# Sustainability Analysis of Structural Materials Used in Multistoried Building Construction: A Cradle to Grave Approach

**Mohammad Masfiqul Alam Bhuiyan, Mohammad Rezaul Karim, and Ahmed Hammad**

**Abstract** Over time, the construction industry's development has been constantly questioned due to low productivity, high energy consumption, generation of wastes, and greenhouse gas emissions. According to a recent United Nations Environment Program report, building and construction account for 36% of global energy use and 39% of energy-related carbon dioxide ($CO_2$) and greenhouse gas emissions. Sustainable construction aims to minimize harm and maximize value by balancing social, economic, technical, and environmental aspects, commonly known as the pillars of sustainability. In general, concrete, timber, steel, masonry, etc., materials are used to construct multistoried buildings. Though technical and economic aspects are always considered while selecting the structural components, other elements like social and environmental are mostly ignored. A sustainable decision is always critical as it combines all technical, social, economic, and environmental factors in the decision-making process. On the contrary, though it seems crucial during the planning and conceptual development phase and costly while designing and construction, a sustainable choice is always more economical, eco-friendly, and convenient, considering the entire life cycle of any construction work. This paper analyzed the characteristics of commonly used structural materials from the sustainability point of view, considering the project's complete life cycle. We have followed a hybrid approach to analyze life cycle sustainability analysis by integrating the outcomes obtained through life cycle cost analysis, environmental life cycle analysis, and social life cycle analysis and taking the opinion of stakeholders. The outcome of the analysis is expected to enhance objectivity in the selection process of structural material by the decision-makers contributing to more sustainable building construction.

**Keywords** Building sustainability · Materials analysis · Multistoried Construction · LCA

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## 1 Introduction

Sustainability entails addressing our own demands without jeopardizing future generations' ability to meet their own [20]. We require social and economic resources in addition to natural resources [2]. Environmentalism is not the only aspect of sustainability. Therefore, concerns for social equity and economic development are found in most definitions of sustainability [7]. Again, as the Brundtland Commission on Environment and Development recognized, economic progress at the expense of ecological health and social fairness did not lead to long-term success. It was evident that the world needed to find a method to balance environmental sustainability and economic growth. It defines sustainable development as "development that meets current demands without compromising future generations' ability to meet their own needs" [20]. Sustainability is a holistic strategy that considers the ecological, social, and economic components, realizing that all three must be regarded to achieve long-term prosperity [2].

Buildings or houses are one of the most necessities of human life. The building industry is an essential part of every economy. With the rapid rise of the population and hence fulfilling their requirements, the construction industry is now liable for significant environmental impact, currently accounting for 36% of global energy use and 39% of energy-related carbon dioxide ($CO_2$) emissions [21]. Building construction, fit-out, operation, and eventual demolition have a significant direct and indirect impact on the environment, both directly due to material and energy consumption and the resulting pollution and waste and indirectly through the effect of inefficient infrastructure. A reduction in the environmental impact of a building during its life cycle is, therefore, an essential target in terms of sustainable development [16]. In this context, there has been a considerable effort over the past few decades to investigate the life cycle energy use and impacts of buildings. However, the building sector is still primarily motivated by economic gain, particularly short-term gain [15]. Hence, to achieve sustainability, it is necessary to transform the practices on a large scale to focus on the environment and society, with the objective of sustainable practice being to have a beneficial influence effectively. It is necessary to encourage businesses to balance long-term benefits with instant returns to pursue inclusive and environmentally sound objectives. This encompasses a wide range of different practices. Cutting emissions, cutting energy consumption, obtaining items from fair-trade organizations, and ensuring their physical waste is disposed of appropriately and with as little carbon impact as possible would all qualify as steps toward sustainability while also lowering the price.

The speed with which steps toward sustainable application are done is determined by decisions made by a variety of participants in the building process, including owners, managers, designers, corporations, and others [4]. The sustainable selection of materials to be utilized in construction projects is a critical decision. The simplest method for designers to implement sustainable concepts in construction projects is to carefully select sustainable structural materials [14]. However, due to a lack of formal and available measuring criteria, the selection of construction materials is viewed as a multi-criteria decision issue [10]. And it would be easier for the stakeholders to decide if numerical approaches can be developed in the life cycle assessment of the building keeping sustainability in mind.

Reinforced concrete is the most often used structural material for building construction. Concrete is a widely used material for a variety of construction applications due to its strength, durability, reflectivity, and adaptability [13]. These features make it a durable and long-lasting alternative for various residential and industrial building construction. However, ironically, concrete is one of the leading sources of environmental degradation and is harmful to our ecosystem and environment. Concrete manufacturing emits 2.8 billion tons of carbon dioxide, accounting for 4–8% of global greenhouse gas emissions [17]. Concrete consumes a tenth of all industrial water around the globe [9]. To achieve sustainability, it is required to look for alternatives in building construction. Steel may be used to replace concrete in structural construction due to its numerous advantages, including high strength, high tensile, ductile, flexible, and cost-effectiveness [12]. On the other hand, steel needs a lot of energy in its manufacturing process and might be expensive in some situations. Masonry is also a time-tested alternative to concrete construction, albeit burned bricks may emit significant levels of carbon during the manufacturing process, and masonry construction requires a substantial amount of cement [5]. So, in recent days, architects, builders, and sustainability advocates have been buzzing about timber, a building material that they believe has the potential to significantly reduce greenhouse gas (GHG) emissions in the building sector, as well as waste, pollution, and construction costs, while also creating a more physically, psychologically, and aesthetically healthy built environment [19]. A life cycle sustainability analysis using these materials in an example of multistory building structure may reveal a clear picture of the aspects influencing sustainability based on its four pillars: economic, social, technical, and environmental. The findings of the research will assist stakeholders in identifying viable materials for future building development from a sustainability standpoint.

## 2 Problem Statement

Traditionally, the structural materials for a building are based on the stakeholder's requirements or value demand. Here, the perspective is mainly influenced by experiences, local tradition, or understanding of construction materials. This is principally determined by affordability, cost–benefit analysis, and return on investment, among other factors, though it is true that while selecting materials, few consumers nowadays search for greenness or environmental issues. However, including the environment sustainability also involves a broader range of economic, technological, and social factors. Each of these four is given due weight in the study of sustainability. In many circumstances, the requirement of sustainability evolves apparently contradicting criteria such as being environmentally friendly while also being affordable or less expensive, having a better aesthetic perspective yet using local materials, having a high efficiency while using less energy, and so on. As a result, focusing merely on the timeframe for constructing a facility may not necessarily provide a good picture of whether these parameters are met. Instead, it necessitates a comprehensive examination of the construction materials from conception to demolition or reuse, commonly referred to as a life cycle analysis (LCA), which can provide a more accurate picture of sustainability when choosing structural material for a building construction project.

## 3 Aim and Objective

This study aims to carry out a sustainability analysis balancing economic, environmental, technical, and social needs for a low to midrise multistoried building construction project with the following objectives:

- Based on the ground survey and literature reviews, select the alternative structural materials for low to midrise multistoried buildings.
- Conduct a sustainable life cycle analysis for each of the alternatives with the view that the building industry will enable identifying parameters and added values needed for an attractive and sustainable solution.
- Expert and stakeholder perspectives on material selection based on analytical results.

## 4 Methodologies

To undertake this study, the critical issue is: How can we ensure more sustainable structural materials for a construction project that can be implemented and considered in the decision-making process while considering all the pillars of sustainability? The authors followed the application of the life cycle perspective to the sustainability pillars, which can provide a method of incorporating sustainable development into decision-making processes. In this context, life cycle sustainability analysis refers to considering the environmental, technical, social, and economic implications of a building across its complete life cycle. The methodology is graphically explained in Fig. 1.

## 5 Selections of Alternative Structural Materials

For structural components of a house build, the construction industry employs several building materials. Architects engage structural engineers on the load-bearing capacities of the materials they design with, the most common of which are concrete, steel, wood, masonry, and stone. Each has its unique strength, weight, and durability,

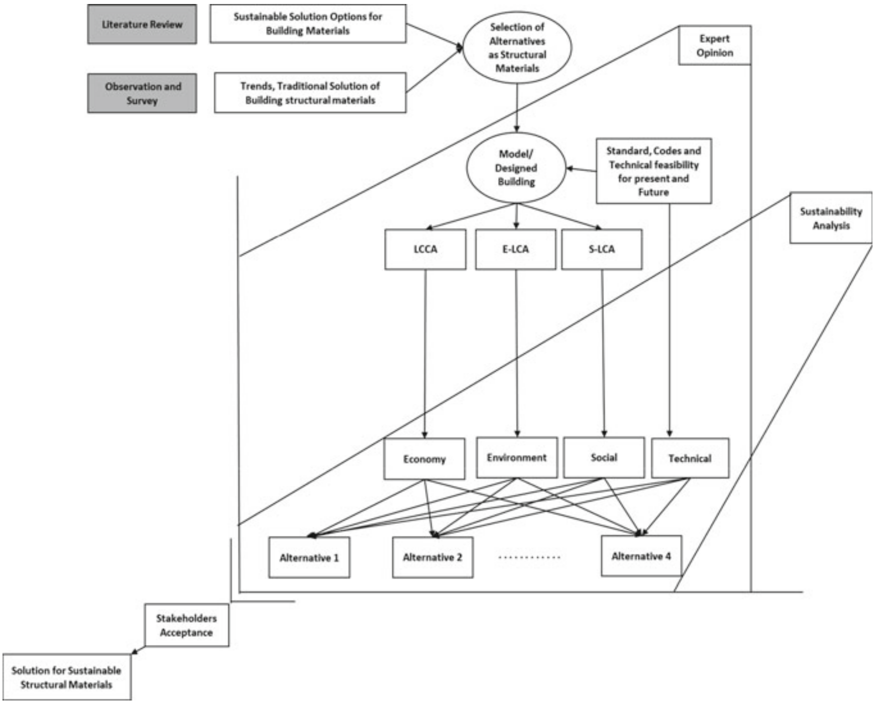

**Fig. 1** Research methodology

making it suited for a wide range of uses. National standards and testing processes control building materials used in the construction industry, so they can be relied on to ensure structural integrity. When selecting materials, architects consider both cost and appearance.

Owners are highly guided by different factors. Though most of them have shallow knowledge of the materials to be used for the building, traditionally it is driven by their experience, local practices, and affordability, with cost–benefit analysis. Other factors to consider include, if the material is long-lasting, reusable, less toxic, uses fewer resources, and is better for the environment, wildlife, and humans. So, choice of materials depends on the location, culture, material availability, materials price, weather susceptivity, etc.

Here, life cycle sustainability analysis (LCSA) is the sum of life cycle cost analysis (LCCA), environmental life cycle analysis (E-LCA), and social life cycle analysis (S-LCA).

$$\text{LCSA} = \text{LCCA} + \text{E - LCA} + \text{S} - \text{LCA}$$

**Table 1** Alternative building materials selected by researchers in sustainability or green building study

| References | Alternative materials selected for assessment |
|---|---|
| Gharehbaghi and Georgy [8] | Timber, concrete, steel for building construction |
| Abouhamad and Abu-Hamd [1] | Reinforced concrete framing (RC), steel framing (SS), and cold-formed steel framing (CFS) framework for the selection of construction systems of low and medium rise buildings |
| Davies et al. [6] | Concrete, steel, wood for life cycle analysis of building construction |

Several studies have been conducted in the past regarding alternative construction materials in the context of green building or sustainability. Table 1 contains a collection of instances.

## 6 Description of the Model/referenced Building

A three-story hypothetical building model exemplified as shown in the Fig. 2 was used as the case study building. The structure was inspired by New Zealand's new NMIT Arts and Media complex [6]. Each level of the building has a gross size of 500 sqm (5400 sqft) and a total height of 9.2 m (30 ft). There are 30 columns having a concrete column footing. Only the essential structural components, such as the foundation, column beam, floor slab, wall, and roof structure are considered while analyzing the building. Other elements are disregarded. The structure is then redesigned using reinforced concrete, masonry, and steel as primary structural materials. Except for masonry, all other scenarios require a concrete foundation. When utilizing concrete, the footing size increases significantly due to the increased self-weight of the structural components.

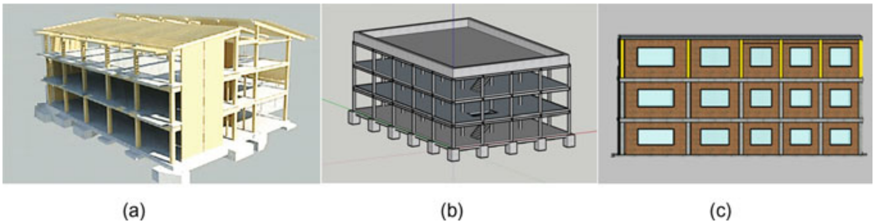

**Fig. 2** Three-story building design in timber, concrete, and masonry [6]

## 7 Life Cycle Sustainability Analysis (LCSA) of the Building

Life cycle sustainability assessment evaluates the negative environmental, social, and economic costs and advantages in decision-making processes toward more sustainable solutions throughout their life cycle (LCSA). An increased interest in developing methods to better understand and address the impacts of products throughout their life cycle has been sparked by a growing global awareness of the importance of environmental protection; an understanding of the risks of trade-offs between possible impacts associated with materials (both manufactured and consumed); and the necessity of taking climate change issues and biodiversity into account from a holistic perspective. LCSA of a building structure can be divided into three essential components, life cycle cost analysis (LCCA), environmental life cycle analysis (E-LCA), and social life cycle analysis (S-LCA). The model building is analyzed for its LCSA for a period of 60 years by using ATHENA [3]. ATHENA Impact Estimator for buildings, the first free software tool intended to analyze entire buildings and assemblies using internationally recognized life cycle assessment (LCA) methods. The Impact Estimator considers the environment with other more typical design elements at the conceptual stage of a project. The estimator considers all aspects of material production, including resource extraction and recycled content. It also considers related modes of transportation, variations in energy consumption, structure type and estimated lifespan, maintenance and replacement effects, disposal, demolition, etc.

### *7.1 Life Cycle Cost Analysis (LCCA)*

The life cycle cost analysis (LCCA) approach is used to calculate the overall cost of facility ownership [18]. It considers the expenses associated with purchasing, owning, and disposing of a building or building system. LCCA is notably beneficial for comparing project options that meet the same performance criteria but differ in terms of initial and running costs to choose the one that optimizes net savings.

LCCA will assist in determining whether the inclusion of structural materials, which may increase initial costs but result in lower operating and maintenance expenses, is cost-effective. The lowest life cycle cost (LCC) is the most straightforward and simple economic assessment metric. Net savings, savings-to-investment ratio, internal rate of return, and payback period are more often used metrics [11]. They are compatible with the lowest LCC evaluation measure if the same parameters and research time are used. Building economists, certified value experts, cost engineers, architects, quantity surveyors, operations researchers, and others may employ one or more of these methods to assess a project. Whether it's termed cost estimates, value engineering, or economic analysis, the method to selecting cost-effective decisions for building-related projects can be relatively similar.

### 7.1.1 LCCA Method

The goal of an LCCA is to assess the total costs of project options and choose the design that assures the facility has the lowest overall cost of ownership while maintaining its quality and function [18]. To achieve a decrease in life cycle costs, the LCCA should be undertaken early in the design phase while there is still time to revise the design. The first and most difficult duty of an LCCA, or any economic evaluation approach, is to evaluate the economic consequences of various building and building system designs and quantify and represent these effects in monetary numbers.

### 7.1.2 LCCA Calculation

There are numerous costs related with operating, maintaining, and disposing of a building or building system. The general LCC formula for buildings summarizing all costs that occur from cradle to grave is given at Eq. 1 [18]:

$$\text{LCC} = I + \text{Repl} + E + W + \text{EOL} \tag{1}$$

where

$I$ = investment costs,
Repl = replacement costs,
$E$ = operational energy costs,
$W$ = operational water costs,
and EOL = end-of-life costs.

However, to combine and compare cash flows incurred at different points over a project's life cycle, they must be made time equivalent. The LCC approach transforms cash flows to present values by discounting them to a single point in time, generally the base date, to make them time equivalent. The interest rate utilized for discounting is a rate that represents an investor's opportunity cost of money over time, which means that the investor wants to earn at least as much as her next best investment. As a result, the discount rate indicates the investor's acceptable minimum rate of return. The present value (PV) formula given at Eq. 2 was employed in the LCC calculation to discount future cash flows to current values [9]:

$$\text{PV} = F_t / \frac{1}{(1+d)^t} \tag{2}$$

where

$PV$ = present value,
$t$ = time in unit of year,
$F_t$ = future cash amount that occurs in year $t$

$d$ = discount rate, which is used for discounting future amounts to the present value.

After identifying all costs by year, they are discounted to the present value, and added to arrive at the total LCC for each alternative, as shown in Table 2 and Fig. 3:

## 7.2 *Environment Life Cycle Analysis (E-LCA)*

E-LCA is a quantified evaluation approach for assessing environmental performance across the life cycle of a product or service. Throughout all stages, the extraction and consumption of resources (including energy) as well as emissions to air, water, and soil are measured. After that, their potential contribution to environmental impact categories is evaluated. Climate change, human and eco-toxicity, ionizing radiation, and resource base degradation are examples of these categories (e.g., water, non-renewable primary energy resources, land, etc.). The life cycle initiative was instrumental in developing the midpoint-damage framework for life cycle assessment, which conceptualizes the linkages between a product's environmental interventions and the ultimate damage caused to human health, resource depletion, and ecosystem quality—information that is critical for decision-makers. Three major indexes, total primary energy, $CO_2$ emission (global warming potential), and fossil fuel consumption are used to evaluate the influence of construction materials on the environment in this case. The ATHENA Impact Estimator for building software was used to calculate the amount, which is depicted in Fig. 4.

## 7.3 *Social Life Cycle Analysis (S-LCA)*

A social life cycle analysis (S-LCA) is a method for evaluating the social and sociological elements of goods and their existing and prospective positive and negative impacts throughout their life cycle. This covers raw material extraction and processing, production, distribution, usage, reuse, maintenance, recycling, and final disposal. S-LCA uses general and site-specific data, can be quantitative, semi-quantitative, or qualitative, and is used in conjunction with environmental LCA and LCC. It can be used independently or in combination with the other methods. The S-LCA material assessment presents an approach for developing life cycle inventories. A life cycle inventory is elaborated for indicators linked to impact categories which are related to five main stakeholder groups: worker, occupants, local community, society, and value chain actors. Here, the score of S-LCA is the sum of the positive and negative scores assigned to the indicators impacting the stakeholders' group. In comparison with the other three choices, timber has a higher social value, generates income for the community, connects people with nature, and reduces waste and pollution.

**Table 2** Comparative statement of the LCC of alternative structural materials [3]

| Stages and cost categories | | | Concrete | | Steel | | Timber | | Masonry | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Actual | PV | Actual | PV | Actual | PV | Actual | PV |
| Production stage | Raw material supply (A1) | Construction cost | 900.5 | 900.5 | 1014.2 | 1014.2 | 973.2 | 973.2 | 880.2 | 880.2 |
| | Transport (A2) | | | | | | | | | |
| | Manufacturing (A3) | | | | | | | | | |
| Construction process stage | Transport to the building site(A4) | | | | | | | | | |
| | Installation into building (A5) | | | | | | | | | |
| Use stage (50 years) | Use/application (B1) | Maintenance cost | 83.2 | 50.7 | 149.6 | 91.2 | 79.9 | 48.7 | 24.4 | 14.9 |
| | Maintenance (B2) | | | | | | | | | |
| | Repair (B3) | | | | | | | | | |
| | Replacement (B4) | Replacement cost | 124.9 | 76.12 | 55.0 | 33.5 | 83.0 | 50.6 | 51.2 | 31.2 |
| | Refurbishment (B5) | | | | | | | | | |
| | Operational energy use (B6) | Operation energy cost | 23.1 | 14.1 | 30.8 | 18.8 | 16.6 | 10.1 | 10.8 | 6.6 |
| | Operational water use (B7) | Operation water cost | 17.2 | 10.5 | 14.6 | 8.9 | 13.0 | 7.9 | 28.2 | 17.2 |

(continued)

**Table 2** (continued)

| Stages and cost categories | | | Concrete | | Steel | | Timber | | Masonry | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Actual | PV | Actual | PV | Actual | PV | Actual | PV |
| End-of-life stage (after 50 years) | Deconstruction/ Demolition (C1) | End-of-life cost | 272.7 | 101.3 | 34.3 | 20.8 | 42.9 | 26.1 | 158.8 | 59.0 |
| | Transport (C2) | | | | | | | | | |
| | Waste processing (C3) | | | | | | | | | |
| | Disposal and reuse (D1) | | | | | | | | | |
| Total | (Thousand USD) | | 1153.3 | | 1187.4 | | 1116.6 | | 1009.4 | |

*Note* Here, $d = 2\%$ and for PV of use stage $t = 25$ years (average of 50 years) is considered. All costs are in thousand USD.

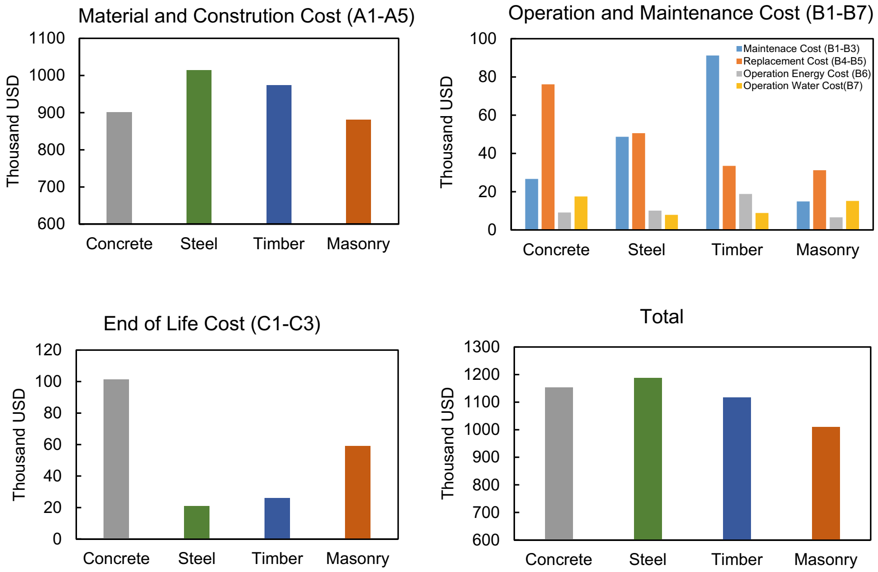

**Fig. 3** LCC of the building using different structural materials

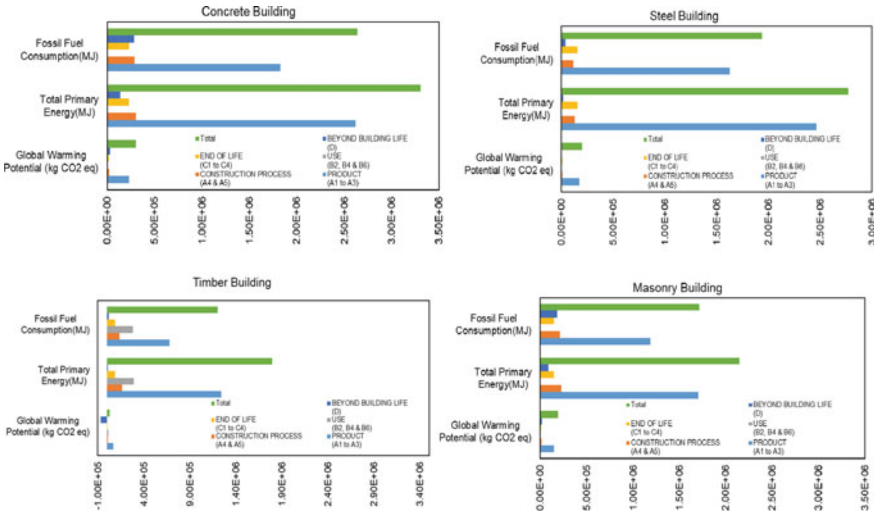

**Fig. 4** Impact of building materials on environmental index

## 8 Analysis Outcomes Based on the Expert Opinion

The statistics and analytical findings of the LCSA show that, despite having the greatest LCC, lumber may have a considerable positive impact on the environment. Although the overall LCC of timber building is just 10% higher than that of concrete, it decreases greenhouse emissions and energy use by nearly half. Masonry is also a more cost-effective option than concrete, and it emits less carbon. Steel is also a little more environmentally friendly and less costly than concrete throughout the course of its life cycle. The findings of this study's research will aid practitioners in organizing complex environmental, technological, economic, and social facts and data. It will assist in clarifying the trade-offs between the three sustainability pillars, life cycle phases and effects, products, and generations, by providing a complete perspective of the positive and negative implications along the product life cycle. It will show businesses how to take greater responsibility for their operations by taking into consideration the whole spectrum of effects associated with their goods and services. It will increase value chain players' understanding of sustainability problems, facilitate the discovery of defects, and enable future product life cycle improvements. It will help decision-makers prioritize resources and invest them where there is a higher possibility of positive results and a lower likelihood of harmful consequences and selecting sustainable technologies and materials. It can value compared to determine if things are more cost-effective, ecologically friendly, socially responsible, and more sustainable. Transparent LCSA information exchange promotes the development of trust among building construction businesses toward sustainability.

## 9 Conclusions

To achieve a sustainable building, it is critical to use sustainable materials. While quantifying all the economic, environmental, technical, and social ramifications of sustainability pillars is difficult, data and analysis of building materials allow for realistic comparisons between solutions based on specific criteria. Different materials can be employed as structural components in constructing a structure. Each of these materials has its sustainability characteristics; therefore, one may be cost-effective but more environmentally harmful or aesthetically incompatible with the environment. The requirement for multi-criteria decision-making is obvious, since several characteristics are beneficial in the end choice of selecting the most sustainable material. The LCSA has the potential to initiate interest in developing methods to understand better and address the impacts of building materials throughout their life cycle, as well as a growing global awareness of the importance of environmental protection; an understanding of the risks of trade-offs between potential infrastructure and its impacts on the environment and society; and the need to think about climate change and biodiversity holistically.

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