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Evaluation of Road Infrastructure Projects: A Life Cycle Sustainability-Based Decision-Making Approach

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Abstract: Economic growth, social wellbeing, and infrastructure are strongly interrelated and jointly contribute to national development. Therefore, evaluation and selection of a road infrastructure project direly need a comprehensive sustainability assessment integrating holistic decision criteria. This study presents an elaborate life cycle sustainability-based project evaluation tool, comprising an assessment framework, an integration model, and a decision framework. In the first phase, a life cycle sustainability assessment (LCSA) framework for road infrastructure is established using mixed methods. In the second phase, interviews are conducted to obtain pairwise comparisons among impact categories and subjective reasoning of their priorities. Analytical hierarchy process (AHP) is adopted to develop the LCSA integration model. The minimum threshold limits of impact categories are evaluated and integrated into the proposed decision framework. Further, thematic and cross-sectional analyses are performed on the interview findings to rationalize the proposed decision framework. The findings include a detailed and customized project assessment framework, an integration model, and a decision framework for the assessment of different project alternatives. This study helps policy- and decision-makers in selecting the project alternative by maximizing sustainability in road infrastructure projects. Insights into environmental and social externalities and their quantitative interpretation throughout the life of the road are also achieved.

Keywords: life cycle sustainability assessment; road infrastructure; project evaluation; decision-making; analytical hierarchy process

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1. Introduction

Sustainability is a subjective concept open to different interpretations and contextual inconsistencies. This is driven by demographics and sectoral dynamics and requires lasting, insightful, and practical solutions. In the case of physical infrastructure, like mega transportation projects, sustainable project delivery is challenging [1,2]. Road infrastructure projects, in particular, are immensely prone to the fiscal, geographical, and societal risks of project development. Being projects of national importance impacting the economic performance and regional trade, delays and failure cause a high number of externalities. These social and environmental externalities are difficult to assess through traditional feasibility assessment methods that ignore life cycle project impacts [3]. For example, if the impacts of roadway construction, operation, and maintenance were added to the operational energy use and greenhouse gas emissions of on-road vehicles, they would roughly be 10% higher than the estimates based on vehicle operations alone [4]. Therefore, such projects require sophisticated sustainability assessment during the planning stage for selection, comparison, and evaluation of suitable projects. Incorporation of holistic life cycle project impacts requires the development of a more integrated approach for sustainability assessment. For the case of road infrastructure projects, two major gaps in the literature are encountered in conducting a life cycle-based sustainability assessment (LCSA):

1. In existing assessment models, the inclusion of qualitative criteria like social impacts and road infrastructure-specific parameters is often overlooked. For a more representative assessment, the sustainability assessment parameters such as systems boundaries, functional units, and study scope need to be representative of the project type under study. Thus, it is important to define sustainability parameters suiting road infrastructure project evaluation [5].
2. Highways are public infrastructure projects catering to a multi-stakeholder system presenting a higher-order complexity to the sustainability problem definition and exploration of necessary solutions [6]. Therefore, the project sustainability system needs to be delineated based on varying stakeholder roles, interests, participation, and understanding [7,8].

Existing tools offer limited capabilities regarding the discussed issues [9] and focus on deepening the understanding of the environment-infrastructure interface and developing sustainable infrastructure solutions as a result. The current study presents an integrated sustainability assessment tool for project assessment, comparison, and evaluation for road infrastructure projects. The developed project evaluation tool consists of (1) an LCSA assessment framework, (2) a post-analysis integration model of the sustainability areas and corresponding impact categories and, (3) a decision framework for the selection of the most sustainable alternative. The tool provides efficient decision-support to support a holistic and comprehensive assessment. It is flexible and allows for iterative processing catering to efficient project selection during the early development stage of planning.

2. Literature Review

Infrastructure development is important for socio-economic well-being, due to which the decision-making for project selection and evaluation is critical. Given the limitations of traditional project evaluation approaches, there is growing interest to develop sustainability-based assessment approaches for infrastructure projects [10]. However, among the three areas of sustainability, the environment has been the main focus for most of the studies [11,12], and the social area of sustainability has been neglected [13]. A list of some recent studies related to the life cycle sustainability assessment of road projects is presented in Table 1.

Table 1. Studies related to life cycle sustainability assessment of road projects.

Year	**2021**	**2021**	**2020**	**2020**	**2020**	**2020**	**2020**	**2018**	**2017**	**2017**	**2015**	**2014**	**2014**
Reference	[14]	[15]	[16]	[17]	[18]	[13]	[19]	[20]	[21]	[22]	[23]	[24]	[25]
Environment	x	x	x	x	x	x	x	x	x	x	x	x	x
Social						x					x	x	
Economic						x	x	x	x	x	x	x	x

Studies focusing on the environmental aspects only are mainly related to pavement material selection [15,17], or pavement maintenance strategies [19,20,26]. Few other studies incorporated the economic criteria along with the environment for project evaluation [20,25]. Some studies incorporated three areas of sustainability while developing a rating system for project procurement [14,23,24]. Such studies mainly focused on the sustainability capabilities of organizations, rather than project sustainability. Few studies incorporated indicators from three areas of sustainability, however, their assessment approaches lack a total life cycle approach [11,13].

Therefore, this study opts to develop an integrated and life cycle sustainability assessment (LCSA) tool for road infrastructure project evaluation. In the realm of LCSA, integration of the life cycle thinking approach with the facets of sustainability provides three sustainability assessment approaches; environmental life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) [27]. To evaluate the attributes of the LCSA assessment of road infrastructure, this study has reviewed relevant literature related to each dimension of sustainability.

2.1. Environmental Life Cycle Assessment (LCA)

2.1.1. Project Level Assessment

In terms of scope, LCA can be performed for a single component of the road, a complete road section, or an entire project [28]. Although studies related to single road components are in abundance [29], most of the past research is focused on asphalt and concrete pavement comparison [30]. However, the application of LCA in road projects could address a wider scope than material properties only [31]. Additionally, the studies at the complete project level are limited and generic [32]. It is primarily because more intricacies arise to address the relevant complexities at higher levels of decision. To explore the potential application of LCA in road construction, few review articles have been published. According to them, existing studies adopted varying goals and scope, system boundaries, and functional units due to which varying pavement LCA results have been observed [31,33]. Furthermore, Balaguera, Carvajal, Albertí and Fullana-i-Palmer [30] reviewed the LCA methodological aspects considered in past studies, focusing on the comparison of impacts from traditional and alternative materials.

2.1.2. Variety of Functional Unit

In road project LCA, a crucial issue is the lack of consensus upon a suitable functional unit [31]. The review by Balaguera, Carvajal, Albertí and Fullana-i-Palmer [30] reveals that the length of the road is overwhelmingly used as a functional unit in past studies. For example, Reza, Sadiq and Hewage [34] used a typical two-lane roadway, and Capony, Muresan, Dauvergne, Auriol, Ferber and Jullien [35] used per kilometer (km) of the road as functional units. Alternatively, few studies used traffic as a functional unit. For example, Stripple [36] used 5000 annual average daily traffic (AADT) for an analysis period of 40 years and Huang, Bird and Bell [37] used 26,000 AADT as a functional unit. Another such example is O'Born, Brattebø, Iversen, Miliutenko and Potting [38]. Few studies also used the volume of road asphalt and other materials as functional units [39,40].

The main factors for the selection of functional units are goal and scope of study along with spatial features, and local design codes and practices [31]. The studies where the functional unit is solely focused on traffic results are at the level of material performance comparison or design evaluations. However, studies that include the length of road in their functional units offer a depiction of comparison at the project level. In the analysis of road LCA, the input data are related to the physical characteristics such as length, width, and thickness. Thus, a section of road per unit length is the simplest and most representative functional unit [36].

2.1.3. Selection of System Boundaries

The complex web of environmental outcomes cannot be explicitly associated with a single stage of product life [41]. Therefore, the system boundary of any life cycle methodology should incorporate the whole of life consideration, from cradle to grave, including both direct and indirect impacts. A review of the life cycle phases considered in existing road LCA studies by Balaguera, Carvajal, Albertí and Fullana-i-Palmer [30] reports that most existing studies fail to incorporate the true cradle to grave approach, except Park, Hwang, Seo and Seo [42] which included all the life cycle phases.

Omitting any project phase from the LCA framework can cause severe deviations in results [33]. For example, Park, Hwang, Seo and Seo [42] report that the extraction phase of construction materials consumes maximum energy over the project life cycle. Construction and demolition phases are more energy-intensive than the maintenance phase. Moreover, the use phase also impacts the life cycle due to traffic fuel consumption, concrete carbonation, urban heat island effect, and radiation [43]. Therefore, an all-inclusive approach covering all project stages is recommended.

2.1.4. Selection of Impact Categories

A wide variety of impact categories exists for analyzing the environmental impacts of roads [31]. However, no considerable pattern for the selection of impact categories can be found within LCA studies for the area of study, or study objectives [30]. Air emissions and energy are widely considered impacts. But impacts like the consumption of water and raw materials, and resource depletion are relatively less reported [12]. Additionally, water emissions or eutrophication impact and hazardous solid emissions are scarcely considered [34,35]. Further, in a review of past studies by Balaguera, Carvajal, Albertí and Fullana-i-Palmer [30], the dominant consideration of midpoint type of impact categories, can be observed as a significant pattern. For details on midpoint and endpoint type of impact categories, [41] has provided a detailed review.

2.2. *Social Life Cycle Assessment (S-LCA)*

Social life cycle assessment (S-LCA) has been established complementary to LCA for a comprehensive sustainability assessment of products. However, its methodological development is still in progress [44,45]. To find S-LCA studies in the context of its practical methodology, literary works between the years 2006 and 2018 using keywords "Social life cycle assessment," "SLCA," "S-LCA," "Social LCA," and "Societal LCA" were searched. Resultantly, 172 relevant articles, including 86 case studies were screened, but no studies on road infrastructure projects were found. Among case studies, some studies developed context-specific indicators and approaches for a variety of industries. However, a significant number of reviewed studies (37%) followed the UNEP/SETAC guidelines as their adopted research methodology [46,47]. Furthermore, 82% of the studies were published after the year 2012, signifying a substantial methodological development stage, marking the UNEP/SETAC guidelines as a breakthrough in S-LCA progression [48].

UNEP/SETAC guidelines and methodological sheets inherited the four-phase LCA framework of ISO 14040 [49] and recommended using the same for S-LCA [44]. S-LCA guidelines presented the social impact categories, identified the important stakeholders, and presented the impact subcategories for each stakeholder [50]. Six main social impact categories are suggested: health and safety, working conditions, human rights, cultural heritage, governance, and socioeconomic repercussions; along with relevant stakeholders including workers, local community, society, consumers, and value chain actors (VCA). The methodological sheets provided the data collection approach and detailed inventory for assessment of impact subcategories. Ever since their publication, the most widely used impact categories, and subcategories are those provided by these guidelines [51,52].

However, the guidelines and methodological sheets did not provide any impact pathways and characterization model, and instead recommended a linear aggregation of impacts for interpretation of S-LCA results, till the development of impact assessment methodology [53]. For impact assessment and aggregation, two types of methodological approaches, performance reference point, and impact pathways are reviewed by Chhipi-Shrestha, Hewage and Sadiq [54]. Reference points are established on the basis of minimum performance levels of indicators agreed by some organizations or standards such as OECD guidelines and the International Labor Organization (ILO) conventions [55]. The method of impact pathways considers the cause-effect relationship between the impact categories and subcategories and utilizes the midpoint or endpoint indicator approach [55].

The recently published "Handbook for Product Social Impact Assessment (PSIA)" [56], proposed a more practical approach having consensus with the previous S-LCA standard and studies, primarily based on UNEP/SETAC guidelines [53,57]. Unlike UNEP/SETAC guidelines, the PSIA proposed three categories of stakeholders (workers, consumers, and local communities) and 19 subcategories. However, the aggregation or impact characterization methodology is per UNEP/SETAC guidelines but explained more comprehensively.

2.3. Life Cycle Costing (LCC)

LCC helps in choosing an economically viable alternative to an investment or product. LCC methodology is intricate and time-intensive [58] for which a variety of standards and guidelines are developed. Davis Langdon [59] has conducted a detailed review of such LCC standards and guidelines.

Although LCC has been considered as the major indicator for evaluation and selection of project alternatives, its framework suffers from consistency and reliability issues of data and assessment of roads [60]. The lack of a generalized methodical approach for data collection in overall life cycle phases makes projects prone to ill-informed investment decisions. Including all the life cycle phases can considerably improve objectivity in the economic assessment of roads [61] resulting in a more efficient project selection process addressing issues of available funds and appropriate resource allocation among ongoing projects [62].

For economic evaluation of construction projects, a wide set of indicators is available with net present value (NPV), internal rate of return (IRR), equivalent uniform annual cost (EUAC), and cost-benefit analysis (CB) being most common [59]. However, the selection of indicators depends on the context of analysis and decision-making level [61]. In developing countries, IRR is the preferred indicator for economic assessment due to the high uncertainty of discount rates in their environment [63]. However, a wide majority of the financial models related to construction projects recommend NPV-based financial assessment [59]. Also, for the assessment of road projects, NPV is the most common and widely used indicator [61,64].

The choice between NPV and IRR-based assessment is contextual to the goal of the study and assessment constraints. Agnes Cheng, Kite and Radtke [65] discussed the key features and differences between NPV and IRR. The features of NPV, such as representing the results in absolute monetary terms, unaffected by cash flow timing variations, and reinvestment of intermediate cash flows at cost of capital rate make it more suitable for decision-making. Also, for a comparison of multiple alternatives, choices, and varying analysis periods, NPV is particularly helpful [64]. Further, for performing LCC, cost component breakdowns need to be selected according to the goal and scope of assessment [66,67]. ASTM [68] provides a generic LCC model as given in Equation (1). Which incorporates capital cost (C), replacement cost (R), annual operation and maintenance cost (A), damages and repair cost (M), energy cost (E), and salvage (S). This model allows the representation of all cost heads separately, hence varying inflations and discount rates on all the cost items can be employed separately.

$$LCC = C + R + A + M + E - S \quad (1)$$

Discounting all costs to present value (PV) through NPV can significantly reduce analytical difficulties in *LCC* analysis because it efficiently incorporates the time value of money variation of incurred costs at a different stage of the project life [59].

2.4. Life Cycle Sustainability Analysis (LCSA)

For policy and business decisions, it is imperative to consider suitability holistically. However, methodological and systematic inconsistencies of the three individual facets of sustainability assessment, LCC, LCA, and S-LCA, make conjoint decision-making confusing [5]. Therefore, an integrated sustainability assessment approach is desired, which may establish a realistic, practical tradeoff between the three sustainability dimensions [69]. Such an integrated approach is termed as life cycle sustainability assessment (LCSA) [70].

The concept of integrated sustainability assessment is not new. Initially, after the development of LCC, the debate over the consolidation of sustainability facets into LCC started [71]. Since then, various proposals have been discussed to explore the possibilities of integration. On the other hand, Azapagic and Perdan [72] discussed the set of indicators for total sustainable development and proposed a general framework to carry out a holistic LCA which includes the environmental, economic, and social indicators. For combining the LCA with LCC and S-LCA, two main approaches have been discussed by Norris [73] and Klöpffer and Renner [70]: (1) develop an integrated framework to carry out a single LCSA assessment (pre-integrated assessment), and (2) perform an individual assessment of each sustainability area and then integrate them (post-assessment integration). Based on their discussions, it was concluded that the single assessment of all the sustainability areas is constrained due to varying methodological approaches, the origin of impact categories, and inconsistency of results. Thus, a theoretical formulation of *LCSA* has been proposed as given in Equation (2).

$$LCSA = LCA + SLCA + LCC \quad (2)$$

2.4.1. Pre-Integration Assessment Approach

For a single LCSA assessment approach, some studies conducted detailed discussions to explore the challenges and possibilities of integrating three dimensions of sustainability and investigated the mutual points of contact and methodical relationships between sustainability facets. Literature has discussed the normative and empirical aspects of methodological frameworks of sustainability areas and drew a broader picture of possible integration [69,74]. Bierer, Meynerts and Götze [75] discussed and proposed a framework for the transdisciplinary integration of micro and macro environmental, economic, social, physical, and technical models. Also, to integrate the LCA, LCC, and CBA (cost-benefit analysis), Hoogmartens, Van Passel, Van Acker and Dubois [5] compared their methodologies and concluded that significant connections exist between these three tools. Despite these efforts, assessment of LCSA through a single analysis of all three areas of sustainability is hindered due to their conflicting intrinsic properties, such as focus points, analysis periods, nature of impact categories, and representation of results.

2.4.2. Post-Assessment Integration Approach

Few studies have adopted the second approach which aims to combine the results of individual sustainability areas for achieving LCSA. In doing so, published research has utilized the normalization, weighting, and multicriteria decision analysis (MCDA) approaches [76]. Such as, Matos and Hall [77] proposed a landscape theory-based framework to incorporate the interdependencies among sustainability parameters. Kucukvar, Noori, Egilmez and Tatari [76] and Santos, Ferreira, Flintsch and Cerezo [20] performed multi-objective optimization for evaluation of environmental and economic impacts of two types of pavements. Similarly, You, Tao, Graziano and Snyder [78] developed a multi-objective integrated linear programming tool for sustainability assessment of design and operation of cellulosic biofuel supply chains. However, these studies focused on multi-objective approaches of MCDM, which are mainly used for design optimization purposes, instead of multicriteria single objective performance assessment [79]. The studies of Santoyo-Castelazo and Azapagic [80] and Atilgan and Azapagic [81] used multi-attribute value theory (MAVT) for the integration of environmental, economic, and social aspects of energy projects using multiple weighting combinations to present the sustainability results at various levels. Similarly, Hermann, Kroeze and Jawjit [82] developed a tool named COMPLIMENT where AHP was performed using weights achieved from the distance-to-target method proposed by Seppälä and Hämäläinen [83]. Similarly, [26] employed AHP for multicriteria evaluation along with a system dynamics approach. However, while adopting the MCDA approach for LCSA the issues of accuracy and assumptions are critical for the same reasons as in LCA [84]. In this regard, Clímaco and Valle [85] argued that issues such as consideration of all impacting actors and affectees, the discrete definition of indicators, the conflicting priorities among all stakeholders, and the data uncertainties must be considered while selecting a robust tool for MCDA. Moreover, a comprehensive and decisive LCSA demands an elaborative decision framework that could incorporate the scaling of indicators, define their target levels or thresholds, and also consider intra-indicator weightings [86]. Moreover, for the accumulation of sustainability results into a single value, weightings are required at three levels; between indicators or subcategories, between the main impact categories, and between the sustainability areas. Keeping in view its strengths, the current study adopts the post-assessment integration approach.

3. Research Methodology

The study was performed in two phases, as illustrated in Figure 1. In phase–1 LCSA assessment framework was developed through the detailed literature review and the interviews with senior government decision-makers, researchers, and consultants. Following the developed framework, further data collection was carried in phase–2. The pair-wise comparison and the analytical hierarchy process (AHP) analysis led to the development of the integration model. Further, based on the collected qualitative data and descriptive statistical analysis the decision framework was developed. The detailed research methodology is discussed in the following sub-sections.

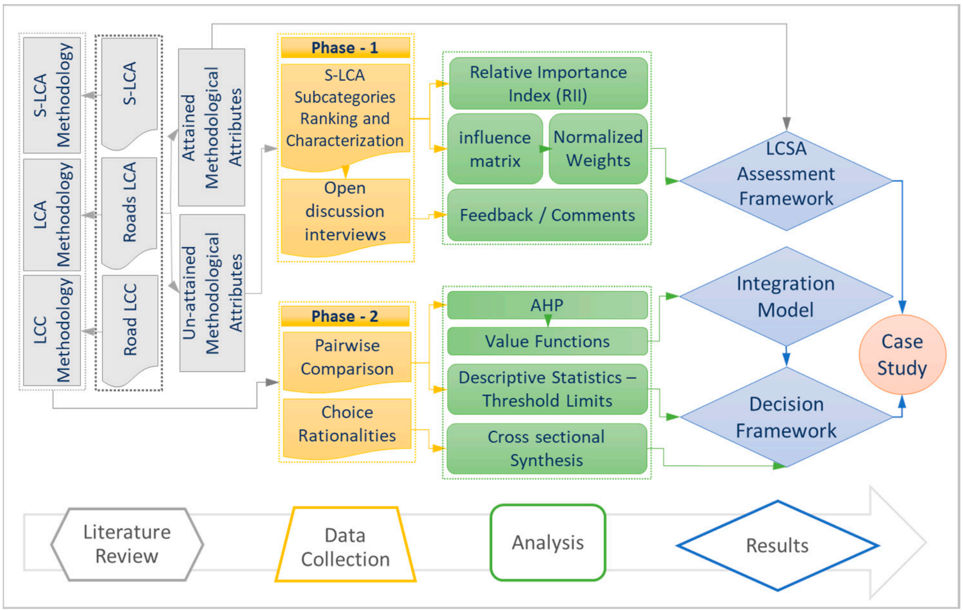

Figure 1. Research methodology.

3.1. Phase–1: LCSA Assessment Framework

The methodological attributes of the LCSA assessment framework were primarily attained from the literature. However, some of the methodological attributes could not be attained from the literature and required further data collection. A summary of such methodological attributes is presented in Table 2.

Table 2. Status of life cycle sustainability assessment (LCSA) methodological attributes.

Sustainability Area	Attained Methodological Attributes	Unattained Methodological Attributes
LCA	System boundaries, functional unit, impact assessment methods	Impact categories
S-LCA	The general framework, general impact categories, general subcategories	Selection of relevant impact categories and subcategories, characterization model for aggregation of subcategories into impact categories
LCC	System boundaries, LCC indicator, or impact category	-

The methodological attributes of LCA are fairly established in literature but are overly focused on material comparison or environmental assessment of a road section. These methodological attributes need to be reconfirmed for the case of complete project comparison and decision-making aspects. For S-LCA, guidelines, and methodological sheets provided by [87] are available [88]. They are mainly focused on the product industry. However, their application in road projects is hindered due to the lack of generic impact categories and stakeholders. Therefore, it is required to reevaluate and configure the S-LCA attributes for the case of road infrastructure projects. Furthermore, there is no characterization model for the aggregation of subcategories into the main impact categories. Thus, these guidelines and subcategories can serve as a baseline for establishing S-LCA part of the LCSA assessment framework for road infrastructure. For LCC, there are two main methodological attributes, system boundaries, and suitable LCC indicators. For performing LCC, system boundaries are fairly established for the analysis of the complete project scope. Though the suitability and superiority of NPV over IRR is debatable, for the case of alternative comparison, literature has established the operational and analytical superiority of NPV.

For the unattained methodological attributes, detailed semi-structured interviews were carried out with 12 senior officials in relevant government departments (40%), researchers from the field of environment, economics, and road construction (40%) and, road infrastructure consultants (20%). All interviewees had a minimum of 10 years of experience, making composition as 60% had 10–15 years, 20% had 15–20 years and 20% interviewees had more than 20 years of experience. Interviews consisted of three sections; in the first section, an open-ended discussion was held regarding the current project evaluation practices and the idea of the current study was appraised. Then for discussion on each unattained attribute, options of methodological attributes gathered from the literature were presented.

In the second section, interviewees were asked to rank the S-LCA subcategories on a Likert scale of 1–5 (1 = least important and 5 = most important). Relative importance index (RII) was calculated for each subcategory using the modal values for obtaining the ranking. In the third section, the interviewees were asked to relate each impact category with each subcategory on a scale of 0–5 (0 = not relevant and 5 = most relevant). Further, an influence matrix of relevance was generated using the modal values. Then characterization weights of subcategories for the impact categories were obtained using the Euclidian norm [89]. Based on the characterization weights, the subcategories were further selected and aggregated for the LCSA Assessment Framework.

3.2. Phase–2: Integration Model and Decision Framework

In light of the literature review related to LCSA studies and to ensure practicability, this study follows the post-assessment integration approach of LCSA. The adopted approach involves MCDM-based aggregation of impact indicators along with the expert opinion to achieve the LCSA integration model of road infrastructure projects. AHP has been used for MCDM in this study for which pairwise comparison was performed. For this purpose, scenario-based structured interviews of policy and decision-makers including senior civil and public servants, experienced industry professionals, and academic peers were carried out.

The sample size for data collection is critical to the reliability and validation of results and establishing quantitative reasoning. Baker, Edwards and Doidge [90] suggested using approximately 30 interviews for qualitative studies. Owing to the specialized nature of inquiries and the unconventional multi-layered structure of this data collection, only the highly experienced professionals from relevant knowledge areas and representing the pertinent decision-making bodies were selected. Participation of interviewees was ensured from across the country to remove any selection bias in the sample.

As a result, 32 interviewees belonging to senior positions in civil and public services (56%), including road infrastructure-related ministries and departments at federal and provincial levels, such as the Ministry of Planning, Development, and Reform; National Highway Authority (NHA), and Public-Private Partnership units; engineering consultancies (28%); and academic institutes engaged in research on environment, economics and road construction (16%) were engaged. All interviewees had a minimum of 10 years of experience, making composition as 47% had 10–15 years, 28% had 15–20 years, and 25% interviewees had more than 20 years of experience.

A comprehensive questionnaire was designed to carry out the structured interviews and was divided into three parts: in the first part, interviewees were asked to make a pairwise comparison of three sustainability areas; in the second part, they were asked to make a pairwise comparison of environmental impact categories; and lastly, qualitative data for pairwise comparison of social sustainability impact categories were obtained. For pairwise comparison, the hierarchy of impact categories for each area of sustainability was considered as established in the proposed LCSA assessment framework.

During the pairwise comparison of each sustainability area and impact categories, the degree of priority of each impact category over the other was also obtained on a five-point Likert scale. For example, if an interviewee believes that "a" is preferable to "b," then how much? Further, they were also asked to explain the reason and justification behind each response; such as, why they believe that "a" is preferable to "b" and in what context? Also, to bring clarity to the questions, suitable real project scenarios were discussed. As a result, priorities of sustainability areas and impact categories in terms of pairwise comparison were obtained, along with subjective rationalities behind these priorities.

The analysis phase comprises two stages. In the first stage, the analysis resulted in the form of a sustainability model for project prioritization and comparison. In the second stage, a decision framework for project prioritization and comparison was formulated. Three sustainability areas and the impact categories of each sustainability area can be represented in a 2-level hierarchy. During the data collection, a pairwise comparison was carried at both levels, thus generating three groups of pairwise comparison results; sustainability areas, environmental impact categories, and social impact categories.

The pairwise comparison by each respondent was used to develop a consolidated matrix and AHP was then applied using customized Microsoft Excel sheets [91,92]. The obtained weights from AHP were further formulated into aggregation equations to achieve value functions for each sustainability area and total LCSA. The expression used for the preference aggregation is given in Equation (3), where "A_j" is a value function of the sustainability area "j," "w_i" is the weight of impact category "i" in that sustainability area and "v_i" is the actual score of impact category "i" in the sustainability area "j." This method is most commonly used for the aggregation of indicators [93,94].

$$A_j = \sum_{i=0}^{j} w_i v_i \quad (3)$$

Further, LCSA integration is achieved using the generic concept of Klöpffer and Renner [70] which can be expressed as Equation (4), where "T_s" is value function of total sustainability, "w_j" is the weight, and "A_j" is the value function of the sustainability area "j."

$$T_s = \sum_{\mathrm{j}=0} \mathrm{w_j}\, A_j \quad (4)$$

In developing the decision framework, it was found necessary to identify the lower threshold values of each impact category and sustainability area. These thresholds were established based on the box plot analysis using the lower quartile of distribution as the logical thresholds of impact categories and sustainability areas.

Further, the reasons and justifications by the interviewees against their selected preferences were thematically analyzed to evaluate the most abundant themes of rationalities. In doing so, a content analysis was performed by grouping the opinions based on their functional commonality, followed by a thematic distribution of these groups. Afterward, a cross-sectional analysis between the impact categories and themes of rationalities was performed to evaluate the variety of impact categories in each theme and frequency of themes for each impact category, results of which directly contributed to the decision framework. Finally, an in-depth case study was performed to demonstrate the developed project evaluation tool.

4. Results and Discussion

4.1. LCSA Project Assessment Framework

The project assessment framework caters to the road infrastructure attributes for inventory analysis and impact assessment phases. Following the ISO 14,040 framework [49], it is typically organized in three phases; inventory analysis, impact assessment, and interpretation, as presented in Figure 2. The selected attributes of the proposed framework are discussed in the following sections.

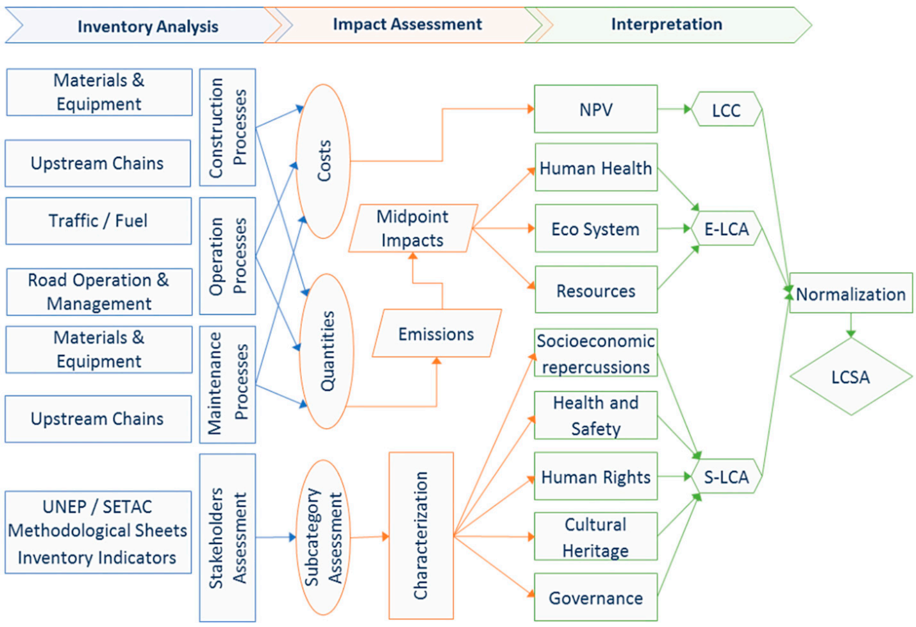

Figure 2. LCSA project assessment framework.

4.1.1. LCA

The proposed assessment framework includes construction, maintenance, and operation phases along with all their upstream chains of material, equipment, and processes. Overall, there is a lack of consensus over the choice of the functional unit as highlighted in the literature and the choice depends on the goal and scope of the study [28,35,38]. For road projects, most interviewees endorsed using the "complete project" as a functional unit while evaluating the project alternatives [12]. As all project alternatives share a common goal, which is to connect two distant points, the total length of the road becomes a significant evaluation parameter. However, an interviewee argued that when different projects are compared for performance ranking or execution priority, instead of alternatives of same projects, the use of "per unit length of the road" is more logical.

Further, to select the suitable impact categories, the majority of studies utilize midpoint impact categories such as energy, GHGs, ozone depletion, and GWP. However, at the project level, decision-makers cannot rationally assess such a variety and range of midpoint impact categories. Therefore, the endpoint impact categories such as human health, ecosystem, and resources are popular at that level of decision-making [95], which can be calculated through the characterization of midpoint impact categories into endpoint impact categories [96].

The selection of the midpoint or endpoint impact categories is critical as both have their own merits and demerits, as presented in Table 3. The certainty of estimation and calculation is much higher for midpoint impact categories but endpoint impact categories are more relevant and appropriate for decision support [97]. Also, the parallel use of midpoint and endpoint impact categories is recommended for decision support by many researchers [97,98].

Table 3. Midpoint vs. endpoint impact categories [95,96].

Comparison	Midpoint	Endpoint
Uncertainty	Depends on the characterization model type	
Comprehensiveness	Lesser	More
Environmental Relevance	More	Lesser
Transparency	More	Lesser
Decision support	Lesser	More

All interviewees from government departments felt more comfortable with the level of understanding of endpoint impact categories and suggested utilizing them. On the contrary, the majority of interviewees from consultancies and academia were interested to have more knowledge of impacts breakdown and hence suggested using the midpoint impact category. Keeping in view the expert opinion and literature, the proposed LCSA framework uses endpoint impact categories along with the consideration of midpoint impact categories. It is recommended to utilize ReCipe 2016 [99] as it presents three endpoint impact categories; resource damage, human health damage, and ecosystem damage, along with a detailed list of midpoint impact categories.

4.1.2. S-LCA

As established in the literature, UNEP/SETAC S-LCA guidelines [100] and methodological sheets [88] are the most widely used social impact assessment approaches for S-LCA. The proposed set of subcategories and engaged stakeholders offered by the guidelines are more comprehensive than the PSIA Handbook. However the latter suggests a more comprehensive impact aggregation methodology. Thus, the proposed assessment framework adopts the impact categories from UNEP/SETAC guidelines and impact aggregation methodology from the Handbook in combination as a baseline for S-LCA.

The guidelines have a product- and industry-focus. Thus, their covered impact categories, stakeholders, and associated subcategories are defined accordingly, which were to be reassessed in the context of road infrastructure. For this purpose, in the second section of interviews, the relevant subcategories were ranked and screened. For doing so, the subcategories having a model value of >2 or RII value of >mean (0.66) were selected. As a result, 17 out of 31 UNEP/SETAC subcategories shown in Table 4 were included. The most significant point in this screening process was that the subcategories related to the stakeholder "workers" were found the least important. Interviewees regarded workers as the least important stakeholder as their involvement is limited to the construction phase only, which is much smaller compared to the overall life of the road.

Furthermore, using the results of the third section of interviews, the characterization weights of the subcategories for the impact categories were calculated. For optimum space utilization, weights for only the selected subcategories are presented in Table 4. All the subcategories related to the workers were characterized for the impact category "working conditions" but eventually screened out including their impact category due to lower importance. Therefore, in the proposed assessment framework shown in Figure 2, the selected S-LCA impact categories are Socioeconomic Repercussions, Health and Safety, Human Rights, Cultural Heritage, and Governance.

Table 4. Characterization weights for selected S-LCA subcategories.

Stakeholder	Selected Subcategories	HR	HS	CH	Gov	SER
Road User	Health and safety	0.272	0.404	-	0.166	0.065
	Feedback Mechanism	0.204	0.243	-	0.277	0.130
Local community	Transparency	0.204	-	-	0.277	0.196
	Access to material resources	0.204	0.243	-	0.277	0.326
	Access to immaterial resources	0.272	0.323	-	0.277	0.326
	Delocalization and Migration	0.340	0.162	0.596	0.222	0.196
	Cultural Heritage	0.272	-	0.745	0.222	0.130
	Safe & healthy living conditions	0.272	0.404	-	0.166	0.196
	Respect for indigenous rights	0.340	-	0.298	0.166	0.130
	Community engagement	0.204	0.243	-	0.277	0.196
	Local employment	0.272	-	-	0.277	0.326
	Secure living conditions	0.204	0.404	-	0.166	0.130
Society	Contribution to economic development	-	0.162	-	0.222	0.326
	Prevention and mitigation of armed conflicts	0.272	0.243	-	0.277	0.326
	Technology development	-	0.243	-	0.277	0.261
VCA	Fair competition	0.204	-	-	0.277	0.326
	Promoting social responsibility	0.272	0.243	-	0.222	0.261

HR = human rights, HS = health and safety, CH = cultural heritage, Gov = governance, SER = socioeconomic repercussions.

4.1.3. LCC

Owing to a comprehensive body of knowledge and the wide application of LCC in road infrastructure projects, the cost breakdown by the American Society for Testing and Materials [68], given in equation 1, is adopted as the system boundaries in the proposed LCSA framework. Further, the review of existing LCC studies revealed NPV and IRR to be the most abundant indicators used for project financial assessment [11,59,61,63]. However, in the literature review section, the superiority of NPV for project comparison over IRR was established through discussion [101]. Further, in this regard, an axiomatic possibility is that the NPV of one project is better than another while still having a lower IRR. In such a scenario, the choice of indicator becomes critical for project selection and prioritization [101]. Therefore, in the proposed assessment framework, NPV is adopted as the only LCC indicator.

4.1.4. Normalization

To aggregate the impact categories, the selection of the normalization technique is critical due to the true and relative representation of impact quantities [85]. In the proposed LCSA framework, a two-step normalization is adopted; in the first step, the nature of impacts is normalized, such as some impact categories bring benefits which means the "more is better" and some categories bring damages which means "lesser is better." Thus, all the impact categories are harmonized accordingly. Further, to normalize the order of magnitude of impact categories, Euclidean vector normalization is proposed [89], as given in Equation (5). The scale of impacts obtained from LCSA analysis is identified as a ratio scale. Thus, a congruence or parallel transformation is required for normalizing it which would produce a normalized version of the results possessing the properties of a vector of length 1 [102].

$$||v_i|| = \frac{x_i}{\sqrt{\sum x_{ij}^2}} \quad (5)$$

4.2. LCSA Integration Model for Road Infrastructure Projects

4.2.1. Interview Results and Discussion

A pairwise comparison of LCSA impacts across each hierarchy level, as presented in Figure 2, was conducted to further obtain the preferences of the experts. Additionally, the rationale behind individual preferences was also noted. In the following sections, the results of the pairwise comparison of each group are discussed.

The findings along with the corresponding opinions and reasoning of pairwise comparison of preferences for sustainability areas are presented in Supplementary Materials Table S1. Social sustainability has been significantly prioritized mainly considering a lower level of social development, a direct role in inclusive growth, immediate impact over people, and irreparable repercussions. In developing countries, social sector development is not a priority area due to a lack of resources and policy preferences [103,104]. But owing to the sustainability assurance, the modern development strategies, which demand inclusive approaches, have started to advocate for a paradigm shift in this context [105]. As a result, many social engineering-based development programs and plans are launched aiming at offering social equities and inclusion [100,106]. Following suit, the local experts have shown their tendency to prioritize this area of sustainability over financial and environmental dimensions.

For environmental sustainability, endpoint impact categories, human health damage, ecosystem damage, and resource depletion were proposed in the assessment framework. The pairwise comparison results (Supplementary Materials Table S2) reveal that human health damage has been overwhelmingly prioritized by the interviewees as it results from an environmental causal chain, demands an urgency of response, and has a direct relation with human development. In the environmental causal chain, human health is the result of ecosystem damage mainly due to resource consumption such as abiotic fuels [107,108]. Considering the retrospective causal chain, the environmental and project feasibility experts prioritized the heavy consumption of abiotic resources as a root cause of environmental damage. However, considering the aspirations and priorities of developing countries [109], the majority of experts ranked human health damage as the topmost concern.

For social sustainability, impact categories of socioeconomic repercussions (SER), human rights (HR), health and safety (HS), cultural heritage (CH), and governance (Gov) were proposed in the assessment framework. The results of the pairwise comparison and corresponding opinions and reasonings for preferences of these impact categories are presented in the Supplementary Materials Table S3. Governance, health and safety, and human rights are the main impact categories that were given major consideration over other impacts, considering them the basic indicators for human development.

Policy reforms for delivering basic needs warrant major changes in the balance of power among society, resulting in improved governance. Since governance has a considerable scope of resource management, which can result in improved performance for delivering basic needs and human development, the experts prioritized this impact following such a singularity [109]. Further, health and safety, and human rights are considered as basics of human development and are a popular measure of the human development index (HDI) [110,111]. Moreover, the priorities given by the experts resonate with the conclusion of the capability approach theory by Sen [112]. In the past two decades, this theory has been established as logical rationality for multifaceted networks of conceptual frameworks of human development and well-being. The definition of human well-being in this approach accentuates the normative aspects, called capabilities, such as reasons to value and personal freedom of choice which are fundamental human rights, instead of income and commodities which are socioeconomic repercussions. The theory defines the deprivation of such capabilities as poverty, which could be enforced by illiteracy or resource mismanagement, with a simple solution of improved governance. It is found that good governance alleviates poverty in middle-income countries [113,114].

4.2.2. Themes of Rationalities

Content analysis of interviews for each pairwise comparison was performed to identify the pattern or themes of rationalities. The results highlight nine major themes of rationalities, as given in Table 5.

Table 5. Thematic analysis of rationalities.

Themes of Rationalities	Financial	Social	Environment	Ecosystem	Resources	Human Health	SER	Human Rights	Health & Safety	Cultural Heritage	Governance	Frequency
Direct vs. indirect impacts		x	x	x		x						4
Impacts in a life cycle perspective		x	x	x	x	x		x			x	7
Impacts over masses vs. individuals		x					x	x				3
Mitigatable impacts			x		x				x			3
Developing countries priorities	x										x	2
Global vs. Local impact				x								1
Cause-effect chain				x	x	x	x					4
An interrelated or comprehensive scope							x	x	x	x	x	5
No compromise possible						x		x	x	x		4
Frequency	1	3	3	4	3	4	3	4	3	2	3	

It can be seen that most of the themes, such as "direct vs. indirect impacts," "impacts in life cycle perspective," "impacts over masses vs. individuals," and "no compromise possible" are directly concerned with the society, representing the area of protection (AOP) of LCSA [115]. Few identified themes, such as "cause-effect chain," "Interrelated or comprehensive scope," and "mitigatable impacts" are related to nature. However, themes like "global vs. local impact" and "developing countries priorities" are related to national priorities. So, it can be concluded that the findings of the interviews relating to the preference of impact categories were in line with the three main cognitive irrationalities; AOP human being, nature of impacts, and national priorities.

Further, a cross-sectional analysis of these themes against the impact categories and sustainability areas was drawn. It can be seen in Table 5 that the theme "impacts in a life cycle perspective" covers most of the impact categories. This signifies that the interviewees were well aware of the impact of the life cycle approach and sustainability. The theme "interrelated or comprehensive scope" covers a significant number of impact categories, all of which fall in the social category, leading to a phenomenon where all social impacts exist in a strongly interrelated and complex system, complementing each other [54,116]. Financial area sustainability is covered by "developing countries priorities," highlighting that the interviewees who preferred it over the other areas prefer due diligence for financial concerns in the context of developing countries [117]. Similarly, cultural heritage is also encompassed by only two themes. Moreover, the theme "cause-effect chain" mainly covers the environmental impact categories [118].

The most significant finding of this analysis is the results of the theme "no compromise possible" which comprehends human health, health and safety, human rights, and cultural heritage. As per the respondents, when such impact categories are compared with other impacts or particularly with each other, the compromise of one over the other becomes inevitable. It is because these impacts have their standalone significance. Thus, a minimum standard must be ensured for such impact categories. Notably, only a few significant themes related to this study are discussed in this paper due to space constraints. However, various other interpretations of these findings can be drawn from the noted rationalities, presented in Online Resources and the themes given in Table 5.

4.3. AHP Results and Integration Model Equations

AHP was applied to the consolidated matrix of pairwise comparisons to obtain weights of impact categories and sustainability areas. The results are shown in Table 6.

Table 6. Weights of impact categories and sustainability areas.

Sustainability Area	Weightage	Impact Category	Weightage
Environment	0.2950	Resource Damages	0.1777
		Ecosystem Damages	0.2566
		Human Health Damages	0.5657
Social	0.4282	Socioeconomic Repercussions	0.1575
		Human Rights	0.1863
		Health and Safety	0.2971
		Cultural Heritage	0.1236
		Governance	0.2356
Financial	0.2768	NPV	1.0000

It has been found that in three areas of sustainability, the weight of social sustainability is considerably high (0.428). However, environmental (0.295) and financial (0.277) categories have comparable weights. In environmental impact categories, human health (0.566) was marked as the most significant area. The weights of resources (0.178) and ecosystem (0.256) were significantly low. For social impact categories, health and safety (0.297) was the topmost weighted impact category, followed by governance (0.236), human rights (0.186), socioeconomic repercussions (0.157), and cultural heritage (0.124). For the financial sustainability area, as there was only one impact category, the weight of "NPV" is considered as 1.0.

The consistencies of AHP results were also checked for the entire sample and each respondent. The final results of consolidated response matrices were found consistent, with consistency ratios >0.1. However, individual results reveal that 69% of responses of sustainability areas, 81% of environmental impact categories, and 84% of responses of social impact categories were inconsistent. The interviewees with inconsistent responses justified and rationalized their opinion as previously discussed.

Using the obtained weights of impact categories and Equation (3), the value functions of environmental, social, and financial areas are expressed in Equations (6)–(8), respectively. Where in Equation (6), v_{Res} is the value of resources, v_{Eco} of the ecosystem, v_{HH} of human health, and A_{Env} is the total value of environmental sustainability; in Equation (7) v_{SER} is the value of socioeconomic repercussions, v_{HR} human rights, v_{HS} health and safety, v_{CH} cultural heritage, v_{Gov} of governance, and A_{Soc} is the total value of social sustainability; and in Equation (8), v_{NPV} is for the financial area of sustainability and A_{Fin} is the total value of financial sustainability.

$$A_{Env} = 0.1777\, v_{Res} + 0.2566\, v_{Eco} + 0.5657\, v_{HH} \quad (6)$$

$$A_{Soc} = 0.1575\, v_{SER} + 0.1863\, v_{HR} + 0.2971\, v_{HS} + 0.1236\, v_{CH} + 0.2356\, v_{Gov} \quad (7)$$

$$A_{Fin} = v_{NPV} \quad (8)$$

Further using Equation (4) and the obtained values of the sustainability areas, the LCSA value function can be expressed as Equation (9).

$$T_{LCSA} = 0.2950\, A_{Env} + 0.4282\, A_{Soc} + 0.2768\, A_{Fin} \quad (9)$$

4.4. Decision Framework for Project Evaluation

Based on the results of pairwise comparisons, thematic analysis results, deductive logic, and damage control policy, a decision framework has been developed. For this purpose, the threshold limits of each impact category and sustainability areas are assessed using the boxplot and lower quartile range. Further, based on Yes/No scenario pathways, a response-based feedback process is developed through which project proposals are evaluated.

4.4.1. Minimum Threshold Values

The AHP weightings were analyzed to establish boxplots of sustainability areas and impact categories presented in Figure 3. The results show that the mean values are comparable for all sustainability areas; 0.30, 0.39, and 0.31. However, the lower quartile values, presented in Table 7, significantly vary. The lower quartile value is 0.26 for social, 0.12 for environmental, and 0.10 for financial sustainability, respectively. The mean value for the impact category of human health is significantly high (0.51). The mean values are lowest for cultural heritage (0.14) and socioeconomic repercussions (0.17). However, for all other impact categories, mean values vary from 0.19 to 0.29. Accordingly, the lower quartile values for these impact categories present the same pattern.

It is pertinent to note that NPV, the impact category for LCC, is not analyzed for the lower quartile range as no pairwise comparison was carried out for this single impact category of LCC. Thus, no response for weights was sought. However, the financial area of sustainability and its impact category was discussed during the interviews (see Section 4.2.1).

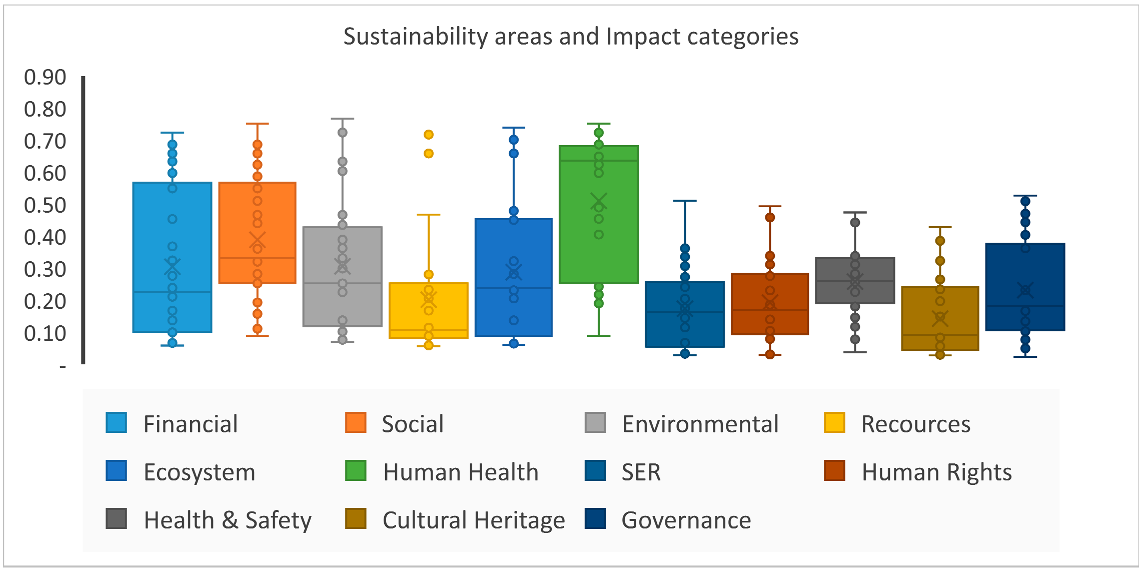

Figure 3. Boxplot representation for sustainability areas and LCSA impact categories.

Table 7. Minimum threshold limits.

Environmental	**0.12**	**Recourses**	**0.09**
		Ecosystem	0.09
		Human Health	0.25
Social	0.26	Socioeconomic repercussions	0.06
		Human Rights	0.10
		Health and Safety	0.19
		Cultural Heritage	0.05
		Governance	0.11
Financial	0.10	NPV	0.00

These lower quartile values for the sustainability areas and impact categories, presented in Table 7, cover the bottom range of weights given by the respondents. This signifies the lowest possible ranges for any of the sustainability areas and impact categories. Thus, these values establish the minimum threshold for the sustainability areas and impact categories. This means implying that a project with values lower than thresholds does not fulfill the minimum criteria of sustainability and should not be preferred.

4.4.2. Decision-Making Workflow

Following the defined threshold values, a response-based feedback process is developed for the evaluation of the most sustainable road alternative, as presented in Figure 4. This decision-making process follows the assessment of all three areas of sustainability to obtain the final values of LCSA impact categories. These values are then compared with their corresponding minimum threshold limits. If all the impact categories meet the threshold criteria, the alternatives are further compared for the three sustainability areas and their minimum threshold limits. If they meet the minimum threshold criteria at both levels, the alternatives can be further compared based on the total LCSA values. As a result, the alternative with the highest LCSA value can be selected as the most sustainable. If any value of the LCSA impact category is found below the threshold, the subsequent most influential or damaging process, material, or linked inventory indicators are identified. For doing so, the most damaging midpoint impact categories or subcategories are tracked upstream into the processes and materials. Once the upstream inventory process or item causing the most damage is identified, the corresponding mitigation or project alterations can be made. If no mitigation or project alteration is possible, the alternative is rejected. In another scenario, after performing changes according to mitigation or alteration, the alternative is reassessed for LCSA and revised values of impact categories are considered for comparison. The threshold limit of some impact categories such as cultural heritage and human rights as outlined in this study may be lower than the international practices. Therefore, their performance must be maintained as per international practices. Ignoring such standards may violate international bindings, resulting in financial and reputational repercussions. So, such special scenarios must be treated accordingly in the decision framework.

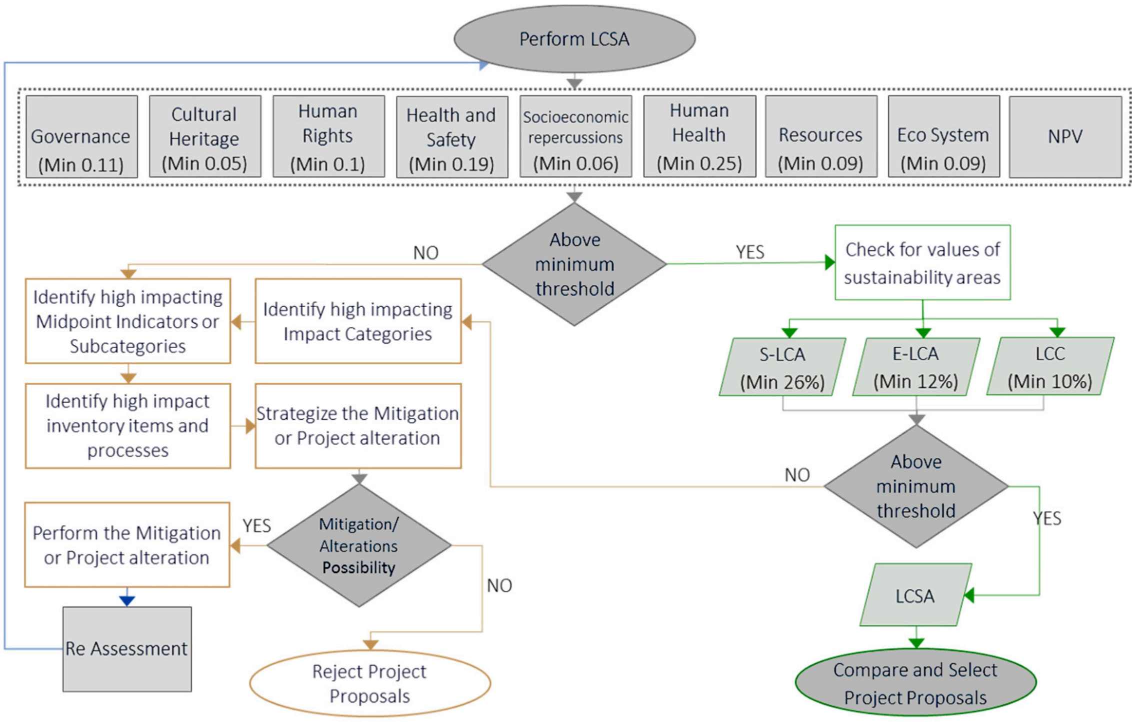

Figure 4. Project evaluation decision framework.

Further, interviewees labeled the importance of cultural heritage as highly contextual. There can be a scenario when the tangible damages and the attained value of cultural heritage are quite low but compromising on it at the cost of people's sentiments may cause public disapproval and angst and may result in project abandoning. Therefore, such scenarios need to be treated carefully with realistic damage consideration. Also, in the case of NPV, though there is no evaluated threshold limit, the interviewees argued that the financial compromise must remain within the extent of recoverable damages.

5. Case Study

To demonstrate the developed LCSA project assessment and decision frameworks, a case study of a major highway project located in Pakistan is performed. During the feasibility phase, this project had three proposals for different alternative routes, R-1, R-2, and R-3 having lengths 110 km, 94 km, and 90 km, respectively. It is important to mention that the decision-making involved in the actual project was majorly influenced by the financial feasibility, leading to the execution of proposal R-3. However, in this study, all alternatives are evaluated based on holistic LCSA. The case study is discussed in line with the steps of the developed assessment framework, integration model, and decision framework.

The system boundaries for this case study include construction, operation, maintenance, and use phases as well as the upstream processes and materials for each phase. An extensive range of materials and processes is covered for the inventory analysis as presented in Table 8. The inventory data is extracted from project documents, including feasibility studies, BOQs, and standard construction material rate lists. SimaPro 8.4 and the Ecoinvent 3.0 database are utilized for the inventory analysis and impact assessment to obtain the environmental impact categories.

Table 8. Scope of inventory analysis.

Materials and Processes	Construction	Maintenance	Operation/Use	Equipment and Processes	Construction	Maintenance	Operation/Use
Concreting	✓	✓		Compaction	✓	✓	
Steel and Reinforcement	✓	✓		Dumper	✓		
Asphalt Layer	✓	✓		Cold milling		✓	
Aggregate for Base and Sub-base	✓	✓		Land Transformation	✓		
Clear and Grubbing	✓			Routine Maintenance		✓	
Excavation	✓			Deforestation/Tree Cutting	✓		
Backfill	✓			Traffic			✓

The upstream processes available in built-in libraries of SimaPro are used. However, those processes which are not available in the built-in library are modeled using the inventories of the Ecoinvent database. The results of environmental impact categories were obtained using the impact assessment method ReCipe 2016 Endpoint (E) V1.00. Further, to quantify the financial impact category, life cycle project costs are estimated using Microsoft Excel.

The required inventory data for all S-LCA subcategories were not available for the case study project. Some suitable indicators are identified from the existing feasibility reports and project records, such as availability of area for the development and right of way (ROW), land acquisition and re-settlement, crop compensation, cutting of trees, perspective in relative economic growth, proximity to the cultural sites, and provision of sound barriers to the villages. The indicators were scored on a scale of 1–5, based on their comparative quantitative values in project records. Further, the subjective relevance of these indicators with the S-LCA subcategories was determined and scores were aggregated considering the equal weightings of all S-LCA indicators. Subcategories with no available indicators were given an average score (3), as shown in Table 9. Then following the characteristic weights of S-LCA subcategories, given in Table 4, the scores of S-LCA impact categories were determined.

After obtaining the scores for all LCSA impact categories, they were normalized according to their nature such as "better is good" or "lesser is good" and on a scale of 1 to 0 using the Euclidean norm. Further, following the developed Equations (6)–(9), the final LCSA values are obtained. The obtained results of impact categories score, sustainability areas, and LCSA are presented in Table 10. The results reveal that overall R-3 is comparatively the best option. However, R-2 is marginally behind R-3 while performing better in the environment and social sustainability areas. The option R-1 is the least sustainable proposal, having the lowest values in all three areas.

Further, following the decision framework, impact categories having values less than the established threshold limits are identified. It can be observed that, though R-3 is the most sustainable proposal, its value of local community health and safety is below the established threshold limit. So, before pursuing this alternative, it needs to be properly addressed by mitigating or altering the concerning inventory. For example, in this case, the inventory indicator considered for this impact category is "cutting of trees" whose impact can be mitigated through enhancing the provision of tree plantation along the road and horticulture development. Proposal R-1 is least sustainable while having values below the threshold for impact categories human rights and local community health and safety.

Such a scenario signifies the reassessment of proposals after responding to the impact categories with below threshold limits through mitigating or altering the corresponding inventory indicators, as highlighted in the developed decision framework. Specific to this case study, there is a potential for change in results after such reassessment, but it has not been performed due to limited access to project records and data.

Table 9. S-LCA subcategories scores.

	S-LCA Subcategories	R1	R2	R3
Consumer	Health and Safety	3	3	3
	Feedback Mechanism	3	3	3
	Transparency	3	3	3
Local Community	Access to material resources	3	3	3
	Access to immaterial resources	3	3	3
	Delocalization and Migration	3	3.5	2
	Cultural Heritage	5	4	3
	Safe and healthy living conditions	1	3	3.5
	Respect for indigenous rights	1	3	2
	Community engagement	3	3	3
	Local employment	3	3	3
	Secure living conditions	1	3	5
Society	Contribution to economic development	3	5	5
	Prevention & mitigation of armed conflicts	1	5	3
	Technology development	3	3	3
VCA	Fair competition	3	3	3
	Promoting social responsibility	3	3	3

Table 10. Case study results.

	Analysis Results				Normalized Scores			Weighted Scores		
	Nature	R1	R2	R3	R1	R2	R3	R1	R2	R3
LCSA Impact Categories										
NPV (Rs. in Millions)	More is Better	−16,837	−9484	6051	0.540	0.567	0.622	0.540	0.567	0.622
Human health (DALY)	Lesser Is Better	20,790	20,433	20,845	0.576	0.581	0.575	0.326	0.329	0.325
Ecosystems (Species.yr)	Lesser Is Better	33.40	28.86	28.53	0.547	0.590	0.593	0.140	0.151	0.152
Resources (1000 × USD)	Lesser Is Better	14,028	15,497	16,671	0.603	0.575	0.553	0.107	0.102	0.098
Socio-Economic Repercussions	More Is Better	10.24	13.08	12.23	0.496	0.634	0.593	0.078	0.100	0.093
Local Community Health & Safety	More Is Better	7.84	10.83	11.12	0.451	0.623	0.639	0.134	0.185	0.190

Table 10. *Cont.*

	Analysis Results				Normalized Scores			Weighted Scores		
	Nature	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
Cultural Heritage	More Is Better	4.62	5.52	5.29	0.517	0.618	0.592	0.064	0.076	0.073
Governance	More Is Better	10.93	13.45	12.87	0.506	0.623	0.596	0.119	0.147	0.140
Human Rights	More Is Better	9.39	12.69	12.11	0.472	0.638	0.609	0.088	0.119	0.113
Sustainability Areas										
Financial					0.540	0.567	0.622	0.150	0.157	0.172
Environment					0.573	0.582	0.576	0.169	0.172	0.170
Social					0.483	0.627	0.610	0.207	0.268	0.261
LCSA Values								0.526	0.597	0.603

From these findings, it can be sufficiently established that decision-making of this scale cannot solely rely on individual areas of sustainability and a holistic vision is inevitable. The long-term implications of such decision-making can be alarming if not entirely disastrous in the form of latent problems and issues of social and economic repercussions.

6. Conclusions and Recommendations

Economic development transcends social development since sustainable infrastructure underpins all economic activity, including achieving inclusive growth, making infrastructure critical to sustainable community development, future well-being, and the day-to-day lives of individuals. For long-term infrastructure viability assessment, LCSA converges all major policy aspects, such as social equity, environmental protection, and financial viability. Moreover, the life cycle thinking approach supports the integration of sustainability at various decision levels of a project [119].

In this perspective, this study provides the decision-makers with a holistic project evaluation tool appraising a detailed set of sustainability indicators to support critical decision-making. First, the LCSA assessment framework was developed, which comprehends the methodological attributes for LCSA impact categories, their impact assessment processes, and inventory material and processes. The framework directly relates the project impacts with the people (local population) throughout the project life cycle, which substantiates the core of sustainability. The framework traces the impacts upstream till the primary resource consumption, which can support the mitigation of impacts.

Second, the developed LCSA integration model integrates all the social, environmental, and financial impacts into a single parameter for the quantitative evaluation of project alternatives. The pairwise comparison rationalizes the relations among LCSA impact categories and areas of sustainability. Social sustainability overrules the financial and environmental aspects signifying the interest of decision-makers towards acknowledging the role of public satisfaction as a means for project success. Social impacts such as health and safety and human rights gained the highest weight. Significantly, though the governance was quoted to have an indirect relation with people, it has obtained the second-highest weight and was considered by the experts as the key solution for many other impacts over people. This is followed by environmental impact categories showing a similar pattern, as human health damage got the highest weight and resources damage obtained the least. Remarkably, the financial concern, which is the most widely used parameter for project evaluation in traditional practices, has achieved the least weight. These results signify that prioritizing end-user benefits and aligning sustainability assessment with the social compass will act as a driver for all facets of sustainability. The pairwise comparison provides an insight into the currently adopted decision-making processes and parameters for the development of large infrastructure projects. Further, the content analysis of rationalities reveals the cognitive drivers of decision-making. In this context, decision-makers largely prefer to deal with the direct challenges with broader lifecycle scope.

Third, the developed decision framework traces pathways to analyze the most impactful inventory processes and inventory materials, enabling us to make best-fit changes in project alternatives and devise mitigation strategies. The established threshold limits are a key feature of the decision framework which also considers the subjective interpretation of the contextual and actual situation of damages. Such as, compromising cultural heritage involves religious and cultural sentiments of the community, and merits proper management. Similarly, the minimum level of road user and local community safety should be managed according to the road safety standards.

The study focuses on baseline sustainability parameters which incorporate all decision-making aspects in a broader perspective. However, criteria such as technological feasibility aspect and financial resource availability can be directly considered to appraise the decision-making. Further, the hierarchy of impact categories and other attributes of this research are selected from the existing literature, which is mainly focused on the assessment of material evaluation and material performance. For the comparison and assessment of the complete project, the attributes and boundaries could be assessed specifically from the real projects and scenarios. Future research can investigate actual road infrastructure project scenarios to formulate refined methodological attributes and system boundaries.

This study significantly critiques the current oversimplified decision-making culture in developing countries where infrastructure development is seen only in the forte of economic development. It opens up the complex interactions between the environment and stakeholders including society, road users, and other value chain actors. Taking the perspective of local experts, it is argued that industry actors are looking for solutions for sustainable infrastructure delivery and realize the importance of considering holistic project impacts. Therefore, the findings merit formalization into policies and standard operating procedures, and the potential for sophistication through wider data collection and deeper case study investigations.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13073743/s1, Table S1. Pairwise comparison of sustainability areas. Table S2. Pairwise comparison of environmental impact categories. Table S3. Pairwise comparison of social impact categories.

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