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Article

A General Framework for Sustainability Assessment of Buildings: A Life-Cycle Thinking Approach

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Abstract: Construction is a manufacturing industry that consumes substantial amounts of natural resources, human resources, and social capital. Activities that occur during building construction and utilization negatively impact the environment and have direct and indirect impacts on the surrounding community and society. Properly assessing the sustainability of buildings is critical to the pursuit and achievement of sustainable development goals. Also, construction project decision-makers and stakeholders currently lack an effective tool for comparing the relative sustainability of different materials, design approaches, construction methods, and building operation alternatives. Thus, an integrated framework for assessing building sustainability in terms of environmental, economic, and social aspects is developed and proposed in this paper based on life cycle thinking. This framework is applicable to different building types and life-cycle assessment scopes and provides a practical tool for construction investment project stakeholders to reference, implement, and use to guide the decision-making process. This framework may also provide a reference for other researchers in the construction field to develop sustainability assessment models optimized for different types of construction projects.

Keywords: integration; building sustainability assessment; framework; life-cycle thinking; sustainable development

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1. Introduction

Sustainable development (SD), a mature concept often applied when making development-related policies, relates to a set of goals necessary to the creation of a system that generates at least a net-zero impact on its three constituent dimensions of environment, economy, and society. Moreover, only products that satisfy specific requirements in all three dimensions can be considered "sustainable" (Figure 1).

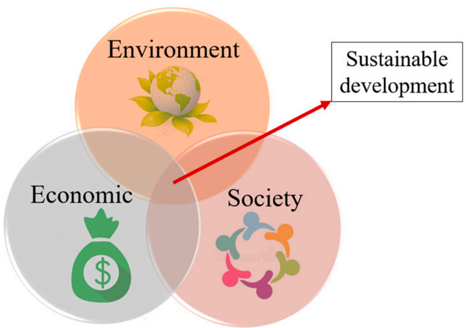

Figure 1. Three pillars of sustainability.

Construction works and built environments contribute significantly to the human impact on the natural environment and to overall life quality. Importantly, the impact of the construction industry on all three sustainable development dimensions (environment, society, and economy) is increasing [1]. The construction industry accounts for as much as 50% of total global energy consumption [2] and over 30% of the total global CO_2 emissions [3]. The negative impacts of the construction industry, in particular, and human activity, in general, result in severe environmental consequences, one of which is climate change. In light of the above, changing traditional approaches to development and construction is essential to achieving sustainability. This is the inspiration underlying many of the modern concepts related to sustainability in the construction sector, such as green buildings, carbon labels, and sustainable construction materials [4–6].

The significant impact of the construction industry on SD, especially in the environmental dimension, makes it important to properly assess building sustainability to provide a basis for investment decision-making. As the concepts of 'green' and 'sustainability' have been vaguely defined and sometimes used interchangeably in both the literature and practice, clarifying these concepts is important. Green buildings may be defined by their performance in terms of factors in the environmental dimension of sustainability, such as types of materials used, land use, water, and energy consumption. Standardized methods such as Building Research Establishment Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), and Green Star NZ may be used to assess the "greenness" of construction works [7], with the results of their related assessment tool referenced when issuing green building certification. However, sustainability in construction has a broader meaning that incorporates all three pillars of SD. Thus, in addition to 'greenness', the social impacts (positive and negative) and economic benefits of the buildings across their useable life should also be considered when assessing their sustainability. Therefore, an assessment framework that comprehensively considers the environmental, economic, and social dimensions of sustainability across the life cycle of construction works is developed and proposed in this paper. This integrated assessment framework may be used by construction investment project stakeholders to reference, practice, and effectively support related decision-making processes.

2. Literature Review

2.1. Life Cycle of a Building

The life cycle of a building (Figure 2) covers multiple stages, including raw material extraction (A1), building materials/components manufacturing (A2–A3), construction site work (A4–A5), building operation and maintenance (B1–B7), and construction demolition and disposal/reuse/recycling of materials (C1–C4, D). At each stage, natural resources, energy, and water are consumed [8], and environmental impacts (e.g., greenhouse gas emissions) are generated [9].

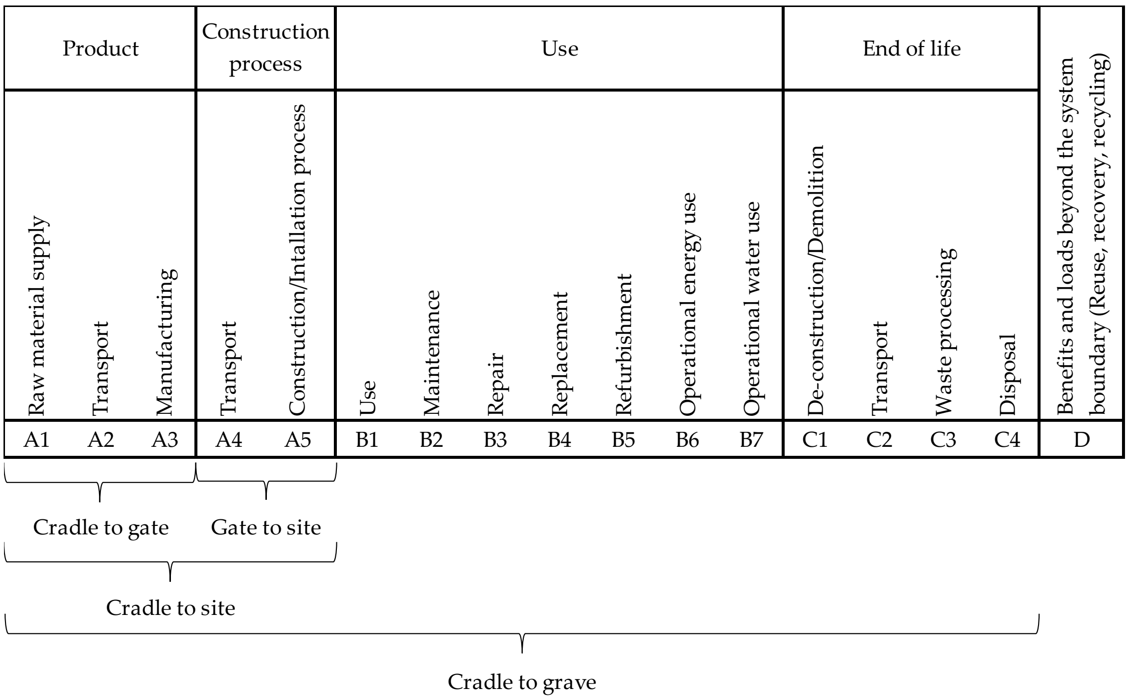

Figure 2. Life cycle of a building and system boundaries (adapted from EN 15978:2011 [10]).

2.2. Sustainable Development in Construction

SD is regular consideration in development policy decision-making. The concept of SD was first established in 1980 in the "World Conservation Strategy" report published jointly by the International Union for the Conservation of Nature, the World Wide Fund for Nature, and the United Nations Environmental Program [11]. This report was updated in 1991 and republished by the same organizations under the title "Caring for the Earth" [12]. The World Commission on Environment and Development also defined the concept of SD in its 1987 report as "Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [13].

Construction is a large-scale manufacturing industry that produces products (e.g., buildings and infrastructure) that significantly impact development in nearly every other sector of the economy. However, construction is also one of the most natural-resource-intensive sectors of the economy. Construction-related activities, particularly during the construction phase, significantly impact the natural environment and emit significant amounts of environmental pollutants. Also, the manufacture of construction materials is a highly polluting activity that releases dust, fibers, particles, and harmful gases into the environment and consumes large quantities of non-renewable energy and minerals such as coal, lead, copper, and zinc, among others [14]. Furthermore, as construction requires available land, new construction activity necessarily reduces the amount of land available for agriculture as well as for forests and other wild ecosystems, influencing flora and fauna and the ecological balance.

In addition to its negative environmental impacts, construction activities frequently have both direct and indirect negative effects on communities and society. Construction work causes noise pollution and traffic congestion that affects other socio-economic activities. Moreover, unplanned construction activity easily stresses technical and social infrastructures and urban landscapes and impairs normal visibility.

Thus, as suggested above, the natural development of the construction industry is at odds with SD, especially in terms of the environmental dimension.

2.3. Sustainability Assessment of Buildings

Bragança et al. stated that only buildings at the intersection of all aspects of sustainability, including environment, economy, society, and culture, may be considered as truly "sustainable" [15]. Assessing the sustainability of a building is important in terms of minimizing the consumption of energy and water resources, maximizing the use of environmentally friendly construction materials, optimizing operations and maintenance, and providing information for decision-making during design, construction, and operational phases.

Currently, there are many methods to assess the sustainability of buildings. These methods are mainly used in granting green building certification to qualified ones. Each method is developed and is often applied in different countries. Some popular international standard methods can be mentioned, such as the BREEAM in the United Kingdom [16], the LEED in the United States [17], and the Deutsches Gütesiegel Nachaltiges Bauen (DGNB) in Germany [18]. In addition to the above international standards, several countries have developed and promoted their building sustainability assessment methods. Noteworthy examples include CASBEE in Japan [19], Green Star in Australia [20], Haute Qualité Environnementale (HQE) in France [21], and LOTUS in Vietnam [22], etc.

In general, constructing and using sustainable buildings contribute to reducing the negative impact of humans on the natural environment while improving the quality of life for building users, reducing costs over the project life cycle, increasing project market value, and increasing transparency for potential project investors [23].

In addition to the abovementioned methods, life-cycle assessment has been used in many studies to assess building and structural sustainability (Table 1). However, few of these studies have adequately addressed sustainability in terms of the environment, economy, and society. Moreover, most do not provide solutions that incorporate these three aspects but rather assess these three aspects in parallel, independently. A key issue hindering the successful integration of these three aspects is their use of different measurement units. Two potential approaches to integrating these aspects include ignoring the related measurement units or restating these units in financial terms (i.e., monetization). The highly subjective and speculative process of monetizing social impacts due to the qualitative nature of many social impact assessment indicators makes ignoring the related measurement units the preferred approach to an integrated, life-cycle-based framework for assessing the sustainability of buildings.

Table 1. Summary of prior research on the integrated assessment of sustainability in construction.

Reference	Object	Scope of Life-Cycle (See Details in Figure 2)	Assessment Aspect	Integration
[24]	Earth-retaining walls	A–C	Environment Economic Society	Yes, using COPRAS technique, weights considered
[25]	Highway	A–C	Environment Economic	No
[26]	Bridge	A1–A4, B2–B3	Environment Economic	No
[27]	Ultra-high-performance concrete	A1–A3	Environment Economic	No
[28]	Bridge deck	B2–B3	Environment Economic	Yes, monetization of environmental impacts, using results from other studies
[29]	Aluminum composite	A1–B3	Environment Economic	Yes, monetization of environmental impacts using The StepWise2006

Table 1. *Cont.*

Reference	Object	Scope of Life-Cycle (See Details in Figure 2)	Assessment Aspect	Integration
[30]	Pavement Maintenance and Rehabilitation	B2–B3	Environment Economic	No
[31]	Pavement maintenance	B2–B3	Environment Economic	Yes, monetization of environmental impacts, using results from other studies
[32]	Pavement	A1–B1	Environment Economic	Yes, monetization of environmental impacts, using results from other studies
[33]	Highway	A1–B3	Environment Economic	No
[34]	Column	A–C	Environment Economic	No
[35]	Office building	A1–B1	Environment Economic	Yes, monetization of environmental impacts, using results from other studies
[36]	External skin of a building	A–C	Environment Economic	No
[37]	Building	A–C	Environment Economic	No
[38]	Wall	A–C	Environment Economic	No
[39]	Building	-	Environment Economic	No
[40]	Soil–steel composite bridge	A–C	Environment Economic	Yes, monetization of environmental impacts, using Ecovalue and Ecotax methods
[41]	Office building	A–D	Environment Economic	No
[42]	Building	A–D	Environment Economic	No
[43]	Building	-	Environment Economic	No
[44]	Selection of building material	-	Environment Economic Society	No
[45]	Infrastructure project	A–C	Environment Economic	Yes, monetization of environmental impacts, using results from other studies
[46]	Pavement	-	Environment Economic	No
[47]	Bridge	A1–B3	Environment Economic Society	Yes, using Pattern method, weights considered
[48]	Residential building	A1–A5	Environment Economic Society	Yes, using AHP method, equally weighting

2.4. Life-Cycle Thinking

In the early 1990s, governments, international organizations, and private companies used Agenda 21 to develop standardized methods and criteria for assessing environmental impact and resource needs over the entire life cycle of products and processes [49]. Life-cycle thinking (LCT) was introduced as part of this effort to assist individuals and households in making environmentally sound purchasing decisions, and by the end of that decade, LCT had taken root in the international dialogue on sustainability, particularly in terms of the environment.

LCT is a top-level decision-making tool primarily addressing sustainable production and consumption. The United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) jointly launched the Life Cycle Initiative as a vehicle to put LCT into practice [50]. According to UNEP Executive Director Klaus Töpfer, assessment tools and LCT must be used to inform production and consumption decisions made at all levels—from governments and businesses to individual consumers [51].

LCT allows product designers, service providers, government organizations, and individuals to make optimal choices for the long term and to avoid the serious problems that often occur between life-cycle stages. LCT-based assessments can inform production and consumption decision-making by assessing the long-term effects of goods and services. Environmental and social life-cycle assessments are two assessment techniques that offer perspectives on impacts across the product life cycle. In addition, life-cycle cost analysis provides information about costs across the product life cycle.

2.5. Existed Framework of Sustainability Assessment of Buildings

Current approaches to assessing the sustainability of buildings independently assess each aspect of sustainability, such as environmental sustainability [52], economic sustainability [53], and social sustainability [54]. However, the aim of this paper is to propose a comprehensive assessment framework that fully integrates these three aspects. The following analyzes the limitations and shortcomings of assessment frameworks proposed in prior studies. Kloepffer [55] first proposed the idea of creating a holistic sustainability assessment tool able to holistically evaluate all three aspects of environment, economy, and society based on Formula (1):

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{S-LCA}, \quad (1)$$

where

- LCSA: Life-cycle sustainability assessment;
- LCA: Environmental life-cycle assessment;
- LCC: Life-cycle cost;
- S-LCA: Social life-cycle assessment.

LCT is critical to assessing product sustainability because limiting one's evaluation to a specific stage in the life cycle of a product risks overlooking negative effects in other stages that may detract from sustainability. Ferrari et al. [56] stated that assessing sustainability comprehensively and correctly is a significant challenge for practitioners because of the complex nature of the assessment process, the difficulty of assigning proper weights, and the difficulty of integrating the values. LCT can be applied in many fields to assess the sustainability of products or production processes. Azevedo et al. [57] proposed a framework to evaluate upstream supply chain sustainability, including seven steps with eight main evaluation criteria. This assessment framework has the advantage of assessing all three dimensions of sustainability. However, using a few evaluation criteria will not be able to evaluate the research problem comprehensively. In addition, the authors use the environmental cost assessment criteria in the economic criteria group, which overlaps with the environmental criteria group. Or as in the energy sector, Dantas and Soares [58] have shown that 25/34 reviewed papers study the sustainability of energy systems by independently assessing environmental, economic, and social aspects, a few of which integrate two aspects in the form of socio-economic or techno-economic.

Some papers studied sustainability assessment in the energy field in construction and HVAC systems. Mostavi et al. [59] developed optimization methods for buildings in terms of cost, environmental impacts, and occupant satisfaction. Holopainen et al. [60] studied the multi-family building design alternatives' feasibility for saving energy and reducing emissions. Chantrelle et al. [61] developed a multicriteria optimization tool, MultiOpt, based on energy consumption, investment costs, environmental impact, and well-being (thermal comfort). Risholt et al. [62] assessed the sustainability of the renovation of dwellings in terms of energy, economics, and home quality. However, these studies only put very few criteria into their assessment model; each aspect is only evaluated by one or two criteria. Social assessment is lackluster and not scientifically supported. In most of these studies, the authors assessed the pillars separately, and the results were used in combination to compare alternatives. Therefore, sometimes it is difficult to choose the most optimal option, in which alternatives have better social and performance indicators yet higher investment costs or vice versa. Chantrelle et al. [61] developed an algorithm to help determine the group of "best" solutions based on the Pareto front but mainly based on the combined results. This study did not consider the life-cycle factor in the cost analysis. Or as Risholt et al. [62], when assessing the environmental aspect, but using only one simple indicator, the annual energy demand, without using the methodology as well as the LCA indicators.

Thus, few authors in the construction literature have proposed integrated frameworks for assessing the life-cycle sustainability of buildings. Ness et al. [63] proposed the general sustainability assessment framework, including the three main components of this framework: indicators and indices, product-related assessment (material, energy), and integrated assessment for policy change or project implementation. The approach used differs significantly from Kloepffer's original sustainability assessment concept. Specifically, rather than starting from the three pillars of SD, the framework is built around three content groupings. Importantly, factors underlying the social aspect are more weakly defined and less distinct than the environmental and economic aspects.

Bhyan et al. [64] reviewed the studies on LCSA for residential projects in the period 2000–2020 and found that there are very few studies on all three parameters of sustainability for the entire LCSA. Tupenaite et al. [65] proposed a sustainability assessment framework for new residential construction projects and used it to assess the sustainability of new projects in the three capital cities of the Baltic states. Although this framework integrates all three aspects of sustainability (environment, economy, and society) in assessing residential project sustainability, neither the framework nor its evaluation indicators consider the life cycle of projects. Furthermore, as most of the environmental impact assessment indicators must be determined qualitatively, accurately assessing the environmental burdens of a target project is not possible using this approach.

Gencturk and Hossain [66] developed a framework for building assessments using a life-cycle perspective. However, rather than addressing the social aspect of sustainability, this framework considers the structural performance aspect. Thus, this framework is suitable only for assessing structural sustainability in buildings under seismic conditions and not for assessing sustainability in terms of SD. Akhanova et al. [67] proposed a multicriteria decision-making framework based on sustainability assessments of buildings in Kazakhstan. This framework is built around standardized building sustainability assessment methods such as BREEAM, LEED, CASBEE, and SBTool and assesses building sustainability synthetically using multiple groups of indicators, including site selection, energy efficiency, water efficiency, materials, waste, management, and economics. With the exception of economics, none of the indicator groups address life-cycle sustainability. Moreover, the environmental, economic, and social assessment indicators are not clearly defined, and the number of social assessment indicators is relatively small. Furthermore, the assessment indicators system and assigned indicator weights reflect the opinions of experts in the fields of architecture, engineering, and construction in Kazakhstan. Hosny et al. [68] have built a sustainability assessment model of infrastructure projects with 100 evaluation criteria divided into the three main pillars of sustainability: economic, environmental, and social. However, these indicators are only evaluated qualitatively by scoring through the opinions of 100 experts in the field of infrastructure.

In general, the few frameworks published for assessing life-cycle sustainability in buildings rely on existing assessment methods such as BREEAM, LEED, CASBEE, and others. However, the assessment indicators used in these methods do not consider the different characteristics of different building types. Moreover, these methods are often used to provide green ratings rather than sustainability assessments because of their inadequate or lack of attention to the social aspect of sustainability. Although other authors have proposed or developed sustainability assessment frameworks for buildings/construction projects, these ignore the life-cycle factor completely. Based on the above-described deficiencies in the sustainability literature, this paper was designed to develop an integrated framework for assessing life-cycle sustainability in building projects.

3. General Framework of Sustainability Assessment of Buildings

3.1. Purpose

SD in production and consumption, particularly in major industries such as construction, is an issue of growing global concern. Today, in addition to maximizing profit, manufacturers must meet government rules and satisfy social concerns related to their production processes, technologies, and products. Even "good" products face elimination if they damage the environment and/or otherwise negatively impact communities and society. For example, in the building materials sector, cement is widely used to produce concrete for building construction. However, the manufacture of cement generates nearly 10% of total global greenhouse gas emissions. Therefore, cement-based products are being gradually restricted in some countries to reduce their use and encourage their replacement by other, more environmentally friendly materials. Intelligent consumption, a rising trend among consumers, prioritizes community and environmentally friendly products and the protection of human health over price and even product quality. In the construction industry, decisions about building materials, designs, and construction alternatives are increasingly being influenced by considerations grounded in the three aspects of SD (economic, social, and environmental). Therefore, integrating these aspects into assessments of building sustainability is a priority concern of the construction industry.

The ability to accurately and concurrently assess the three aspects of SD is critical for all decision-makers involved in the construction sector (e.g., government agencies, project investors, and building users) to implement and achieve SD, circular economy, green building, and other related objectives.

3.2. Scope of Application

One of the characteristics of a building is that it has a long construction and use period. The life cycle of a building is usually from a few tens to hundreds of years, including many stages and activities in it. Using a life-cycle perspective when assessing a building project is necessary to give stakeholders an overall and comprehensive view of that project. However, assessing the complete life cycle of a building is complex and challenging due to the many unpredictable factors and risks involved. An appropriate assessment scope should be selected that reflects the assessment purpose. Within LCT, examples of different assessment scopes include "cradle-to-gate", "cradle-to-site", and "gate-to-site", which consider partial (incomplete) life cycles, and "cradle-to-grave" and "cradle-to-cradle", which consider entire (complete) life cycles (Figure 2).

The building sustainability assessment framework proposed in this paper is designed to be applicable to both complete and incomplete life-cycle assessment scopes and to a wide range of building types.

3.3. *Proposition of a General Framework*

Taking into consideration the necessity of conducting comprehensive assessments of building sustainability covering all three of the abovementioned aspects of sustainability, the theoretical framework for an effective integrated assessment approach is presented in Figure 3.

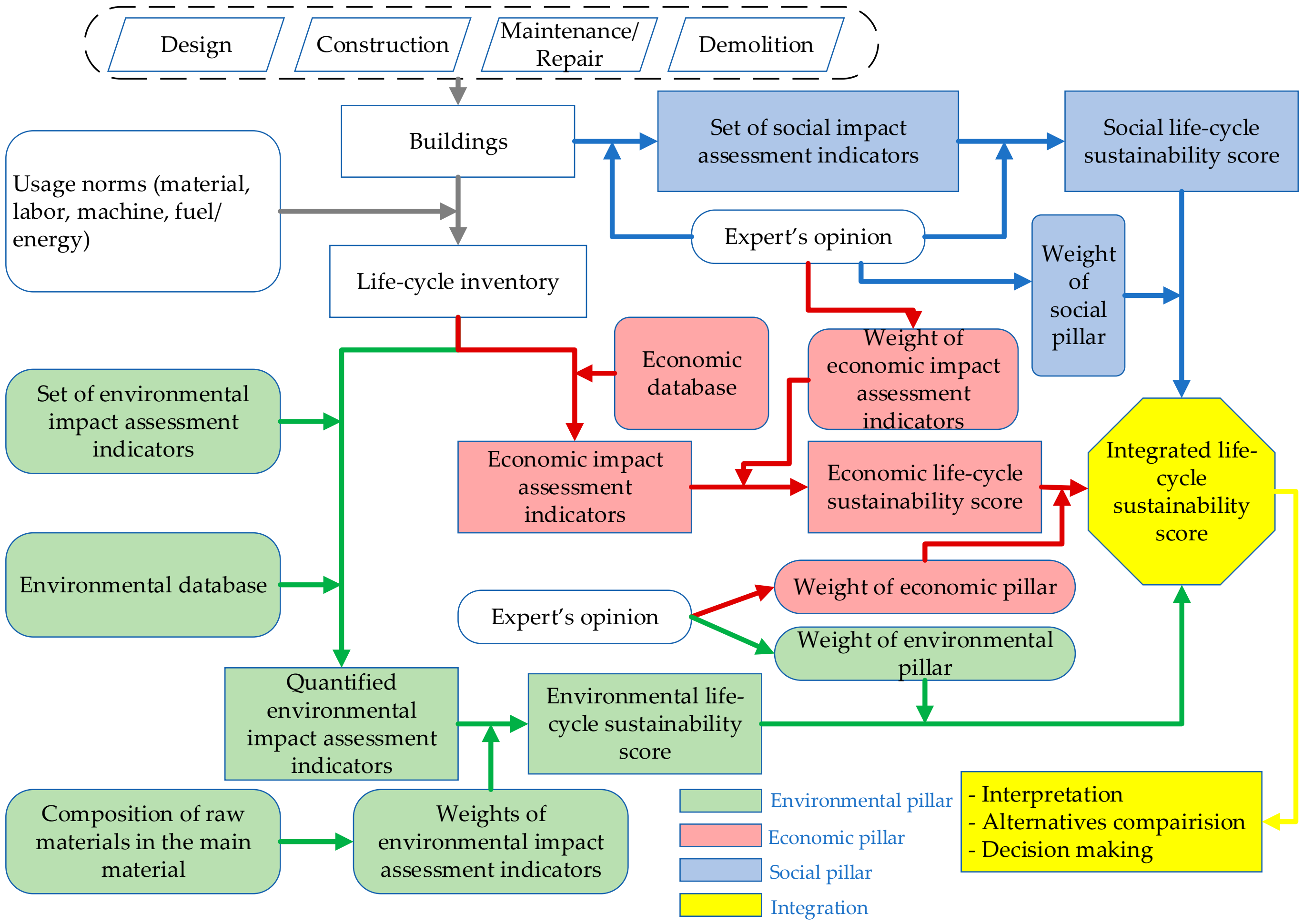

Figure 3. Proposed framework for sustainability assessment of buildings.

This integrated framework involves a complicated and time-consuming process, including many implementation steps distinguished into three main branches that correspond to the three sustainability aspects of the environment, economy, and society. The environmental impacts are quantified using the life cycle assessment method (LCA), economic efficiency is measured using the life cycle cost analysis method (LCCA), and social sustainability is scored using the social life cycle assessment method (S-LCA). The steps used to implement the integrated assessment framework are described in Section 4.

4. Results and Discussion

The building sustainability assessment framework is implemented in the order described in the following.

4.1. *Input Data Acquisition and Preparation*

The input data are used as the basis for calculations, analysis, and assessment. Data collection must be carried out carefully and accurately to ensure data reliability. Different data will be collected depending on building type (e.g., civil works, traffic works) and assessment scope (complete or incomplete life cycle). Also, as each building is unique, the data associated with each building are unique. However, missing datapoints for a particular building may be filled by data from buildings similar in terms of type, scale, and function, although doing so increases the risk of error in the analysis and assessment phases.

As previously detailed, the life cycle of a building consists of multiple stages, each of which consists of many activities. The sustainability assessment of a construction project should be accomplished during or before design plans are made to help stakeholders make informed decisions. Comparing design alternatives will help identify the optimal structural and material choices for a project, while the design plan will determine the technology and construction methods to be used during the construction phase, ensuring resource use is minimized during both construction and use.

During the use phase of a building, the management agency must make an energy usage (e.g., electricity, water, gas) plan and set a maintenance and repair schedule that meets current regulations. As these activities occur in the future, input data for these activities will be taken from the forecast plan. Similarly, at the end of a building's service life, the owner will decide either to continue using the building or to demolish it. Assessing the quality of a building at the end of its life cycle is difficult due to the many uncertainties involved. Thus, the assumption in this paper is that at the end of life, buildings are decommissioned and either demolished or disposed of/recycled. Therefore, demolition and disposal/recycling options must also be forecasted to provide input data for the sustainability assessment. In general, the input data required for a complete life cycle assessment of building sustainability include design documents (e.g., structural, architectural, electromechanical), technology and construction methods, plans for use, maintenance and repair schedules, and plans for building demolition and the disposal/recycling of its constituent components and materials.

4.2. *Assessment of the Environmental, Economic and Social Impacts*

The impacts on each aspect are assessed independently and do not relate to the other aspects. The assessment of impacts in these three aspects may be carried out concurrently or sequentially.

4.2.1. Environmental Impacts Assessment

Step 1: Determine life-cycle inventories

This important step takes significant time and effort to perform. Based on the input data identified in the previous section regarding building type and assessment scope, the main activities that will take place over the life of a building from the construction phase through to the demolition phase may be determined. Based on this, a list of construction works with their execution quantity can be built. Combined with material usage norms, machine usage norms, and fuel/energy usage norms, it is possible to calculate material needs, machine shift needs, and fuel/energy consumption using Formulas (2)–(4), respectively.

$$N_{material\ j} = \sum_{i=1}^{n} Q_i \times Norm_{material\ ij} \quad (2)$$

$$N_{machine\ k} = \sum_{i=1}^{n} Q_i \times Norm_{machine\ ik} \quad (3)$$

$$N_{fuel\ m} = \sum_{k=1}^{v} N_{machine\ k} \times Norm_{\ fuel\ km} \quad (4)$$

where

- $N_{material\ j}$: Need of material "type j";
- Q_i: Quantity of the ith construction work;
- $Norm_{material\ ij}$: Usage norm of material "type j" for the ith construction work;

- $N_{machine\ k}$: Need of machine "type k";
- $Norm_{machine\ ik}$: Usage norm of machine "type k" for the ith construction work;
- $N_{fuel\ m}$: Need of fuel/energy "type m";
- $Norm_{fuel\ km}$: Usage norm of fuel/energy "type m" for the machine "type k";
- n: Number of construction works;
- v: Number of machines.

Usage norms are the consumption of materials, labor, and construction machines to complete one unit of construction work. For example, to build 1 m^3 of a brick wall, how many bricks and mortar should be used; what are the number of labor dayworks, number of machine shifts, etc.? The usage norms for materials, machines, and fuel/energy may be referenced from documents issued by the government management authority responsible for construction and/or individual norms of internal construction enterprises or from norms developed by professional consulting organizations. The results provide information on the amount of materials, the number of machine shifts, and the amount of fuel required over the complete life cycle of the building.

Step 2: Select environmental assessment indicators

Environmental impact over the life cycle of the building is assessed using the LCA method, which uses assessment indicators to quantify environmental impact categories. Buildings impact the environment through the exploitation, production, and transportation of construction materials, the use of construction machinery and equipment, and the use of energy/fuel to operate both machinery and the building. Each of the many different impact assessment indicators used in the LCA method reflects a specific negative impact on the environment (e.g., atmosphere, water environment, soil environment, system ecology, biodiversity). LCA practitioners select the types of indicators used based on building type and the main building materials used. Different types of buildings impact the environment in different ways. For example, civil works significantly impact the soil environment, while irrigation works have a larger impact on the water environment. In addition, the main types of materials used also influence the selection of impact assessment indicators. For example, cement production greatly impacts the atmosphere, while steel production pollutes water and soil environments. Environmental impact assessment indicators widely used in LCA research include Global Warming Potential (GWP), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), and Ozone Depletion Potential (ODP), among others. For a construction project, the degree of environmental sustainability can be assessed through the following criteria in Table 2.

Step 3: Reference environmental databases

Environmental databases are important sources of information that may be used to quantify the value of environmental impact assessment indicators. The United States, as well as countries in Europe, Asia, and Oceania, have built their own environmental databases in support of conducting life cycle assessments. Most of the major environmental databases charge fees for usage, while those that are open-use typically offer only a limited number of datasets. When environmental databases are not available, data may be borrowed from other sources with the associated increase in the risk of error during analysis related to the different sources used for raw materials, different production technologies used, and different geographic locations. For example, the emissions generated by thermal power and nuclear power plants differ significantly. Also, the emissions generated by cement manufacturers in China and Vietnam differ significantly.

Currently, dozens of databases worldwide, such as GaBi, Ecoinvent, etc., provide data sets to perform LCA for many fields. When applying this assessment framework, the practitioner needs to choose and use the database for each specific case based on the research objectives and the environmental impact assessment indicators selected in Step 2.

Table 2. Environment assessment indicators for building.

No	Indicators	Unit	Description
1	CO_2 emission	kg CO_2	This is a common environmental indicator used to measure emissions of greenhouse gases converted to CO_2.
2	Energy consumption	MJ	Levels of energy use in the construction, use, and demolition phases. At the stage of construction and demolition, energy consumption mainly comes from using construction machinery and equipment. In the operation phase, the energy consumption comes from the shell structure and the equipment used in the building (heating, cooling, etc.).
3	Dust pollution (air)		This criterion is mainly considered in the construction and demolition phases. The use of construction materials and construction equipment can cause dust to be released into the air. If the building is not properly fenced, the dust emission will directly affect the surrounding environment. In addition, industrial buildings can also cause dust and smoke pollution during operation.
4	Water pollution		The whole life of the building is associated with water use, including water supply and drainage. Therefore, it is necessary to evaluate the level of use of clean water (water resources) and the quality of wastewater after use.
5	Noise pollution	Db	This criterion is mainly considered in the construction and demolition phase, where the use of construction materials and construction equipment may cause noise. During the operation phase, solutions using different soundproofing materials cause different levels of noise pollution.
6	Resource Consumption	Point	Building materials are indispensable inputs for any construction work. Currently, most of the materials used in construction are exploited and produced from natural resources. Therefore, construction works indirectly affect the depletion of natural resources.
7	Usage of recycled materials	Point or %	A circular economy is one of the new SD directions, emphasizing the need for and importance of recycling and using recycled materials. Using recycled building materials helps reduce the environmental burden and improve the sustainability of the building.
8	The use of environmentally friendly materials	Point or %	The trend of using green and sustainable materials in construction is becoming increasingly popular. Environmentally friendly building materials help to increase the sustainability of the building and significantly reduce energy consumption during the operation phase of the building.

Step 4: Quantify environmental impact assessment indicators

Each environmental impact assessment indicator identified in Step 2 is quantified in this step, with their values determined based on the life-cycle inventory data identified in Step 1 and the environmental database selected in Step 3. Life-cycle inventory assessment can be calculated using software such as SimaPro, GaBi, OpenLCA, etc.

Step 5: Calculate the environmental life-cycle sustainability score

Because the quantified environmental impact assessment indicators use different units of measurement (e.g., kg CO_2, kg CFC, kg SO_2), they must be homogenized to generate an overall "environmental sustainability score" for the building. The identification of criteria with the type of measurement unit may be conducted with calculation techniques in combination with a weight for each indicator. The homogenization of assessment indicators with the different measurement units may be conducted with calculation techniques in combination with a weight for each indicator that represents its importance in relation to all of the other indicators. This weight may be determined using the proportion of raw materials used in the main material used in the building. The environmental life-cycle sustainability score is calculated as in Formula (5):

$$LCS^{env} = \sum_{i=1}^{n} Env_i \times W_{Envi} \quad (5)$$

where

- LCS^{env}: Environment life-cycle sustainability score;
- Env_i: ith environmental indicator;
- n: Number of environmental indicators;
- W_{Envi}: Weight of ith environmental indicator.

4.2.2. Economic Impacts Assessment

Step 1: Determine life-cycle inventories

The life cycle inventory data used to calculate economic impact is essentially the same as the life cycle inventory data used to calculate environmental impact, including material needs, machine shift needs, and fuel/energy consumption. Life-cycle inventory data here are also determined using Formulas (2)–(4). In addition, when calculating LCC, it is necessary to add inventory data on labor needs using Formula (6).

$$N_{labor\ l} = \sum_{i=1}^{n} Q_i \times Norm_{labor\ il} \quad (6)$$

where

- $N_{labor\ l}$: Need of labor "type l";
- Q_i: Quantity of the ith construction work;
- $Norm_{labor\ il}$: Usage norm of labor "type l" for the ith construction work;
- n: Number of construction works.

Step 2: Determine the economic impact assessment indicators

The economic impact of a building is reflected in the costs incurred over its useable life, as assessed using the LCCA method. The cost of activities over the life of a building (also known as life cycle costs) may be determined based on the life cycle inventory data (identified in Step 1) and the costs of materials, labor, machine, and fuel. Costs incurred during a building's life cycle are often classified into different cost groups, as described in ISO 15686-5:2006 [69], including initial investment costs, management and operation costs, maintenance costs, residual value, and other cost variables.

LCC is an indicator of economic life cycle assessment, but this criterion only considers the cost aspect of the building. Moreover, a construction project is also evaluated through many other economic indicators. Indeed, each different construction project will bring different economic effects. Economic efficiency can also be measured through other economic benefits such as revenue, profit, added value, etc. Therefore, the authors propose criteria to evaluate economic aspects in the life cycle of a building, as in Table 3.

Step 3: Calculate the economic life-cycle sustainability score

As economic impact assessment indicators are all expressed in terms of monetary value, they do not require harmonization. However, due to the long duration of the building life cycle, prices are expected to change over time based on the rate of inflation and other economic factors. Furthermore, costs occurring at different times during the life of the building will have different values considering the time value of money. Thus, life cycle costs cannot simply be summed together and must consider changes in monetary value over time. Therefore, when using the LCCA method, the selection of analytical parameters (e.g., interest rate, analysis period, indicators) is very important.

Table 3. Economic assessment indicators for building.

No	Indicators	Unit	Description
1	Initial investment cost	Money	Including costs such as project planning, design, construction, etc. Initial investment costs are governed by the investor's budget and directly affect the design and construction plan alternatives.
2	Annual maintenance costs	Money	The repair and maintenance costs depend on building types, design plans, and materials solutions.
3	Annual operating costs	Money	This type of cost accounts for up to 70% of total costs over the life of a building and has a great influence on decision-making in the early stages of a project.
4	Life-cycle cost	Money	Provide an overview of the cost aspect of a construction project as a basis for comparing and selecting design and construction options in terms of economic aspects.
5	Annual revenue	Money	The revenue that a building brings will vary depending on the construction type and the source of investment capital for the construction project.
6	Annual profit	Money	Profit is one of the crucial criteria for project investors, especially construction projects using private capital.
7	Net present value (NPV)	Money	The value of cash flows (including benefit flows and cost flows) is accounted to the present time (at the beginning of the project) and used to compare and select options to support the decision-making process.
8	Internal rate of return (IRR)	%	The profitability of the project's investment capital is used to compare and select options to support the decision-making process.
9	Return On Investment (ROI)	%	The profitability of the project's investment capital, not considering the money fluctuations over time, is used to compare and select options to support the decision-making process.
10	Contribution to local and national economic development	Money	Value added created by buildings.
11	Contribution to the local budget	Money	Taxes and fees that construction project investors must pay into the State budget.

The total life-cycle cost of the building may be discounted to the present time using Formula (7).

$$LCC = \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \tag{7}$$

where

- LCC: Life-cycle cost of building;
- C_t: Costs occurring in the tth year;
- i: Interest rate;
- n: Number of years in the building's life cycle.

In the private sector, an investor's discount rate is set equal to their minimum acceptable rate of return, adjusted by the available investment opportunities and their level of risk tolerance. Differences in investment opportunities and risk tolerance levels mean that discount rates may vary significantly among different investors. When life cycle costs are discounted to the present, selecting a suitable discount rate is an important decision in LCC analysis, with high discount rates tending to favor options with low cost of capital, a short life cycle, and high periodic costs, and low discount rates tending to favor the opposite. The discount rate can reflect not only the purchasing power of investment capital over time but also the effects of inflation [70].

In the case of a construction project that only needs to be assessed in terms of cost, LCC in Formula (7) is used as the economic sustainability score. But in the case of using a combination of many other economic indicators, the economic sustainability score is calculated according to Formula (8), and LCC is only one among the economic indicators used to evaluate. This economic sustainability score is calculated as the sum of the values of the economic indicators in the evaluation model, combined with the weight of each indicator. The weights of the indicators are determined based on expert opinion.

$$LCS^{econ} = \sum_{i=1}^{n} Econ_i \times W_{Econi} \quad (8)$$

where

- LCS^{econ}: Economic life-cycle sustainability score;
- $Econ_i$: ith economic indicator;
- n: Number of economic indicators;
- W_{Econi}: Weight of ith economic indicator.

4.2.3. Social Impacts Assessment

Social life cycle assessment (S-LCA) is a technique for assessing the impacts (and potential impacts) on the social aspect across the life cycle of a product. These impacts may have positive or negative implications for society and, in this study, may directly impact (positively or negatively) stakeholders throughout a building's life cycle. These aspects may relate to firm behaviors, socio-economic processes, or effects on social capital. Social impacts are consequences of social relationships (interactions) created in the context of a certain activity (production, consumption, or disposal). Depending on the assessment objective, indirect effects may also be considered. For example, how does road construction affect those living nearby? How does the road benefit the community, and what are the consequences of road construction? How does this road affect businesses in the area? How does the road change traffic behavior? Also, at the macro level, what are the regional and national impacts of the road? S-LCA may be performed as a standalone method or in combination with other life-cycle analysis methods such as LCA and LCCA.

Step 1: Select social impact assessment indicators

Social impacts are usually classified into five main categories that correspond to each key group of stakeholders in a construction project, such as workers, local communities, society (national and international), consumers, and value chain actors (Figure 4) [71]. Criteria are then proposed based on the specific case study to assess the social impacts on each main category group.

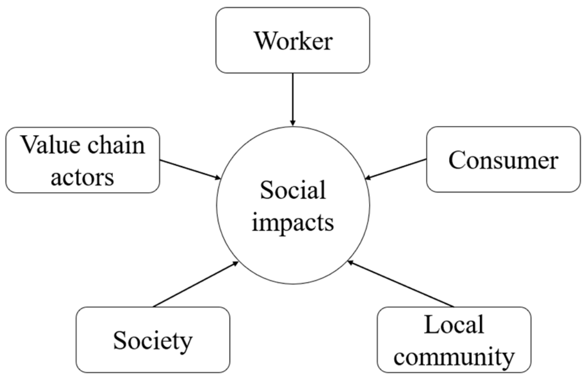

Figure 4. Social impact categories.

Because the social impact on a building is assessed based on building type and characteristics, the assessment indicators and affected stakeholder groups must be separately determined for each project. An appropriate set of indicators may be determined in consultation with experts in light of a building's specific characteristics. For the buildings, the indicators for assessing social aspects are proposed in Table 4.

Table 4. Social assessment indicators for building.

No	Indicators	Unit	Description
1	Job creation	Number of jobs	The ability to create jobs for workers directly related to construction works, for example, labor during construction and operation of works.
2	Meeting the needs of society	Point or %	Construction buildings solve one or more societal needs, such as travel needs, goods trade, entertainment, etc.
3	Impact on workers' health	Point	The health of workers is directly affected by the working environment and the use of construction materials or construction machinery.
4	Impact on the health of the population	Point	Most construction works affect the health of the surrounding community during the construction and demolition phases. Some notable buildings, such as waste treatment plants, wastewater treatment plants, etc., can also affect the operation process.
5	Reducing social evils	Point	Construction work helps create jobs for workers and stimulates the consumption of local products and services, promoting local economic development and reducing social evils.
6	Impact on cultural and historical heritage	Point	The construction work can directly or indirectly affect the landscape or the value of cultural heritages and historical relics. Therefore, it is necessary to consider this criterion in the investment preparation stage.
7	The aesthetics of the building	Point	Expressed through the shape, color, and architectural features of the building. Aesthetics have a direct impact on the residential community.
8	Level of safety in use and prevention of fire and explosion	Point	Fire protection solutions and safety in use are mandatory requirements in the design phase. Different design options have varying degrees of assurance about this criterion. Especially for public buildings, this criterion has a great influence on the community.

Step 2: Determine social impact assessment indicators

Social impact is often difficult to assess due to the qualitative nature of most related indicators. Therefore, the value of these assessment indicators is usually calculated in terms of points based on the opinions of experts.

Step 3: Calculate the social life-cycle score

Social impact assessment indicators may be either qualitative or quantitative, and their respective weights should be determined in consultation with experts. As the units used in assessment indicators may vary, their value must be standardized on a single unit of measurement to obtain a unified "social sustainability score". The social life-cycle sustainability score is calculated as in Formula (9).

$$LCS^{soc} = \sum_{i=1}^{n} Soc_i \times W_{Soci} \quad (9)$$

where

- LCS^{soc}: Social life-cycle sustainability score;
- Soc_i: ith social indicator;
- n: Number of social indicators;
- W_{Soci}: Weight of ith social indicator.

4.3. Integrated Assessment of Environmental, Economic, and Social Impacts

As discussed and presented in Section 4.2, the core of the integrated sustainability assessment framework for buildings is the assessment of their environmental, economic, and social impacts, which results in three respective scores for environmental sustainability, economic sustainability, and social sustainability.

Step 1: Determine weights for the environmental, economic, and social aspects

The relative importance of the environmental (α), economic (β), and social (γ) aspects differs from project to project and even among different stakeholders in a particular project. For example, business stakeholders typically prioritize the economic benefit of their products and downplay social and environmental benefits, while government agencies typically give greater weight to community values and environmental issues. Nevertheless, for each building project, these different perspectives and priorities must be harmonized with the assistance of expert opinion into a single relative weight for each aspect.

Currently, many weighting methods exist, such as point allocation, direct rating, ranking method, pairwise comparison, etc. Depending on the complexity of each specific case, the practitioner will choose the appropriate one. The authors propose to use the direct rating method according to expert opinion to determine the weights for the three pillars of environment, economy, and society. The selected experts must have a deep understanding and experience in construction enterprises, project managers, state agencies in charge of construction, or training organizations on construction. The weights of these three pillars will change depending on the expert's point of view. Therefore, the selection of a group of survey experts is very important. A practitioner needs to choose the experts based on the purpose of LCSA performance, for example, evaluating the LCSA from the investor's point of view (in favor of the economic aspect), from the point of view of the State agencies when approving the project (in favor of the environment), or from the building user's point of view (in favor of the social aspect). The importance of a construction project's three environmental, economic, and social aspects will be scored on a Likert scale of five levels according to experts' opinions, corresponding to 1-Not Important, 2-Less Important, 3-Important, 4-Rather Important, and 5-Very Important.

The weight of each aspect is calculated by averaging the scores of experts for that aspect according to Formula (10):

$$\alpha,\ \beta,\ \gamma = \frac{\sum_{i=1}^{n} P_i^{env,econ,soc}}{n} \tag{10}$$

where

- α, β, γ: Weights of environmental, economic, and social pillars, respectively;
- $P_i^{env,econ,soc}$: Scores of environmental, economic, and social pillars, respectively;
- n: Number of experts.

These weights will be normalized before calculating the LCSA score of the building according to Formula (11):

$$\alpha^{norm},\ \beta^{norm},\ \gamma^{norm} = \frac{\alpha, \beta, \gamma}{\alpha + \beta + \gamma} \tag{11}$$

Step 2: Calculate the building life-cycle sustainability score

The "environmental sustainability score" and "social sustainability score" are expressed in terms of scored points, while the "economic sustainability score" is expressed in terms of a monetary unit. Thus, integrating these three scores requires harmonizing these measurement units using established calculation techniques such as COPRAS, TOPSIS, and the Pattern method. Sustainability scores for the three aspects after the removal of their measurement units are combined with their respective weights using Formula (12) below to generate a single "sustainability score" for the building.

$$LCSS = \alpha^{norm} \times LCS^{env} + \beta^{norm} \times LCS^{econ} + \gamma^{norm} \times LCS^{soc} \tag{12}$$

where

- $LCSS$: Integrated life-cycle sustainability score;

- LCS^{env}: Environmental life-cycle sustainability score;
- LCS^{econ}: Economic life-cycle sustainability score;
- LCS^{soc}: Social life-cycle sustainability score;
- α^{norm}, β^{norm}, γ^{norm}: Normalized weights of environmental, economic, and social pillars, respectively.

The "sustainability score" distills the proposed design characteristics of a building into a single assessment of sustainability. For buildings with multiple proposed designs, the sustainability score of each design must be determined and then ranked to provide a reference for construction investor decision-making, government agency appraisal and approvals, and society to make informed choices regarding the selection and use of construction products.

4.4. Discussion

As discussed in Section 2, it is essential to comprehensively evaluate the sustainability of a building. The authors used theoretical research methods to synthesize and analyze existing studies on evaluating the sustainability of buildings. The results show that most of these studies only evaluated one or two aspects, and very few studies comprehensively evaluated all three pillars of environment, economy, and society. In addition, sustainability assessments are often carried out individually in each aspect rather than integrating the aspects. Several authors have proposed a framework for assessing sustainability for construction, but these frameworks still have some limitations, such as not covering all three sustainability pillars or not assessing their whole life cycle, etc.

Therefore, a comprehensive sustainability assessment framework for buildings has been proposed and presented in this paper. Basically, the idea of a comprehensive assessment follows the core content of SD, so this assessment framework covers all three pillars of environment, economy, and society. Furthermore, the proposed assessment framework is developed based on an LCT approach to provide an overview for decision-makers on a construction investment project. In fact, this assessment framework can also be applied to a specific stage in the life cycle of a building, such as a plan to repair, renovate or plan to operate a building. The proposed framework can be applied to many building types. Indeed, when applying to specific work, practitioners need to base on the characteristics of the building to customize this assessment framework and adjust the assessment indicators and the databases in their analysis.

Assessing a building's sustainability for its entire life is laborious and time-consuming; thus, practitioners must pay attention when collecting input data, selecting evaluation criteria, and determining weights. The assessment results are very useful in comparing and choosing options. The alternative with a higher sustainability score is the more effective for all three aspects of the environment, economy, and society. Theoretically, this assessment framework is the basis for the authors to build a specific assessment model for each type of construction in future research because each type has its characteristics and different assessment indicators. In practical terms, this assessment framework is not only a reference but also a support tool for the stakeholders of a construction project in the decision-making process, helping to select the most effective investment option and creating the most sustainable constructions.

5. Conclusions

In this paper, the authors reviewed previous studies on the life-cycle assessment of buildings, especially assessment frameworks, and identified research gaps. On that basis, an integrated sustainability assessment framework for buildings was developed in line with LCT to help identify project designs that optimize all stakeholders' interests in terms of sustainability. This integrated assessment framework is a practical tool for construction investment project stakeholders to reference, implement, and use to guide the decision-making process. The framework may also provide a reference for other construction-field researchers to develop sustainability assessment models optimized for different types of construction projects.

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