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Article

An integrated multi-criteria decision-making approach for life cycle approach in road construction projects

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Abstract: Sustainability in road construction projects is hindered by the extensive use of non-renewable materials, high greenhouse gas emissions, risk cost, and significant disruption to the local community. Sustainability involves economic, environmental, and social aspects (triple bottom line). However, establishing metrics to evaluate economic, environmental, and social impacts is challenging because of the different nature of these dimensions and the shortage of accepted indicators. This paper developed a comprehensive method considering all three dimensions of sustainable development: economic, environmental, and social burdens. Initially, the economic, environmental, and social impact category indicators were assessed using the Life cycle approach. After that, the Analytic Hierarchy Process (AHP) method and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) were utilized to prioritize the alternatives according to the acquired weightings and sustainable indicators. The steps of the AHP method involve forming a hierarchy, determining priorities, calculating weighting factors, examining the consistency of these assessments, and then determining global priorities/weightings. The TOPSIS method is conducted by building a normalized decision matrix, constructing the weighted normalized decision matrix, evaluating the positive and negative solutions, determining the separation measures, and calculating the relative closeness to the ideal solution. The selected alternative performs the highest Relative Closeness to the Ideal Solution. Lastly, a case study was undertaken to validate the proposed method. In three alternatives in the case study (Cement Concrete, Dense-Graded Polymer Asphalt Concrete, and Dense-Graded Asphalt Concrete), option 3 showed the most sustainable performance due to its highest Relative Closeness to the Ideal Solution. Integrating AHP and TOPSIS methods combines both strengths, including AHP's structured approach for determining criteria weights through pairwise comparisons and TOPSIS's ability to rank choices based on their proximity to an ideal solution.

Keywords: life cycle costing (LCC); life cycle assessment (LCA); social life cycle assessment (social LCA); AHP method; TOPSIS method

1. Introduction

Sustainability in road construction projects faces significant challenges, primarily due to the high environmental impact associated with material extraction, manufacture, and construction activities. In practice, the sustainability of road construction projects must be considered comprehensively. Sustainability is a concept that encompasses the integration of economic, environmental, and social aspects (triple bottom line). The economic aspect of sustainability relates to its influence on the financial condition and contributions to the economic growth, competitiveness, and vitality of communities (Kumari et al., 2022; Tsinarakis et al., 2023). The environmental element revolves around the conservation and improvement of the natural environment (Abedin Khan et al., 2024; Aryan et al., 2023). The social aspect of sustainability refers to the consideration of human factors in development and decision-making processes, aiming to enhance the well-being, equity, and quality of life for individuals and communities (Ahmad et al., 2024; Figueiredo et al., 2024).

Some studies-built models to address sustainable issues that arise during the different phases of the construction process, such as multi-objective optimization model (Shehadeh et al., 2024), Machine Learning (ML) algorithms (Almasabha et al., 2023; Odey Alshboul et al., 2023), and GDP-based mathematical model (Odey Alshboul et al., 2022). However, their models mostly neglect the social impacts. Assessing the sustainability performance of construction projects is crucial for enhancing economic, environmental, and social performance within the construction industry. It enables the identification and implementation of the best alternatives that minimize resource consumption, reduce greenhouse gas emissions, and promote the use of recyclable materials. Besides, roads are long-lived infrastructure investments, often lasting for some decades. Comprehensive sustainability ensures that roads are built to withstand changing environmental conditions, such as climate change impacts, without requiring frequent repairs or replacements, thus reducing total costs and environmental burdens. However, the integration of economic, environmental, and social aspects in sustainable development faces some challenges. Establishing standardized metrics to evaluate and compare economic, environmental, and social impacts is challenging due to the different nature of these dimensions and the lack of universally accepted indicators (Soust-Verdaguer et al., 2022). The consensus on sustainability priorities and actions is often challenging, so stakeholders may lack understanding and awareness about the importance of integrating all three sustainability aspects, leading to insufficient support for comprehensive sustainability initiatives (Oladazimi et al., 2021). Developing and implementing methods and tools that effectively integrate economic, environmental, and social data and considerations can be technically complex. So, it is necessary to build a method ensuring that trade-offs between economic, environmental, and social goals are balanced, leading to more comprehensive and informed decision-making. This method can enhance resource efficiency by identifying the balance between economic activities and environmental conservation, while also ensuring social benefits.

In the academic context, some studies also emphasize the importance of comprehensive sustainability assessment (Fauzi et al., 2019; Figueiredo et al., 2024; Zhou et al., 2007). It helps stakeholders make informed decisions in accordance with the requirements for sustainable development. Besides, integrating sustainability performance assessment methods ensures that construction projects contribute positively to sustainable goals. However, these studies mainly focus on one or two aspects of sustainability instead of all three dimensions. For example, Mohamed et al. (2022) provided a comprehensive summary of previous studies and offered insightful reviews on how to address the economic and environmental challenges associated with the life cycle of road pavement. Although the study reviewed and summarized some methods for assessing the economic and environmental burdens, the social impact was not considered.

In general, developing a method for assessing the sustainability performance of road construction projects during the construction phase is imperative. This method must consider all three dimensions of sustainable development: economic, environmental, and social aspects.

2. Literature review

According to Norouzi et al. (2017), sustainability is a concept that encompasses the integration of economic, environmental, and social aspects (triple bottom line) to ensure the long-term well-being of present and future generations. The economic dimension of sustainability pertains to an impact on the economic status and contributions to economic development. The concept of the environmental aspect centers on preserving and enhancing the natural environment to sustain nature. The social dimension of sustainability involves taking into account human aspects in the processes of development and decision-making, with the goal of improving the well-being, fairness, and quality of life for individuals and communities. Achieving sustainability necessitates the consideration of all three facets of the triple bottom line. Nevertheless, the incorporation of triple bottom line in sustainable development encounters certain obstacles. The task of developing consistent metrics to assess and compare the economic, environmental, and social effects is a challenging undertaking, because these dimensions have distinct characteristics and units, and there is a dearth of globally recognized indicators (Soust-Verdaguer et al., 2022). Stakeholders may face difficulties in reaching a consensus on sustainability assessment when including all three components of sustainability. Technological complexity arises from the development and implementation of assessment methods. This, in turn, leads to inadequate support for comprehensive sustainability programs (Oladazimi et al., 2021).

Life cycle cost analysis (LCC), Life cycle assessment (LCA), and Social Life Cycle Assessment (Social LCA/SLCA) are proposed as methodologies for assessing the economic, environmental, and social aspects in the construction phase of road construction projects. Life cycle cost analysis (LCC) is advantageous for evaluating the economic aspects of road construction projects. For example, after reviewing 5,120 full articles, Mohamed et al. (2022) confirmed that the LCC was widely applied to estimate the agency and user costs endured during the pavement life cycle. It helps track expenses from the initial phase through the construction phase till the close-out phase and compare different alternatives (Kumari et al., 2022; Tsinarakis et al., 2023). For instance, the cost of concrete items should involve maintenance costs rather than only manufacturing costs (Odey et al., 2024). By incorporating the time value of money, LCC converts future cash flows to present values, aiding in long-term value assessment (ISO, 2017; RICS, 2014). Previous studies showed the LCC's ability to minimize total cost by identifying significant cost impacts (Hasan et al., 2024; Todor et al., 2017). Additionally, LCC supports informed decision-making, resource usage optimization, risk management, budget estimation, and project performance enhancement (Hasan et al., 2024; Kumari et al., 2022; Tsinarakis et al., 2023). Life cycle assessment (LCA) is a comprehensive method for evaluating environmental impacts throughout all stages of a project's life cycle (Aryan et al., 2023; Khan et al., 2024). It is valuable for assessing environmental burdens and offers insights into the environmental performance of construction projects (Wang et al., 2019). The LCA can evaluate green infrastructure by analyzing various phases and their impacts, like global warming potential and water use. In the construction industry, Mohamed et al. (2022) pointed out that the LCA should involve in planning phases and MandR activities to account for the environmental problems provoked during the pavement life cycle. Besides, Hafner and Storck also pointed out that this method is able to compare construction materials to identify the optimal choice based on environmental impacts (Hafner and Storck, 2019). Overall, the LCA supports stakeholders in making informed decisions by optimizing environmental cost and environmental performance. The Social Life Cycle Assessment (Social LCA/SLCA) can be applied in the construction industry to evaluate social impacts (Ahmad et al., 2024; Figueiredo et al., 2024). For example, Y. H. Dong and Ng (2015) developed a Social LCA methodology called SMoC to evaluate the social impact of construction projects. Liu and Qian (2019) also developed the Social LCA analysis following UNEP guidelines by constructing a model with weightings and on-site social indicators to conduct the social performance evaluation. In summary, Social LCA supports decision-making for construction projects and can integrate with LCC and LCA to assess sustainable performance (Figueiredo et al., 2024).

The life cycle approach, which encompasses LCC, LCA, and Social LCA, represents distinct components of sustainability, so their outcomes provide an inadequate representation of sustainable development (Fauzi et al., 2019; Figueiredo et al., 2024; Zhou et al., 2007). Several methodologies combined LCC, LCA, and Social LCA results to evaluate road construction projects' sustainability performance. For example, Mohamed et al. (2022) developed a road maintenance and rehabilitation (MandR) strategy to solve sustainable problems concerning management systems (e.g., management objectives, decision variables, life cycle stages, …), rehabilitation strategies (e.g., construction materials, treatment types…), and case context (traffic level, climate zone, material prices…). However, the social burden was not emphasized in this study. Moreover, the life cycle sustainability assessment (LCSA) is a holistic way of analyzing and selecting alternatives to support sustainable development (Fauzi et al., 2019; Figueiredo et al., 2024; Zhou et al., 2007). The LCSA considers the comprehensive effects (including economic, environmental, and social effects) on sustainability. In addition, the pertinent data is systematically arranged, and the outcomes are visualized in a structured format. However, this method requires consolidating LCC, LCA, and Social LCA analyses into a single score, which is challenging when considering social aspects. Besides, Alshboul et al. (2022) developed a mathematical model combined with machine learning techniques to analyze data from 3578 green construction projects in North America. The model explored the balance of supply and demand under deflationary conditions for external green construction support and the accompanying spending adjustment processes. The model enhances the cost reduction to increase the environmental benefits of buildings, but the social issues were not considered. In addition, the TOPSIS is another method that is applied to combine the LCC, LCA, and Social LCA results for assessing the sustainability performance in the construction phase of road construction projects (Behzadian et al., 2012; Falqi et al., 2019; Fazeli et al., 2019; Mousavi-Nasab and Sotoudeh-Anvari, 2017). The method is also positively adaptable and can incorporate quantitative and qualitative criteria. It is also reasonably easy to comprehend and does not necessitate sophisticated mathematical expertise. Hence, it is accessible to a broader spectrum of applications. However, this method faces challenges concerning the sensitivity of weightings, which can significantly influence the final ranking of alternatives. Besides, the AHP is also applicable for assessing the sustainable performance of construction projects. It provides a comprehensive framework that helps in structuring a complex decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. This hierarchical structure makes the decision-making process more manageable and transparent. However, the method relies on the questionnaire results to compare the pairwise, so it may result in inconsistency in comparisons and subjectivity in judgment. The methods presented above pose challenges in combining economic, environmental, and social aspects in sustainable assessment due to their distinct characteristics, units, and the shortage of recognized indicators.

To solve these problems, integrating AHP and TOPSIS methods combines their strengths: AHP's structured approach for determining criteria weights through pairwise comparisons and TOPSIS's ability to rank alternatives based on their proximity to the best possible solution. This integration enhances decision-making accuracy by leveraging AHP's consistency and TOPSIS's ranking process, leading to more reliable and comprehensive evaluations. By integrating the prioritization capabilities of AHP with the ranking mechanism of TOPSIS, decision-makers can thoroughly evaluate and effectively balance economic, environmental, and social aspects. This combination ensures a comprehensive and systematic approach to sustainable decision-making, fostering meaningful outcomes that align with the principles of sustainability.

This research is conducted to find a methodology to investigate the incorporation of LCC, LCA, Social LCA, AHP and TOPSIS methods to assess the sustainability performance in the construction phase of road construction projects. Firstly, the LCC, LCA, and Social LCA will be applied to evaluate the economic, environmental, and social performance. Secondly, the AHP method was applied to assess the weightings. Lastly, the TOPSIS method was carried out to rank the alternatives using the Weighted Normalized Decision Matrix.

3. Methodology

Road construction projects are divided into six phases (Awng, 2018; Banihashemi et al., 2023; Oladazimi et al., 2021). The construction phase of a road construction project involves several primary steps to ensure that the selected design is implemented accurately and efficiently, including (1) pre-construction, (2) construction, and (3) construction management.

- Pre-construction step: Legal procedures are completed by obtaining a construction permit, cleaning the site, and preparing the budget. Concurrently, contractors mobilize laborers, machinery, and equipment to the designated construction site while also seeking material suppliers.
- Construction step: The contractor is responsible for transforming construction blueprints into tangible construction products, utilizing various resources such as materials, energy, laborers, and equipment. In this phase, the contractor assumes

a crucial role, while the owners, designers, and supervisors oversee the contractor's activities.

- Construction management: Owners oversee several aspects, such as time, quality, cost, resources, environmental consequences, hazards, and safety.

The construction phase of any road construction project can significantly impact sustainability. It consumes extensive amounts of energy, water, and raw materials and generates waste, including construction debris, materials, and demolition waste.

To evaluate the sustainability level of a road construction project, all three pillars must be considered, including economic, environmental, and social dimensions.

3.1. Life cycle approach

The economic performance of construction projects can be estimated according to the life cycle cost (LCC) approach (AlJaber et al., 2023; Mashhadi et al., 2021; Soust-Verdaguer et al., 2022). It includes ten main steps (see **Figure 1**):

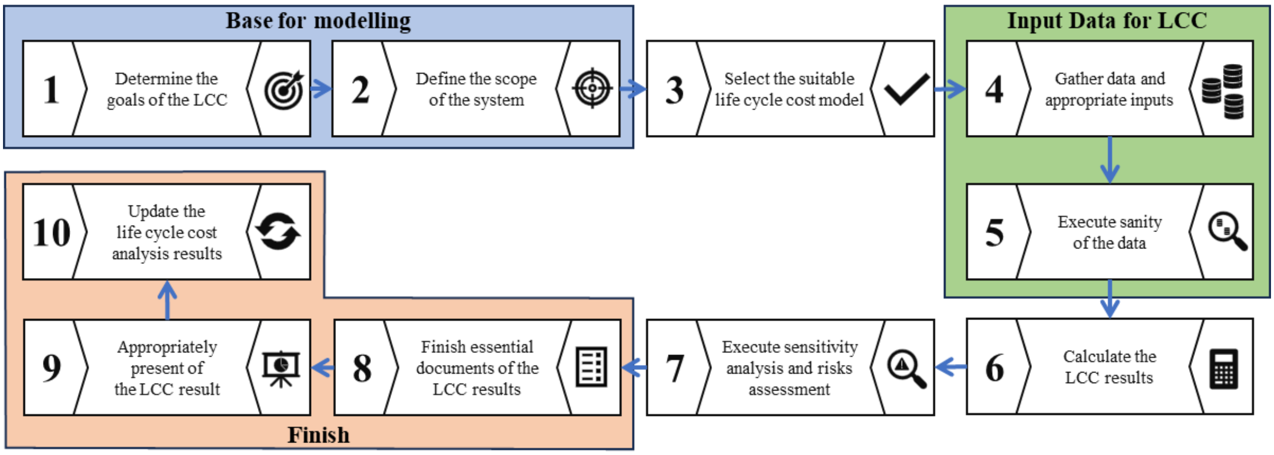

Figure 1. Detailed life cycle cost analysis steps.

Sources: Barringer (2003); Elkhayat et al. (2020); Greene and Shaw (1990); Ho and Rahman (2004); Mashhadi et al. (2021); Moins et al. (2020).

In the construction phase, the total LCC result is the sum of cost elements incurred during this phase. Besides, the costs incurred in the construction phase can be separated into direct costs (e.g., material costs, labor costs, equipment costs), indirect costs (e.g., management costs, administrative costs), and contingency costs. Based on the typical LCC equation, the LCC equation for construction costs is illustrated below:

$$\mathrm{LCC} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (1)$$

where: LCC denotes the life cycle cost in the construction phase from year 0 to year t (currency unit); C_t: denotes cost flows in year t in the construction phase (currency unit). This cost flow includes the direct costs (e.g., materials, labor, equipment…) and indirect costs (e.g., management costs…) incurred in year t; t is year being analyzed (with $t = 0, 1, 2, 3, \ldots, T$); T denotes the duration of the construction phase (years); r is the discount rate (percentage) in the construction phase. This equation calculates the LCC value by summing all the costs incurred from year 0 to year T. The selection of alternatives is determined by the LCC results, with the most significant alternative having the lowest LCC value.

Life cycle assessment (LCA) refers to a methodical examination and evaluation of the environmental impacts that may arise from the inputs, outputs, and services throughout the life cycle of a service or product (ISO, 2006a). In general, the LCA analysis is a thorough and methodical approach for determining the environmental burden of a product, process, and service during its life cycle. The typical LCA includes four main steps: Goal and scope definition; Life cycle inventory analysis; Life cycle impact assessment; and Interpretation (Balasbaneh et al., 2023; Dong et al., 2023; Olowo, 2022; Vega et al., 2022). Firstly, the designers and experts define the whole life cycle's goals, scopes, functions, functional units, and reference flows. Secondly, the inventory analysis phase (or life cycle inventory analysis—LCI) handles the collection, categorization, and calculation of physical material characteristics and inventory flows. For the life cycle impact assessment phase (LCIA), the significance of the quantified environmental burdens defined in the LCI is determined. LCIA phases involve the mandatory elements (selection, classification, and characterization) and optional elements (normalization, grouping, weighting, and data quality analysis), as suggested by Ec et al. (2010); Guinée (2002); and ISO (2006b). In the life cycle interpretation steps, the findings of an LCI and LCIA are compiled and discussed in accordance with the purpose and scope specification in order to derive conclusions and provide a basis for suggestions and decision-making. The following equation estimates the LCIA value:

$$\mathrm{LCIA}_c = \sum_{i=1}^{n}(\mathrm{CF}_i \times E_i) \quad (2)$$

where, n is the total number of LCI inputs and outputs type i in the construction phase; LCIA_c denotes the LCIA value of impact category c in the construction phase; CF_i refers to the characterization factor of LCI inputs and outputs type i in the construction phase. The characterization factor can be drawn from (Goedkoop et al., 2009; Huijbregts et al., 2017; Rivm, 2020); E_i denotes the individual inventory data of LCI inputs and outputs type i in the construction phase. For instance, the LCIA value of the impact category "climate change" will be estimated based on a formula such as:

$$\mathrm{LCIA}_{CC} = \sum_{i=1}^{n1}(\mathrm{GWP}_i \times E1_i) \quad (3)$$

where, $n1$ is the total number of LCI inputs and outputs type i concerning climate change in the construction phase; GWP_i denotes the characterization factor of LCI inputs and outputs type i concerning climate change in the construction phase (for example, CO_2 and CH_4), and $E1_i$ denotes the amount of LCI inputs and outputs type i concerning climate change. In a case study, the GWP_{CO2} for climate change is 1 kg CO_2 eq. (Goedkoop et al., 2009; Huijbregts et al., 2017; Rivm, 2020) and the total LCI inputs and outputs of CO_2 is 158.02 kg. So, the LCIA value of climate change is 1 × 158.02 = 158.02 (kg CO_2 eq.).

Lastly, the social life cycle assessment (Social LCA) method has the potential to assess the social performance of a project (Backes and Traverso, 2023; Dong and Ng, 2015; Jørgensen, 2013; Siebert et al., 2018; Zheng et al., 2020). The Social LCA analysis is built based on the traditional LCA analysis; hence, it displays the same framework as the LCA. The main steps employed in this method include (1) Goal and scope definitions, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation

(Unep and Setac, 2009; Unep and Slca, 2020). The Social LCA goals include the study's objectives, the application of the results, reasons for carrying out the study, the stakeholders, and the target audiences. In the second phase, the experts prepare to complete the flow diagram, collect data, and relate data to the functional unit and unit processes. Social life cycle impact assessment is the third phase, which estimates the magnitude of the selected social impact categories and subcategories. Lastly, the interpretation phases include the identification of significant issues, consideration of consistency and completeness, participation of stakeholders, recommendations, and reporting documents. The Social LCI result is calculated by the equation below:

$$I_{\mathrm{c}} = \sum_{s=1}^{m} I_{\mathrm{c,s}} \tag{4}$$

where: m is the total number of tasks in the construction phase; I_c is the Social LCI result of Social LCI indicators type c in the construction phase; $I_{c,s}$ is the Social LCI result of Social LCI indicators type c in task s in the construction phase.

3.2. The analytic hierarchy process (AHP)

The Analytic Hierarchy Process (AHP) was developed during the early 1970s by Saaty (1980). It is a technique that simplifies complicated problems and transforms them into a hierarchy (Abdel-malak et al., 2017). The method divides the target into sub-targets to simplify and structure it in a hierarchy. The created hierarchy includes multiple target levels, and the alternatives are put at the hierarchy's lowest level(s). According to Götze et al. (2015), the AHP consists of the subsequent steps: Formation of the hierarchy; Determination of the priorities; Determination of local priority vectors (weighting factors); Examination of the consistency of the priority assessments; Determination of (global) priorities/weightings. The consistency of the priority assessments is estimated based on the index of consistency (IOC):

$$\mathrm{IOC} = \frac{L_{\max} - C}{(C-1)} \tag{5}$$

where, $L_{\max}$ is the maximum eigenvalue and C denotes the dimension of the matrix. Then, a value of consistency (VOC) is calculated:

$$\mathrm{VOC} = \frac{\mathrm{IOC}}{\mathrm{RI}} \tag{6}$$

According to Saaty (1980), pair comparison matrices with VOC ≤ 0.1 are considered consistent, while matrices with VOC > 0.1 require more examinations.

3.3. Technique for order preference by similarity to ideal solution (TOPSIS)

The TOPSIS, developed by Hwang and Yoon (1981), selects the alternative that performs the shortest distance from the positive-ideal solutions and the farthest distance from the negative-ideal solution. TOPSIS method can be effectively applied to road construction projects to aid in decision-making processes. It identifies and assesses criteria relevant to the road construction project, such as cost, time, environmental impact, safety, quality, durability, maintenance, and social impact. Behzadian et al. (2012) confirmed that the TOPSIS procedure involves five steps: (1) Building a normalized decision matrix; (2) Building the weighted normalized decision matrix; (3) Evaluating the positive and negative solutions; (4) Determining the separation measures; (5) Calculating the relative closeness to the ideal solution. The first step transforms the attribute dimensions into non-dimensional attributes, which allows comparison with the attributes to build the Normalized Decision Matrix:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (7)$$

where, m denotes the number of road construction projects; r_{ij} is non-dimensional attribute of project i and economic, environmetal, or social criterion j; x_{ij} denotes the original economic, environmental, or social impact indicators of project i and sustainable criterion j in the decision matrix. In which, the weighted normalized decision matrix is:

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1j} & \cdots & v_{1n} \\ \vdots & \vdots & & \vdots & & \vdots \\ v_{i1} & v_{i2} & \cdots & v_{ij} & \cdots & v_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mj} & \cdots & v_{mn} \end{bmatrix} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \cdots & w_j r_{1j} & \cdots & w_n r_{1n} \\ \vdots & \vdots & & \vdots & & \vdots \\ w_1 r_{i1} & w_2 r_{i2} & \cdots & w_j r_{ij} & \cdots & w_n r_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \cdots & w_j r_{mj} & \cdots & w_n r_{mn} \end{bmatrix} \quad (8)$$

where: w_j: weightings of corresponding economic, environmental, or social criterion j. These figures are estimated based on the aforementioned AHP method.

The ideal and negative-ideal solutions are determined:

$$A^* = \{(\text{max-}v_{ij}/j \in J), (\text{min-}v_{ij}/j \in J'), i = 1, 2, 3, ..., m\} = \{v_{1*}, v_{2*}, ..., v_{n*}\}$$
$$A^- = \{(\text{min-}v_{ij}/j \in J), (\text{max-}v_{ij}/j \in J'), i = 1, 2, 3, ..., m\} = v_{1-}, v_{2-}, ..., v_{n-}\} \quad (9)$$

where, n is the number of sustainable criteria; $J = \{j = 1, 2, 3, \ldots, n$ and j are associated with advantage criteria}; $J' = \{j = 1, 2, 3, \ldots, n$ and j are associated with disadvantage criteria}. After that, step 4 calculates the separation measure, such as the distances of each project from the ideal and negative-ideal solutions:

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2},\ i = 1, 2, 3, \ldots, m$$
$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2},\ i = 1, 2, 3, \ldots, m \quad (10)$$

Relative Closeness to the Ideal Solution is calculated by the equation below:

$$C_{i*} = \frac{S_i^-}{S_i^* + S_i^-},\ \text{where } 0 < C_i < 1 \text{ and } i = 1, 2, 3, \ldots, m \quad (11)$$

The TOPSIS was applied widely in the construction industry. For example, the environmental burden of asphalt and concrete alternatives was assessed by Heidari et al. (2020). In their study, carbon emissions and energy consumption were firstly estimated by the LCA. Accordingly, they evaluated the number of CO_2 emitted to nature to analyze the carbon emissions, and the amount of energy was applied to analyze the energy consumption. Lastly, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to select the most environmental-friendly option. This study also confirmed that the TOPSIS can be applied to assess the sustainable performance of construction projects.

An integrated multi-criteria decision-making framework for Life cycle approach in road construction projects.

A 5-steps framework for integrating AHP and TOPSIS in Life Cycle Approach is developed (see **Figure 2**).

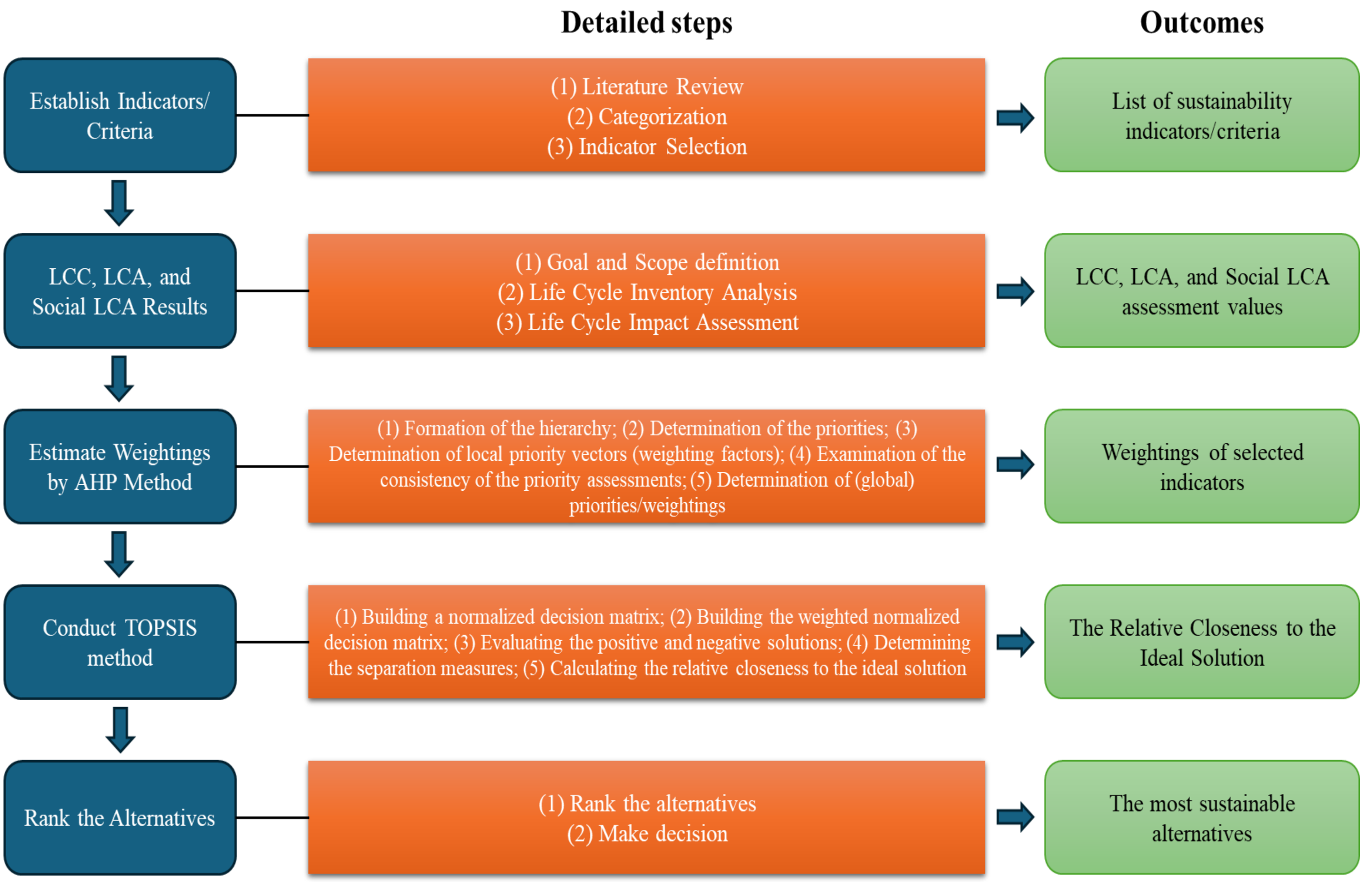

Figure 2. An integrated multi-criteria decision-making framework for life cycle approach in road construction projects.

The assessment starts with establishing indicators/criteria. For example, environmental criteria include carbon footprint, energy consumption, water usage, when social indicators involve health and safety, job creation, and community impact. After that, the LCC, LCA and Social LCA methods are applied to evaluate the economic, environmental, and social values. In the next step, the AHP method is applied to evaluate the relevant indicator weightings. Accordingly, the distances of each alternative from the ideal and negative-ideal solutions are estimated to calculate the Relative Closeness to the Ideal Solution. Lastly, the alternatives are ranked and selected based on the estimated relative closeness.

4. Case study

The proposed method is applied in the project "Upgrading and expanding Provincial Road 671 section from Km46 + 500–Km55 + 500 (intersection with Ho Chi Minh road)". Three types of pavement structures are (1) Cement Concrete; (2) Dense-Graded Polymer Asphalt Concrete; and (3) Dense-Graded Asphalt Concrete. The sustainability performance will be assessed during the construction phase, involving transporting, storing, and building, which perform some critical activities, such as excavation, grading, and site leveling. In the economic aspect, the total direct cost (X1), indirect cost (X2), and contingency costs (X3) are calculated, while the total amount of CO_2 emission (X4), the rate of recycled materials (X5), and the rate of raw materials (X6) are selected as the environmental impact indicators. The total CO_2 emission is calculated by aggregating the emissions from all equipment (such as automobiles, bulldozers, and excavators) and labor. The rate of recycled materials is calculated by comparing the total amount of materials used during the construction phase to the amount of recycled materials. This calculation is similar to how the rate of raw materials is determined. Besides, the number of created jobs (X7), average salary per month (X8), and the rate of local employment (X9) are chosen as the social impact indicators. Before applying the AHP-TOPSIS methods, the LCC, LCA, and Social LCA are conducted to assess the economic, environmental, and social performance of this project. Equation (1) is applied to estimate the total direct cost (X1), indirect cost (X2), and contingency costs (X3) of 3 alternatives. Total LCC value of direct costs from alternative A1 is estimated in **Table 1**. In this table, the total direct cost value is estimated based on the sum of discounted direct costs during the construction phase of a project

Table 1. Total LCC value of direct costs from alternative A1.

Ref	Year	Construction works	Unit	Quantity	Unit cost	Cost	Discount rate	Presented value
Section 03400		**Embankment Construction**						
03400-01	0	Construction of Subgrade (30 cm Layer)	m^3	8526.65	6.4913	55,349.21	10%	55,349.21
03400-02	0	Construction of Subgrade (50 cm Layer)	m^3	3381.11	6.4913	21,947.87	10%	21,947.87
03400-03	0	Construction of Embankment (below Subgrade)	m^3	17,393.42	3.2053	55,751.48	10%	55,751.48
03400-05	0	Settlement Compensation	m^3	13,227.89	5.8572	77,477.87	10%	77,477.87
03400-06	0	Embankment for Settlement	m^3	18,302.74	3.0196	55,266.22	10%	55,266.22
03400-07	1	Reused Excavated Material Filling	m^3	17,485.17	1.9476	34,054.82	10%	30,958.92
Total direct cost								**1,345,323.00**

Similarly, the LCA and Social LCA values were estimated based on Equations (2) and (4) (see **Table 2**).

Table 2. Total LCA value of CO_2 emission from alternative A1.

Ref	Construction works	Unit	Total LCI inputs-outputs	Characterization factor	LCA result
Section 03400					
03400-01	Construction of Subgrade (30cm Layer)	kg CO_2 eq.	43.3423	1	43.3423
03400-02	Construction of Subgrade (50cm Layer)	kg CO_2 eq.	32.5334	1	32.5334
03400-03	Construction of Embankment	kg CO_2 eq.	78.3432	1	78.3432
03400-05	Settlement Compensation	kg CO_2 eq.	65.3223	1	65.3223
03400-06	Embankment for Settlement	kg CO_2 eq.	82.3423	1	82.3423
03400-07	Reused Excavated Material Filling	kg CO_2 eq.	61.2312	1	61.2312
Total LCA results					**19,107.00**

After estimating the LCC, LCA, and Social LCA results, the proposed AHP-TOPSIS method is applied to integrate these results in the sustainable assessment. Firstly, AHP method is applied to estimate the weightings of 9 indicators. A questionnaire is designed based on the points Liker scale to ask the respondents to evaluate the importance of the indicators. The questionnaire, accompanied by a letter and a pre-paid envelope, was distributed to 105 chosen professionals in the Vietnamese construction sector and from the environmental and economic sectors. The group consisted of 33 architects and 50 designers, primarily responsible for selecting appropriate construction materials in the design of roads and bridges. The questionnaire was also sent to 12 cost estimators and 10 environmental engineers. The responders' contact information was acquired from some sources, such as the author's personal connections, company phonebook databases, and previous construction projects. A total of 65 valid and completed questionnaires were received from the respondents, yielding a reply rate of 61.9 percent. After that, Cronbach's alpha was assessed using SPSS software to test the reliability of the results. The alpha (α) coefficient normally ranges between 0 and 1. According to Hair et al. (Hair et al., 2013), the generally accepted lowest limit of Cronbach's alpha coefficient is 0.70. All alpha values were greater than 0.7, thus indicating that all the reliability coefficients were acceptable.

To conduct the AHP method, the hierarchy of economic, environmental, and social indicators is formulated, including 3 levels (sustainability assessment (level 1); LCC, LCA, and Social LCA results (level 2); and specific indicators (level 3)). After that, all levels' priorities and local priority vectors (weighting factors) are evaluated. For example, **Table 3** presents the weightings of economic indicators in the relationship with economic aspects.

Table 3. Weightings of each economic indicator in the economic aspect.

	NormalizedX1	NormalizedX2	NormalizedX3	Weightings
X1	0.3596	0.3596	0.3596	35.97
X2	0.3284	0.3284	0.3284	32.84
X3	0.3120	0.3120	0.3120	31.19

Then, **Table 4** illustrates the pairwise comparison matrix of economic, environmental, and social aspects and their weightings.

Table 4. Weightings of economic, environmental, and social aspects.

	Economic aspect	Environmental aspect	Social aspect	Weightings
Economic aspect	1	1.3864	1.5042	41.92
Environmental aspect	0.7212	1	1.085	30.22
Social aspect	0.6648	0.9217	1	27.86

Lastly, the consistency of the priority assessments determines the suitable weightings. All VOC values of the weightings are lower than 0.1, meaning that all weightings are acceptable. The summarized weightings of indicators are presented in **Table 5**.

Table 5. Original values of economic, environmental, and social impact indicators.

	X1	X2	X3	X4	X5	X6	X7	X8	X9
A1	1,345,323.00	280,899.41	162,622.24	19,107.00	0.24	0.28	120.00	520.00	87.00
A2	1,034,543.00	218,164.29	125,270.73	20,916.00	0.31	0.29	130.00	526.00	102.00
A3	876,298.00	200,566.97	107,686.50	23,301.00	0.25	0.25	108.00	485.00	65.00
Weightings	15.08	13.77	13.07	10.70	10.04	9.49	8.73	9.12	10.01
Sum of Squares of criteria	1,909,992.507	408,322.4752	231,808.3915	36,680.9638	0.4650	0.4743	207.2776	884.4778	148.9899

Table 5 presents the value of sustainable indicators and their relevant weightings. In this project, the values of economic, environmental, and social impact indicators are LCC, LCA, and Social LCA results. The weightings are evaluated based on the AHP method. Then, the TOPSIS method was used to rank the alternatives. At first, the Normalized Decision Matrix was constructed based on the values of specific indicators (see **Table 6**).

Table 6. Normalized decision matrix of economic, environmental, and social impact indicators.

	X1	X2	X3	X4	X5	X6	X7	X8	X9
A1	0.7044	0.6879	0.7015	0.5209	1.9374	0.5903	1.7273	1.7009	0.5839
A2	0.5416	0.5343	0.5404	0.5702	1.4999	0.6114	1.5944	1.6815	0.6846
A3	0.4588	0.4912	0.4645	0.6352	1.8599	0.5270	1.9192	1.8237	0.4363

Next, the Weighted Normalized Decision Matrix was formulated to determine Ideal and Negative-Ideal Solutions (see **Table 7**).

Table 7. Weighted normalized decision matrix of impact indicators

	X1	X2	X3	X4	X5	X6	X7	X8	X9
A1	10.6208	9.4705	9.1725	5.5725	19.4496	5.5995	15.0769	15.5147	5.8468
A2	8.1673	7.3554	7.0657	6.1001	15.0578	5.7995	13.9172	15.3377	6.8549
A3	6.9180	6.7621	6.0739	6.7957	18.6716	4.9996	16.7521	16.6343	4.3683
Max	10.6208	9.4705	9.1725	6.7957	15.0578	5.7995	13.9172	15.3377	4.3683
Min	6.9180	6.7621	6.0739	5.5725	19.4496	4.9996	16.7521	16.6343	6.8549

The weighted normalized decision matrix of economic, environmental and social impact indicators is illustrated in **Figure 3**.

The Ideal and Negative-Ideal Solutions are determined based on max and min values chosen from weighted normalized impact indicators (see **Figure 3**). In this study, the ideal solutions involve min values, while negative-ideal solutions cover max values. After that, the Relative Closeness to the Ideal Solution is evaluated to rank three alternatives.

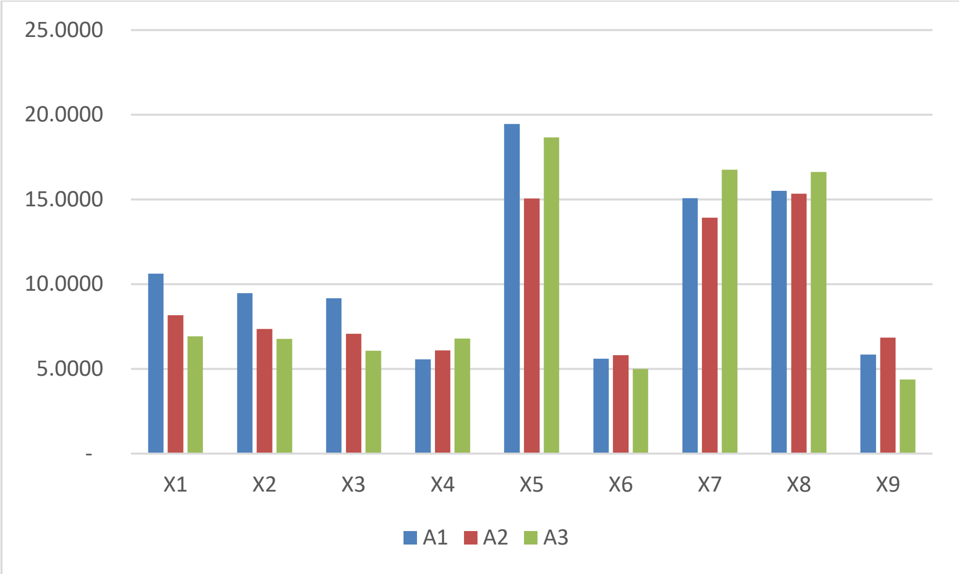

Figure 3. Weighted normalized decision matrix of economic, environmental and social impact indicators.

5. Results and discussion

The Relative Closeness to the Ideal Solution is presented in **Table 8**.

Table 8. Ideal solutions, negative-ideal solutions and relative closeness of alternatives

	Ideal solutions	Negative-ideal solutions	Relative Closeness	Rank
A1	6.0069	4.9383	0.4512	2
A2	5.7290	4.6474	0.4479	3
A3	2.8783	7.3529	0.7187	1

In **Figure 4**, the Relative Closeness values of A1, A2, and A3 are 0.4512, 0.4479, and 0.7187, respectively. Hence, the Relative Closeness of A3 is the highest value. So, option 3 (Dense-Graded Asphalt Concrete) should be selected as the highest sustainable performance level.

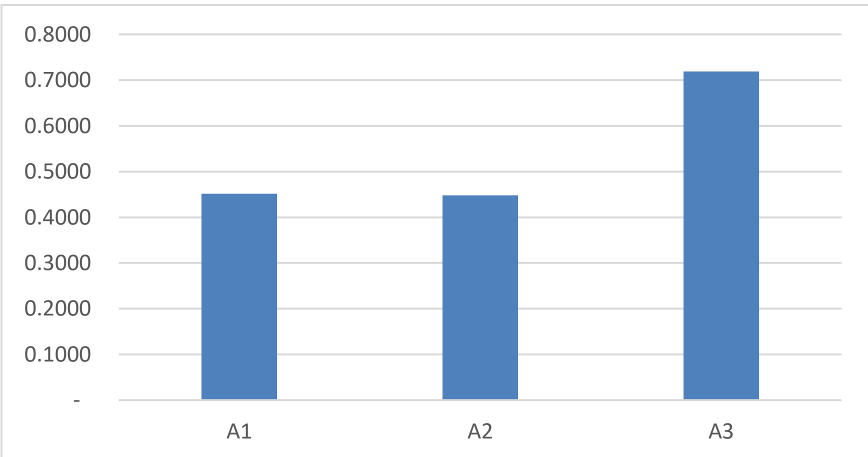

Figure 4. Relative closeness of alternatives.

The result is estimated based on the combination of AHP and TOPSIS methods. AHP helps in structuring complex decision-making problems by breaking them down into a hierarchy and assigning weights based on their relative importance. This ensures a thorough evaluation of economic, environmental, and social criteria, leading to more balanced and sound decisions. TOPSIS facilitates the ranking of alternatives based on their distance from an ideal solution. By combining it with AHP, the method not only considers the weighted importance of criteria but also ranks the alternatives in a way that identifies the most sustainable option, enhancing the decision-making process by highlighting the best choice in terms of sustainability. The integration of AHP and TOPSIS allows for the simultaneous consideration of multiple criteria from LCC, LCA, and Social LCA. This holistic approach ensures that all relevant aspects of sustainability—economic, environmental, and social—are incorporated into the decision-making process, promoting more sustainable outcomes, and enhancing the transparency and consistency of the evaluation process, making it easier to justify and communicate the decisions made. In addition, by explicitly incorporating stakeholder preferences and priorities through AHP and providing clear rankings through TOPSIS, the combined approach facilitates better stakeholder engagement and acceptance of the decision-making process.

The life cycle sustainability assessment (LCSA) is a popular method for integrating LCC, LCA, and Social LCA. Some authors used this method to evaluate the economic, environmental, and social burdens of road construction projects (Fauzi et al., 2019; Figueiredo et al., 2024; Zhou et al., 2007). This method considers the comprehensive effects (including economic, environmental, and social effects) on sustainability. However, the results of LCA and Social LCA with various units must be converted into a single score by normalization techniques. This technique helps to eliminate the different units between impact category indicators in the LCA and Social LCA, normalize the results to a reference system, and facilitate integration in the LCSA. Normalization transforms data to a common scale, potentially stripping away the context and meaning inherent in the original units. When different datasets are normalized independently, it may lead to misleading comparisons. Normalized scores may not be directly comparable if the meanings of the original data differ significantly. The integration of AHP and TOPSIS allows for the simultaneous consideration of multiple criteria from LCC, LCA, and Social LCA without normalization. Furthermore, the combined approach enhances stakeholder engagement and acceptance of the decision-making process by explicitly incorporating stakeholder preferences and priorities through AHP and providing unambiguous rankings through TOPSIS.

6. Conclusion

Evaluating the sustainability performance of road construction projects during the construction phase is essential for enhancing sustainable development in the construction industry. This phase presents an opportunity to solve critical environmental and social problems, such as resource depletion, greenhouse gas emissions, and local community impacts. Project managers can implement best practices in resource efficiency, waste reduction, and pollution control by systematically assessing sustainability criteria. This minimizes the environmental burden of construction activities and promotes economic and social benefits.

Some studies tried to integrate LCC, LCA, and Social LCA to evaluate the sustainable performance of construction projects. However, in these methods, the outcomes of LCA and Social LCA, measured in different units, need to be transformed into a single score using normalization methods. It can result in misleading comparisons, and comparing normalized scores is potentially unreliable if the original data have drastically different interpretations. In order to resolve these issues, the integration of AHP and TOPSIS methods utilizes their respective strengths: AHP's structured approach to determining criteria weights through pairwise comparisons and TOPSIS's capacity to rank alternatives based on their proximity to the optimal solution. By utilizing AHP's consistency and TOPSIS's ranking procedure, this integration improves the accuracy of decision-making, resulting in more comprehensive and reliable evaluations. This method considers all three dimensions of sustainable development: economic, environmental, and social aspects. Decision-makers can achieve a comprehensive evaluation and effective balance of economic, environmental, and social aspects without normalization by combining the ranking mechanism of TOPSIS with the prioritization capabilities of AHP. This combination guarantees a comprehensive and systematic approach to sustainable decision-making, thereby promoting meaningful outcomes that are consistent with the principles of sustainability.

This study developed a system incorporating the LCC, LCA, and Social LCA into the AHP-TOPSIS method to assess the sustainability performance of road construction projects during the construction phase. Firstly, the economic, environmental, and social impact category indicators were assessed using the LCC, LCA, and Social LCA. Second, the AHP method was applied to assess the weightings. After that, the TOPSIS method was applied to rank the alternatives using the Weighted Normalized Decision Matrix. Following that, a case study was carried out to validate the proposed methodology. The outcomes confirmed that the method can assess the sustainability performance of road construction projects during the construction phase.

However, this proposed method faces a problem concerning the scope and data management. The method requires a vast amount of data analysis during the life cycle approach, including data from LCC, LCA, and Social LCA analyses. The application of Big Data can provide a potential answer to this challenge. The proposed method only focuses on the construction phase instead of all phases in construction projects. Furthermore, the AHP and TOPSIS method has several issues, such as rank reversal. In this context, the alternatives' order of preference changes when an alternative is added to or cut off from the decision problem. Future work may focus on developing a database for evaluating sustainability impact indicators and merging the AHP and TOPSIS methods with other methodologies to address the rank reversal issue. Besides, the proposed method can be expanded to include other phases of road construction projects.

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