al., 2023).

2.2.2. Life Cycle Cost (LCC)

LCC is an essential financial analysis tool that companies, governments, and organizations use to make informed decisions about investments and various projects. Building life cycle cost usually includes the following components (AlJaber et al., 2023):

1. Cost of construction or acquisition: The initial cost of construction or acquisition includes all expenses related to the building's design, construction, and purchase. This includes materials, labour, permits, fees, and any other costs associated with the construction of the building.
2. Operation and Maintenance Costs: These are the ongoing costs required to efficiently operate the building and maintain it in good condition throughout its lifespan. It includes utilities such as electricity, water, heating, and cooling, as well as cleaning, repairs, maintenance, and other recurring expenses.
3. The cost of renovation and upgrades: Buildings may require renovations or upgrades to accommodate changing needs, comply with new regulations, or improve energy efficiency. These costs are considered in the life cycle assessment.
4. Energy and Resource Efficiency Costs: Investments in energy-efficient systems, renewable energy technologies and sustainable building practices can add additional costs during construction or renovation. However, they can lead to long-term savings in operating expenses.
5. End-of-Life Costs: Eventually, a building may reach the end of its useful life, and costs related to decommissioning, demolition, and disposal are considered in the life cycle assessment.

2.2.3. Social Impact Assessment (SIA)

It is a systematic and comprehensive assessment of potential social consequences and impacts on the surrounding community and stakeholders that may arise from undertaking a construction or development project. A social impact assessment aims to identify and understand both the positive and negative social impacts of a project. It also aims to develop strategies to enhance positive impacts and mitigate negative impacts. It helps ensure that building development is aligned with social sustainability goals and addresses the concerns of the affected community. An assessment of the social impact of a building may include the following main steps (Liu et al., 2019):

1. Impact Determination: Evaluate the potential social impacts of the construction project on the surrounding community and stakeholders. This may include changes in employment opportunities, housing affordability, public services, local culture, and social cohesion.
2. Impact Assessment: It involves evaluating the scale, importance, and duration of identified social impacts. Distinguish between short-term and long-term effects, considering both direct and indirect consequences.
3. Mitigation and Enhancement Strategies: Develop strategies to mitigate negative impacts and enhance positive impacts. This can include community involvement programs, local job opportunities, conditions for affordable housing, measures to preserve cultural heritage, and initiatives to promote social inclusion.
4. Monitoring and Management Plan: Develop a monitoring and management plan to track the actual social impacts during and after the construction of the building project. This ensures that the proposed mitigation and enhancement measures are effectively implemented, and any necessary adjustments are made (Tokede et al., 2023).

2.3. Integrated Methods Approach and Decision-Making (IMDM)

Green building design and construction are part of broader social, economic, and environmental systems. Decision-making regarding green buildings must consider the impacts on these integrated systems and the potential trade-offs or synergies between various sustainability objectives. Decision-making tools that consider life cycle effects can help identify the most sustainable options for green building design and construction. There are two levels of decision-making that should be noted. Holistic decision-support mediation for policy focuses on comparing options to achieve a policy goal and understanding the consequences of selecting a policy (Seduikyte et al., 2023; Pamu et al., 2022). Life cycle assessment can be improved by obtaining more accurate standards and evidence that can help inform informed decision-making. The most crucial modelling methods used for Life Cycle Assessment will be reviewed to enhance the reliability of its results. *Figure 3* shows models used to improve the life cycle assessment of buildings.

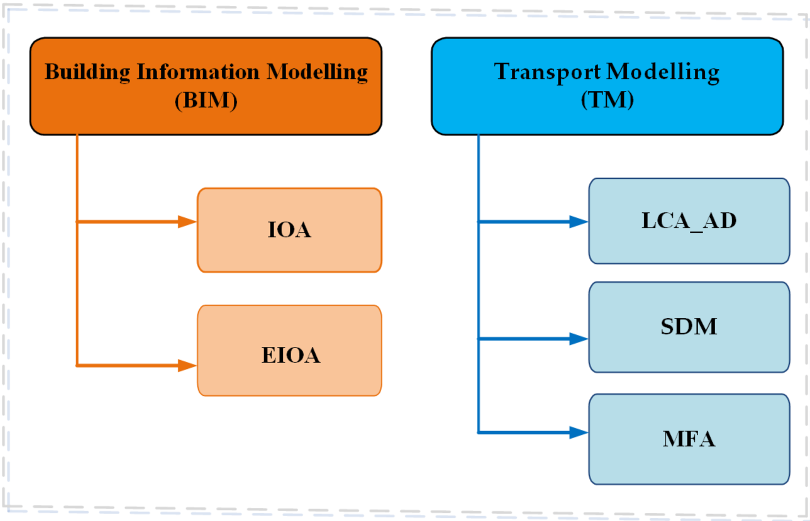

Figure 3. *Models used to improve the life cycle assessment of buildings*

2.3.1. Building Information Modelling (BIM)

The relationship between Building Information Modelling (BIM) and LCA of buildings centres around their complementary roles in improving the sustainable design, construction, and operation of buildings. BIM is a digital representation of the physical and functional characteristics of a building. It involves creating and managing a 3D model that contains information about various elements, such as architectural features, structural components, building systems, materials, and more (Spudys et al., 2023). BIM facilitates collaboration among architects, engineers, contractors, and other stakeholders throughout the lifecycle of a building. It is primarily used for design, construction, and facility management purposes. The relationship between BIM and LCA for buildings is as follows:

1. <u>Data integration:</u> BIM provides a comprehensive digital model of a building, encompassing information about the materials, components, and systems used in its construction. This data can be combined with LCA software to analyse the environmental impacts of various design and material choices.

2. Design optimization: With BIM, architects and engineers can explore different design alternatives and select materials. LCA data integrated into BIM allows for the assessment of the environmental impacts of these alternatives and enables more informed decisions that prioritize sustainability.
3. Performance Analysis: During the building commissioning phase, BIM can be connected to real-time data and performance monitoring systems. This integration allows for continuous assessments of the LCA to analyse the environmental performance of the building over time and identify opportunities for improvement.
4. Retrofitting and Renovation: BIM, together with LCA data, can help assess the environmental benefits of retrofitting or refurbishing existing buildings. Helps identify upgrades and modifications that can result in the most significant reduction in environmental impacts.
5. Facility Management: BIM models can be valuable for the management and maintenance of ongoing facilities. By incorporating life cycle assessment information, facility managers can optimize resource usage and implement environmentally friendly practices.

2.3.2. Transport Modelling (TM)

The relationship between transportation modelling and LCA of buildings is rooted in their shared objective of evaluating and understanding the environmental impacts associated with transportation and the entire life cycle of a building. Transportation modelling (TM) involves creating mathematical or computational models to simulate and analyse the movement of people, goods, or vehicles within a transportation network. This modelling helps us understand traffic flow, travel patterns, energy consumption, emissions, and other factors related to transportation. The integration between Transport Modelling and LCA for buildings primarily involves considering transportation-related aspects throughout the various stages of the building's life cycle (Jallow et al., 2021).

1. Material Transportation: Transportation modelling data is used to assess the energy consumption and emissions associated with transporting raw materials to the construction site. This includes moving materials such as steel, concrete, glass, and other building components.
2. Construction Phase: Transportation modelling helps analyse the environmental impacts of transporting construction workers, equipment, and materials to and from the construction site during the construction process.
3. Occupancy and Use: The LCA considers transportation impacts related to occupants, such as commuting to and from the building, the use of public transportation, and the energy consumed by private vehicles parked in the building.
4. End-of-Life: Transportation modelling data can be used to analyse the energy consumption and emissions associated with transporting demolition debris to recycling or disposal facilities.

By combining transportation modelling data with the building's LCA, stakeholders can gain a more comprehensive understanding of the building's overall environmental impact. This integrated approach helps identify areas where transportation-related impacts are significant and allows decision-makers to implement strategies to improve transportation options, thereby reducing the overall environmental impact of a building. Moreover, it helps in making informed decisions regarding the location, material sources, transportation methods, and other factors that contribute to the sustainability and environmental friendliness of the building throughout its lifecycle (Jallow et al., 2021).

2.3.3. Input-Output Analysis (IOA)

Input-output analysis (IOA) is a technology that tracks the flow of goods, services, and monetary transactions between different sectors of the economy. It creates a matrix that shows the interdependencies and relationships between sectors and how other sectors use inputs from one sector to produce goods and services. The integration between IOA and LCA for buildings is as follows:

Supply chain analysis: an IOA can provide valuable insights into the upstream supply chain for building materials. By analysing the economic interdependence between sectors, an IOA can help determine the energy, resource and emissions intensity associated with the production of building materials (Mattila, 2018).

Environmental impacts of building materials: Integrating IOA data into LCA allows for a more comprehensive assessment of the environmental impacts of building materials. The IOA can provide data on the energy consumption and emissions associated with the production and transport of building materials (Fahlstedt and Bohne, 2022).

2.3.4. Environmental Input-Output Analysis (EIOA)

Environmental input-output analysis (EIOA) is an extension of traditional input-output analysis (IOA) that includes environmental data, such as greenhouse gas emissions, energy consumption, water use, and other environmental indicators. EIOA is a powerful tool for understanding the environmental impacts of economic activities. It provides valuable insights into the environmental impacts associated with producing and consuming goods and services. The main characteristics and features of an environmental input-output analysis include:

Environmental Extensions: EIOA extends traditional input-output tables with environmental data, enabling the assessment of environmental impacts associated with producing and consuming goods and services.

System of Environmental Accounts: In EIOA, the economy is represented as a system of environmental accounts that tracks flows of materials, energy, and emissions between different sectors. This helps in understanding the links between economic activities and environmental impacts.

Ecological Footprint Assessment: The EIOA allows for calculating the ecological footprint of various economic sectors, products, or regions. It provides a comprehensive view of economic activities' direct and indirect environmental impacts (Schuerch et al., 2012).

2.3.5. LCA with Advanced Database (LCA_AD)

Advanced databases play a critical role in enhancing the accuracy and comprehensiveness of LCA studies. These databases provide more detailed and up-to-date information on the environmental impacts of various activities, materials, and technologies. Some of the widely used advanced databases for LCA include:

1. GaBi: GaBi is another extensive LCA database containing data on various processes and products. It is often used in industry-specific assessments and includes information on material and energy flows, emissions, and resource consumption.
2. Ecoinvent: This is one of the most comprehensive LCA databases, covering various processes and materials from different regions worldwide. It includes data on energy production, agriculture, transportation, manufacturing, and waste management.
3. ELCD: The European Life Cycle Database (ELCD) focuses on providing LCA data specifically for European processes and materials. It is maintained by the European Commission's Joint Research Center and contains a wealth of data on various sectors.
4. US LCI Database: Maintained by the US Environmental Protection Agency (EPA), this database provides life cycle inventory data for various US products and processes.
5. AGRIBALYSE: This database is specifically designed for agricultural operations and includes data on crop production, livestock raising, and other related activities.

Advanced databases allow LCA practitioners to model processes more accurately and efficiently, as they have access to data that reflects the latest technological developments, regional changes, and specific data about different stages of the product life cycle (Kalakul et al., 2014; Kupfer et al., 2018; ISO 14040:2006, 2016; ISO 14044:2006, 2016; Kiss et al., 2021).

2.3.6. System Dynamics Model (SDM)

System dynamics is a modelling approach used to understand the behaviour of complex systems over time. It is a valuable tool in various fields, including engineering, management, economics, and environmental science. System dynamics models (SDMs) help analyse the dynamic interactions between different components within a system, enabling researchers and decision-makers to study feedback, delay, and linear loops that influence system behaviour (Ige et al., 2022).

<u>Main Components of SDMs:</u>

1. Stocks and Flows: Stocks represent accumulations or quantities of items in a system, such as stock, population, or capital. Flows represent rates of change in these stocks over time, such as production, consumption, or growth rates.
2. Feedback loops: System dynamics models often include feedback loops, which can be reinforcing (positive) or balancing (negative). Reinforcement loops amplify changes while balancing loops tend to stabilize the system.
3. Delays: Delays refer to the time it takes for an action to impact the system. Delays can lead to oscillations and complex behaviour in the model.
4. Feedback loops and causal links: Causal links describe cause-and-effect relationships between different system components, while feedback loops represent causal chains that create dynamic behaviour.
5. Time: System dynamics models are based on time and usually simulate the behaviour of a system over discrete periods.

<u>Construction-related applications:</u>

- Building life cycle assessment
- Building energy performance
- Indoor Environmental Quality (IEQ)
- Occupant behaviour
- Building control systems
- Urban Planning and Infrastructure
- Retrofitting and renovation

2.3.7. Material Flow Analysis (MFA)

Material flow analysis (MFA) is a method used to track the flow of materials within a system or economy. It aims to understand the use of materials, identify sources of contamination, and manage material losses. The MFA method helps to analyse the amounts of material entering and leaving the system and to identify the flows and wastes that can be improved through effective management.

The integration between MFA and LCA for buildings is as follows:

1. <u>Material tracking and quantification:</u> The MFA provides valuable insights into the flow and quantity of materials used in the construction sector. It tracks materials from extraction to their incorporation into building materials and products. Data from the MFA can be integrated into the LCA to assess the environmental impacts of resource consumption associated with the life cycle of a building.

2. Determination of material-intensive processes: The MFA can help identify processes or building components that require high materials or generate significant waste during their life cycle. This information is valuable for the LCA to focus on the stages with the most significant environmental impacts and identify improvement opportunities.
3. Resource Efficiency Assessment: By combining MFA and LCA, decision-makers can assess resource efficiency in the construction sector and identify opportunities to reduce material consumption, waste generation and environmental impacts.
4. Circular economy and recycling: MFA can provide insights into the flow of materials after the life of a building. This information can inform the LCA about the possibility of recycling and adopting circular economy principles in construction and demolition operations.
5. Policy formulation and design of sustainable buildings: Integrating the MFA with LCA enables policymakers and designers to develop strategies and policies that target the most resource-intensive and environmentally impact aspects of building construction, operation, and disposal (Scherz et al., 2022).

2.4. Measurement Combinations (MC)

The life cycle assessment results differ according to the different data based on it. There are three types of life cycle assessments, namely:

1. Process-based LCA
2. LCA-based input-output
3. Hybrid LCA

The types of life cycle assessments are interrelated and can be derived from one another. For example, an LCA-based input-output analysis can serve as the foundation for a process-based LCA and a hybrid LCA. This connection is indicated by a double arrow in *Figure 4*.

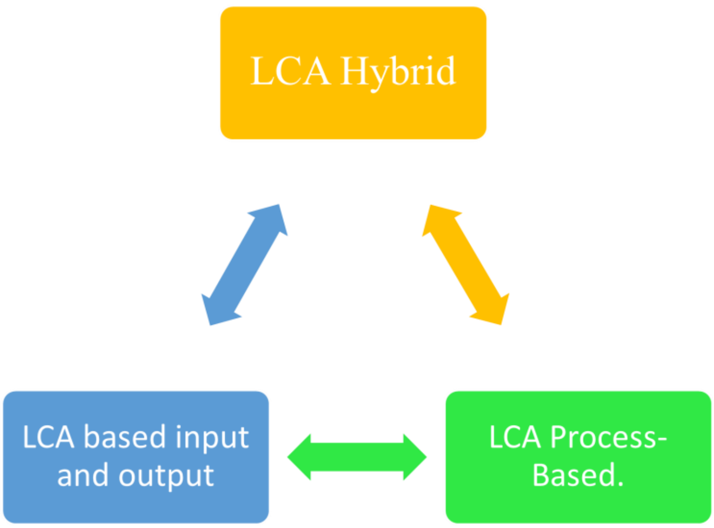

Figure 4. *Types of Life Cycle Assessment*

2.4.1. Process-based LCA

Process-based life cycle assessment involves explicitly modelling individual processes within the product life cycle. It involves collecting detailed data on each process, such as raw material extraction, manufacturing, transportation, use, and end-of-life. This method is highly accurate in capturing specific environmental effects associated with each process (Scherz et al., 2022).

2.4.2. LCA-based input and output

On the other hand, input-output cycle assessment relies on economic data and national or regional input-output tables. It evaluates both direct and indirect environmental impacts by examining economic transactions and the interdependence among different sectors of the economy. This approach is useful for capturing the overall impacts of product consumption and economic activities (Schuerch et al., 2012).

2.4.3. Hybrid LCA

A Hybrid Life Cycle Assessment is an approach that combines the strengths of a process-based LCA and an input-output-based LCA to provide a comprehensive and accurate assessment of the environmental impacts of products, services, or systems. Hybrid LCA integrates information and benefits from both process-based and input-output LCAs to overcome some of the limitations of individual methods (Nakamura et al., 2016).

1. Addressing Data Gaps: Operations-based life-cycle analysis may encounter data gaps or limitations, especially when dealing with intricate supply chains or emerging technologies. By integrating input and output data, Hybrid LCA can fill in these data gaps and provide a more comprehensive understanding of the overall life cycle effects.
2. Economic Impact Assessment: Input-output cycle assessment excels at capturing the economic consequences of product consumption and trade. A hybrid LCA can identify both direct environmental impacts through process-based modelling and indirect impacts resulting from economic activities using input-output data.
3. System Boundaries: Hybrid LCA allows for greater flexibility in defining system boundaries. It can include detailed process data for crucial stages of the life cycle, while relying on input and output data for less significant processes or those with limited available data.
4. Scale and Complexity: Hybrid LCA can handle the complexity of large-scale assessments that involve multiple products, industries, and regions. It is particularly useful for assessing the environmental impact of entire economies or sectors.

4. Summary

Green buildings aim to reduce their environmental impact by integrating sustainable design, construction, and operational processes. The Life Cycle Assessment is valuable for assessing and enhancing building environmental sustainability. By considering the entire life cycle of a building, LCA helps make informed decisions, optimize material and energy resource use, reduce environmental impacts, and create more sustainable built environments. Applying LCA to green building design and construction, we can make informed decisions to reduce a building’s environmental impacts and implement other sustainable practices. This article reviews scientific studies on building life cycle assessment, focusing on improving construction data quality, expanding the assessment to include environmental, social, and economic impacts, and using various models like BIM, transportation, economic, and environmental modelling. Context-specific LCA provides actionable insights, and comparing assessments based on different databases improves the quality of results. Developing robust impact assessment methods can enhance the accuracy and comprehensiveness of environmental impact assessment. Integrating life cycle thinking in decision-making helps stakeholders consider environmental impacts of products or buildings, utilizing integrated methods and measuring data for holistic approaches and improvement in green building practices.

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