sustainability

Review

Systematic Review of Life Cycle Assessment and Life Cycle Cost Analysis for Pavement and a Case Study

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Abstract: Development of the pavement network systems, which is inevitable due to the rapid economic growth, has increasingly become a topic of significant concern because of the severe environmental impacts of road expansion. For achieving the sustainable development goals (SDGs), the policies and actions towards the pavements' life cycle assessment (LCA) and life cycle cost analysis (LCCA) must be carefully assessed. Consequently, the purpose of this review is to present an overview of LCA and LCCA used in pavement engineering and management. Through the quality control of PRISMA, fifty-five most relevant documents were extracted for a thorough investigation. The state of the art review reveals that a limited number of the papers considered environmental impacts of the pavements. Consequently, to assess the environmental impact cost, a conceptual framework was developed to better consider the LCA and LCCA on various aspects of the pavement projects including the sustainability aspects. Besides, a case study was given to validate the literature review towards proposing a novel framework for the incorporation of environmental impact cost.

Keywords: pavement; life cycle assessment; life cycle cost analysis; review; construction; PRISMA; sustainable development; mobility networks; infrastructures; transportation; circular economy

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1. Introduction

Mobility networks are expanding in a fast paced. Sustainability and environmental aspects of the expansion of the road networks and pavements development have become the major concerns. In addition to the major attention towards pavement projects and economic growth, the severe environmental impacts had been widely neglected. Currently, the value of pavement projects is very immense, where not only the capital cost, but the operation, maintenance, and disposal cost also need consideration [1]. Likewise, with the immense growth of the pavement projects, the environment faces sustainability issue with toxic gaseous emissions, pollutant emissions, added fuel consumption, and noise pollution. Significant monetary procedures are required to overcome the issues of sustainability throughout the project life from the initial construction phase to the rehabilitation phase or end life to enhance serviceability. To maintain the proper functionality of the project, the user phase of the pavement project needs timely upgrading, as it has the longest duration in the life cycle [2–4].

In the long run, the pavement projects have been enhanced because of the dynamic relationship between economic and socio-environmental stressors with the decision-making processes of organizations [5]. Evaluating the expense of the life cycle and environmental impact, essential measures were taken to integrate environmental goals into pavement projects [6,7]. The Life Cycle Assessment (LCA) is a method that provides the ability to thoroughly identify and evaluate the environmental impact and its influence on social aspects of infrastructure paving systems across their lifetime. The LCA approach was first defined by the International Organization for Standardization (ISO) [8]. The LCA assessment is referred to as the "cradle-to-grave" approach consists of four main steps which are goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. The goal and scope of the analysis may determine the life cycle of the project [9]. The project life cycle involves the extraction of raw materials to disposal or recycling. However, there is no fixed life cycle for pavement systems [10], as all the components of a pavement system cannot provide a definite time [11,12], which need a scheduled rehabilitation to maintain the pavement over the life span. In addition, the goal and scope also determine the functional unit of the project, which is consider as a reference for the whole project. The second stage of pavement LCA consists of inventory evaluations that accumulate and compile input and output data of a project under investigation. The inventory data provide possible resources, material, and waste or discharge materials listing during the life cycle of a project [13]. The third step of the pavement LCA is an impact assessment where the inventory data collected for the various phases of the life cycle are to be classified into their categories of impact [14]. This means that the life cycle inventories of each alternative decision are aggregated into a single file against every impact group. Moreover, interpretation is the final step of pavement LCA at which decisions are taken based on the outcome of the inventory and impact evaluation [15]. LCA will have the most significant impact if the evaluation analyses are used for policy review and management. However, the understanding of the LCA conclusions puts a serious restraint on policy analysis and pavement performance measures.

LCA evaluate the environmental impact of a project and the consequences generated throughout life from different aspect such as materials acquisition, its construction, operation and maintenance, disposal, and finally the end life treatment [16–19]. The assessment of material acquisition and transportation impact is the primary step of pavement projects, for which LCA was carried out by practitioners. Many of these assessments included comparative LCAs performed for comparisons of various construction material forms such as bitumen and cement pavement or virgin materials with recycled or secondary materials [20–22]. Many LCAs are carried out on the pavement alone, whereas some studies also examined the complete pavement networks, including the preparation of the site and the construction of road [23–25]. In addition, attempts were made to define usual energy consumption and carbon dioxide (CO_2) emissions of various types of regular roads [21,26,27]. Although, the environmental impact in pavement projects is assessed, though the alarming increase in the impact needs policies to overcome the increasing environmental impact or compensate for the harmful consequences. With the growth of the pavement network system and the increasing number of automobiles, carbon emissions from the transport industry have risen. A report indicates that gross vehicle emissions on the world's roads increased by about half a gigaton between 2010 and 2020 [28]. In 1920, Arthur Pigou proposed that the emission of CO_2 should be charged to monitor the damages caused by the emission to the society and environment [29]. Later on, the proposal of considering charges for CO_2 was agreed upon with the implementation of the carbon price by most of the nation to overcome the global warming potential (GWP) [30]. To implement the idea of the carbon price, a cap-and-trade system and carbon taxes was introduced. The cap-and-trade is a general concept by a government regulatory scheme intended to regulate activities of total emissions level. In the cap-and-trade system, the state grants restricted annual permits allowing businesses to release carbon dioxide in such levelled amount. Companies are fined if they generate emissions greater than their quotas permit. Unused permit allowances may be marketed or "trade" from businesses who reduce their emissions to other companies. Whereas the CO_2 tax is a consumption tax on transportation and energy fuels emissions. Carbon taxes aim to decrease emissions of carbon dioxide by rising prices which aims in reducing the demand for fossil fuels [31]. Incorporating the carbon cost in the LCA assessment of pavement projects could be a possible solution to minimize the harmful impact.

Likewise, LCA, Life Cycle Cost Analyses (LCCA) is considered an appropriate methodology by decision-makers to evaluate the economical and socio-environmentally sustainable pavement project's consequences [32–36]. LCCA has many applications, among which it allows the decision-makers to compare and choose the best alternative to achieve sustainable development [37,38]. LCCA is utilized in the decision-making process during the planning and design stage to evaluate all the constraints related to a project [39–41]. To meet sustainability goals, it is necessary to evaluate all economic practices and activities over the life cycle of a project. Planning at the early stage of the pavement projects may be more cost-effective with a resilient and productive construction over the life cycle with less environmental impact [42–46]. In recent decades, substantial attention in research was paid to the application of LCCA in pavement projects. Whereas the practical implementation of the process is observed considerably very low.

In the economies of many nations, the pavements network system plays an important part. Economic development is related to the construction of pavement projects, that is why a huge investment has been made in this sector. Where a huge contribution of pavement projects in the Gross Domestic Product (GDP) through investment in various countries has been evident. In 2018, the Chinese average capital investment as a proportion of the country's GDP was 10 times higher than the US in pavement projects. Chinese investments were considerably higher than in all other countries. Compared to its western European counterparts, investments in central and eastern Europe were larger [47].

Globally, new pavement projects face delays and cost overruns, which lead to the inefficient use of public resources [48–51]. The root causes include the lack of transparency in project selection, the lack of project preparation, the silo approach by public entities in assessing feasibility studies, and the lack of public sector capacity to fully develop a bankable pipeline of projects [52–54]. To tackle these issues, the government need a smarter investment approach and to do so critical policies for sustainable achievements are required. Given financial limitations, agencies need to utilize systematic decision-making methodologies that offer insight into long-term economic viability. One such approach is the LCCA, which measures the economic risk when considering the economic sustainability of pavement projects [55–57]. However, the functional implementation of LCCA depends on a variety of factors such as the availability of supporting project documentation, the degradation insights into the state of the pavement, and the availability of guidance for calculating usage costs [41,58].

Over the last decade, numerous research on LCCA has been performed to determine the cost of pavement projects [20,59–67]. Most of the studies have concentrated on comparing materials used in the rigid and compact pavement or have sought to reduce the cost and the environmental effect of pavement by utilizing advanced, bio-based, or recycled materials [20,59–64]. In 1960, the American Association of State Highway and Transport Officials (AASHTO) released a detailed guide on project procedures. As per guidelines, AASHTO introduced LCC in its pavement Construction Guide in 1972 [68,69]. Thus, according to AASHTO, LCC should comprise all expenses and advantages connected with the provision of pavement during their whole life span [41]. It covers costs due to the construction, repair, reconstruction, and disposal of the pavement facilities and costs related to travel time, vehicle service, injuries, and time delays during the initial development, maintenance, or rehabilitation of road users [70–73]. Because these costs do not appear at the execution stage, the interest rate or time value of the investment has become significant, therefore, the terms Net Present Value (NPV) and Equivalent Uniform Annual Cost (EUAC) were added into the process of LCCA [74,75].

The popular approach to LCCA is the NPV [41,76–78], for which the cost is discounted. The discount rate is a significant factor in LCCA as it has a clear influence on the final costs [79,80]. Discounting is a central methodology in LCCA which considers the time value of money as it is more in the present than in the future [81,82]. All costs are attributed to their NPV after discounting them to find the complete LCC for each project [83–85]. This approach is often utilized where the expense of the item is to be compared over a different period. Furthermore, the value of cost comparisons focusing on the operating period, as maintenance in the operation period can have a serious impact on LCC. Moreover, the US Department of Defense developed a framework to introduce LCCA for defense logistics in feasibility stage to increase its cost-effectiveness in the awarding of competitive bids, whereas LCCA has also acquired significance in other industries that aim to make sustainable developmental decisions [86–88].

To achieve the sustainability goal the integration of LCA and LCCA provides an efficient decision-making evaluation system. The LCA evaluation provides data required by quantifying environmental assessment for a comprehensive LCCA. LCCA assessment is responsible for the agency costs, i.e., the financing department expenditures. In addition to the agency costs, it also accounts for usage costs which are the expense of the vehicles induced by the design of the pavement. Moreover, the environmental costs such as the costs for emissions generated by construction and operating phases can also be considered for which LCA is the core assessment approach that generates useful data for LCCA. The data generated by the process of LCA can be utilized in the process of LCCA in which the indicators of LCA could be converted into the cost parameters.

While conducting the systematic literature review, a variety of publications related to LCA and LCCA were identified. Historical evidence was analyzed using the Scopus database [89], which suggest that the reported publications in this field of study are changing significantly, where the number of publications from 1999 to 2020 was indicated. From the 1999s to the 2007s, less work was performed on the implementation of LCA and LCCA in pavement projects, although, after 2007, sustainability was established as a moderate research priority in pavement projects and gained a foothold in research to add improvement to the field after 2012. To date, the usage of LCA and LCCA in sustainability, project management, construction productivity, and cost-effectiveness in pavement projects is of primary importance by the researchers. Although massive research was carried on LCA and LCCA, there is still less interest among stakeholders in its application in construction projects [90–93].

The impact of life cycle evaluation research was evident in the field of engineering, as it acts as a significant measure that allows the engineering industry to determine efficiency based on sustainability, along with the serviceability and resilience of any project. In the process of life cycle evaluation, the costs and impact from cradle-to-grave of a project are included that delivers a momentous project. In addition to the importance of LCA and LCCA, its adoptability in pavement projects seems less. Thus, the purpose of this systematic review was to examine the existing literature conducted with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement on the implementation of LCA and LCCA in pavement projects and to highlight the influence of it on different aspects of pavement projects to ensures sustainability. While adopting the PRISMA statement approach, selection criteria were defined to limit the study to the life cycle evaluation of a project with LCA and LCCA approach at various phases of the project, during materials selection as well as agency and users' cost and impact. In addition, the integrated LCA and LCCA approach was highlighted to quantify the impact of pavement projects on economic, social and environmental aspects of sustainability. Whereas, in previous researches and literature assessment, the environmental impact cost was not considered. Thus, to assess the environmental impact cost, a conceptual framework was developed to support the literature, which integrates the LCA and LCCA considering the cost and impact along with impact assessment cost to enhance sustainable decision making. The developed framework classifies the impact of different costs associated with pavement projects and their impact on sustainable constraints. Thus, it will help the decision-makers to boost sustainable project with the consideration of these costs in the planning and design phases. Additionally, to validate the carried out literature and the framework, a case study was performed with an integrated LCA and LCCA approach to quantify the associated costs and impact. In addition, carbon prices were incorporated into the framework to compensate the harmful impact of the pavement project. In previous studies, the carbon price was not focused, whereas in this study the carbon price was incorporated in the developed model for integrated LCA and LCCA, which will assess the practitioners to consider the impact reduction cost to deliver a sustainable project.

2. Methodology

The following study consists of a Systematic Literature Review (SLR), which is a methodology to collect secondary data from different sources and analyze them according to the scope of the study. During SLR, the protocol or plan of the study is to be defined, where the selection criteria for the published documents to be reviewed are stated before conducting the review process. The methodology of this systematic review consists of three phases to achieve the research aim which was to examine the existing literature conducted on LCA and LCCA for pavement projects and to illustrate how LCA and LCCA affect different aspects of pavement projects and ensures sustainability during decision making. In the first phase, the problem was identified, the objective was established where an overall literature review was conducted. Then a methodological approach, i.e., Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [94–101] was chosen to conduct the systematic literature review. The second phase of the research was focused on the selected PRISMA statement, which was followed by several researchers. The motivation for selecting the PRISMA statement in this review paper was the systematic dissemination after the screening of the collected published documents, which would make it simpler for researchers to carry out a thorough review. The flowchart for the PRISMA statement is shown in Figure 1.

The PRISMA statement methodology adopted for this analysis consists of four steps. In the first step, data search policy, databases, keywords, and search limitations were defined. In the PRISMA statement, the selection criteria were developed. In the second step, the data were screened and filtered, where the titles followed by the abstracts of the selected publications were assessed with inclusion and exclusion criteria. The inclusion and exclusion criteria were limited to the publications focused on life cycle evaluation of pavement projects at various phases, i.e., during materials selection, and agency and users' impact, and cost of pavement projects. Firstly, the titles of the overall selected publications were checked and the publications having a title with close relevance to the scope of the study were included, which were then followed by a thorough review of the abstracts. While reviewing the abstracts of the remaining publications, the publications which have a broader scope than the current study were excluded from the list. In the third step, the determination of eligibility was carried out in full text and the publications which did not fall into the scope were excluded. Data were retrieved from the selected databases in the fourth step of PRISMA to conduct further interpretation.

Furthermore, in the third phase of the research, the results were identified, and a review of the extracted publications was interpreted followed by a detailed discussion. Moreover, based on the literature, a framework was developed to integrate the LCA and LCCA with the incorporation of emission impact cost. In addition, to validate the carried out literature review and the developed framework, a case study was conducted on a road project that justifies the impact of integrated LCA and LCCA on a pavement project.

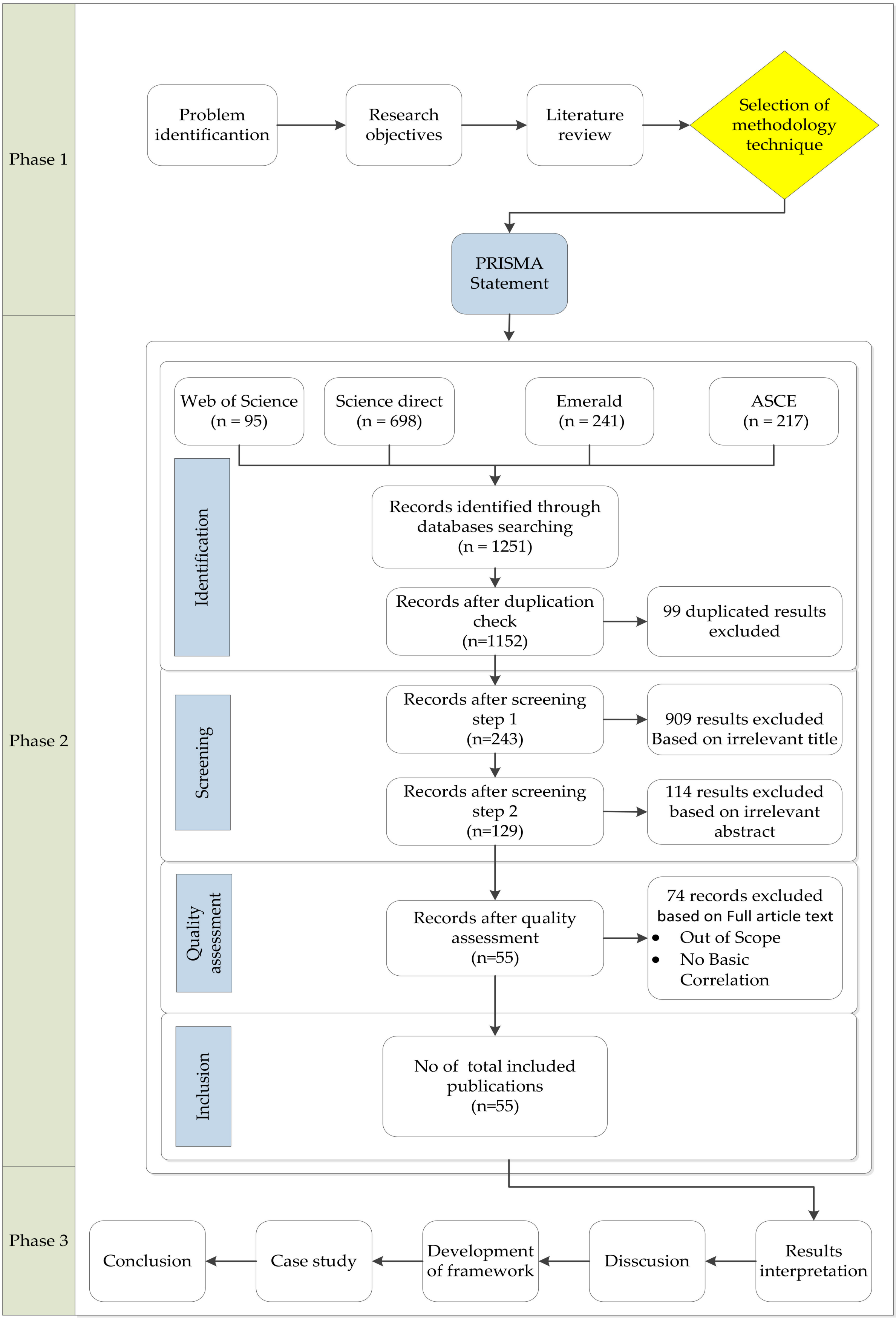

Figure 1. Methodology flowchart.

2.1. Research Strategy

A technique for this systematic review was designed to collect data from different databases for the related literature depending on the nature of this research. Four databases were selected, i.e., Web of Science [102], Science Direct [103], Emerald [104], and Scopus [105] which were known to be the top databases that include all indexed publications. The scope of this study focuses on "Life Cycle assessment", "Life Cycle Cost Analysis," and integration of both LCA and LCCA in the "pavement projects". Data was checked in these databases using the search string (([“life cycle assessment analysis” OR “LCA”] AND [Life cycle cost analysis]) AND (pavement)). The corresponding keyword phrase was described based on the search algorithm of the selected databases, which contains the main keywords related to the scope of the research. In addition, the limitation for the type of publication, i.e., research articles, review articles, and conference papers were also considered. The scope of the research was then narrowed down to the construction industry and eventually to the LCA and LCCA of pavement projects at different phases such as materials selection, rehabilitation, and impact on agency and users' cost. Moreover, the publications in English were chosen only.

2.2. Selection Criteria

The methodology approach used for this systematic review was focused on the PRISMA statement established by Moher, et al. [106]. The primary objective was to perform a state-of-the-art study of integrated "Life Cycle Analysis" and "Life Cycle Cost Analysis" in pavement projects and its role in "sustainability" and "project management" at various stages of the project. During the initial searching phase, a total of 1251 publications were identified by applying the constraint of document types such as research articles, conference papers and review paper, whereas the book chapters, editorial materials, online blogs, and reports were excluded. In addition, the documents published only in English were considered and no time limit was considered. Following the initial search strategy, a selection criteria for final selection of the publication was established which were limited to the life cycle evaluation of pavement projects at various phases such as during materials selection, rehabilitation and agency and users' impact and cost of pavement projects. Thus, only those publication were included in the final review analysis which fulfilled the developed selection criteria.

2.3. Quality Assessment

The data obtained from the four databases were combined into a single file getting 1251 results which were reviewed for duplication. The duplication often exists because some of the publication exists in multiple databases. In the analysis total of 99 publications were noticed as duplicated which were omitted from the list and 1152 results remained for further screening. Subsequently, 1152 results were reviewed, followed by deleting publications with irrelevant titles in screening step 1, where 243 publications were left for further screening. In the next step 2, the abstracts were reviewed to include only those publications which fulfil the scope of this review. After reviewing publications based on titles and abstracts, 129 publications were chosen for quality assessment. In the quality assessment step, a full-text study of the 129 publications was completed, where 74 results were excluded based on irrelevancy and only 55 related publications were left to include for a thorough review and analysis.

3. Results and Interpretation

The overview of the number of publications over the years is outlined in this portion. In addition, a keyword review conducted with VOSviewer software is provided. Subsequently, the interpretation of the included papers, along with a philosophical framework, which indicates the impact of LCA and LCCA on the pavement projects. To validate the proposed framework a case study was conducted that enhance the adaptability of the framework.

3.1. Summary of Extracted Articles

For this systematic literature review, four databases were chosen, i.e., Scopus, Web of Science, ASCE Library and Emerald. In the data assessment, 14 publication from Scopus, 33 from WOS, and 4 from ASCE and Emerald each were considered for the interpretation. These databases provide information from the largest research, publishing, and patent library in the world, offering access to the most reputable material. These databases frequently classify, interpret, and exchange the most significant data, uncover new developments in the research field, and identify influential collaborators. Moreover, out of 55 publications, 46 were research articles, 5 were conference papers, and 4 were review papers.

3.2. Keywords Analysis

A systematic analysis of the keywords in specific fields of science helps to clarify the dynamics of development and inequalities in the research sector. By examining the keyword co-occurrence relationships, the role and purpose of internal components can be better understood in a certain academic area and the limits of the discipline can be revealed. In the current systematic analysis, with the help of VOSviewer software, a keyword based map was created, as shown in Figure 2 for the data searched by the keywords (([“life cycle assessment analysis” OR “LCA”] AND [Life cycle cost analysis]) AND (pavement)). Map generated utilizing VOSviewer comprise of the keyword as items, which were the objects of interest, whereas items in the map could also be articles or scholars as well. A map typically contains only one type of item, where only keywords were taken into consideration in this study. Among the items of the map, there exists a relationship between any two items that determine the association or relation between them with a link number. Each link comprises a value known as link strength, which is a positive number. The better the relation, the higher this value. The number of publications in which two words appear together can be used to determine the strength of a relation. The items and links in the map combine make a network.

The frequency of keywords was evaluated using the “complete count” methodology available in the VOSviewer. The minimum occurrence of keywords was set as three such that the VOSviewer can consider a keyword having an occurrence of more than three times. With 3 keyword occurrences, a total of 77 eligible words were found by the VOSviewer that reaches the threshold. A mapping network of 77 linked frequent keywords with four fuzzy clusters was created. The cluster nodes demonstrate the keywords that connect to other nodes indicating the connection between them and the keywords used in these publications frequently.

The first cluster of Blue nodes was assembled around the term “life cycle assessment” with a maximum occurrence of 61 and a term “life cycle cost” having occurrence 43. Inside the same cluster, the terms “environmental impact” and “energy consumption” with occurrence 12 and 7, respectively, demonstrate the assessment of the environmental impact of pavement projects and the associated cost were focused on by the researchers. Construction projects have a significant influence on the environment and the economy, which is often assisted by decision-making strategies such as life cycle assessment and LCCA to ensure sustainability.

The second cluster of green nodes reflects the second large cluster assembled around the most used word “sustainability” with the occurrence of 57 and “life cycle cost analysis” with the occurrence of 23. This cluster comprises several primary terms such as: “concrete,” having 11 occurrences, “pavement” with 9 occurrences, “performance” with 7 occurrences, “economic analysis” with 5 occurrences, and other related words. This cluster demonstrates the researchers focus on the identification of economically sustainable pavement. Optimizing the environmental impact and expense of the project may be accomplished by implementing special approaches, such as recyclable materials, and ensuring sustainability by decision-making tools such as LCCA, as after assessment of the sustainable socio-environmentally sustainable options, the final decision is only based on the available economic resources.

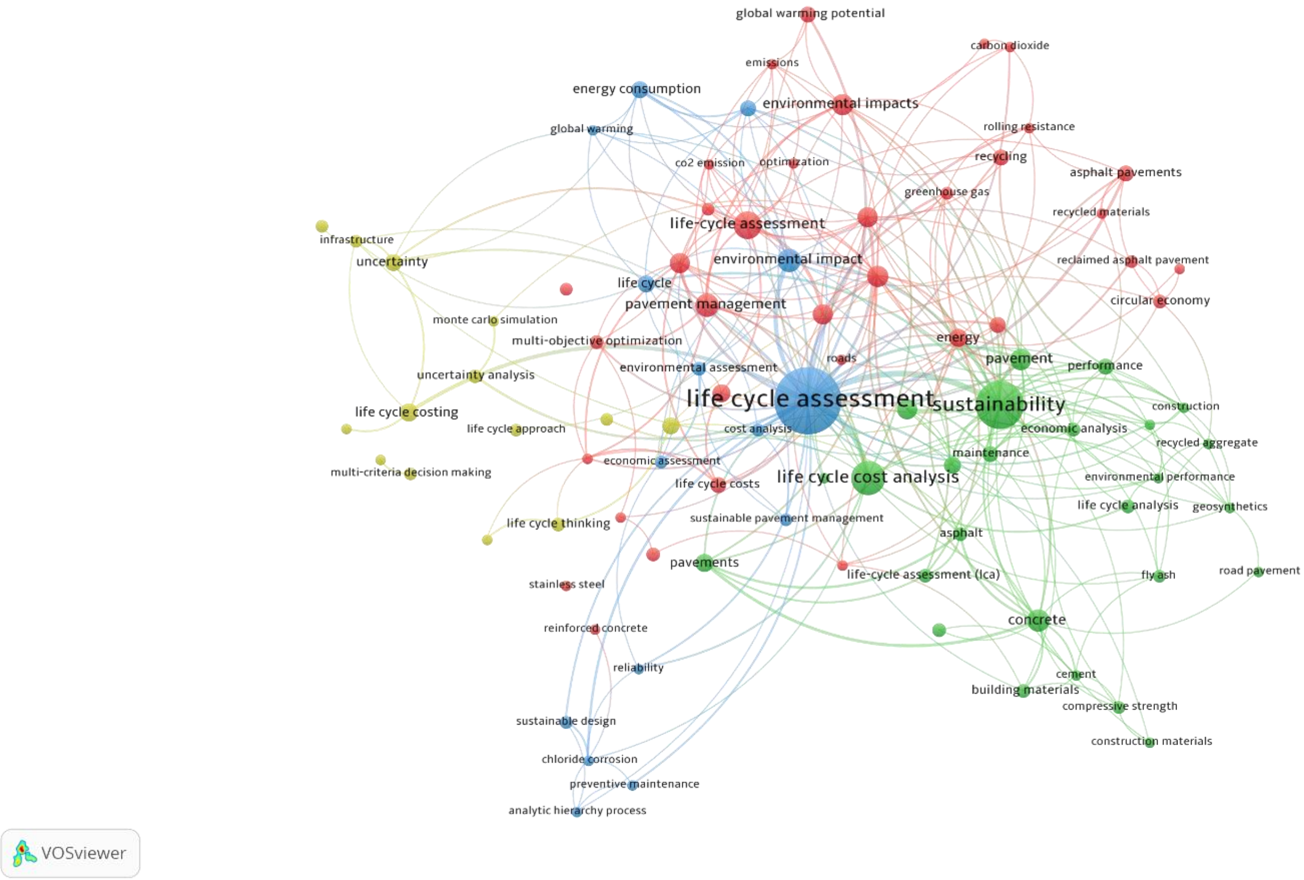

Figure 2. Mapping of Co-occurrence Keywords.

The third cluster with red nodes was assembled around “pavement management” with 16 occurrences near “life cycle assessment” with 12 occurrences. The surrounding words within this cluster are “asphalt pavement”, “greenhouse gas emissions” both with nine occurrences, and “sustainable development” and “energy” both with eight occurrences. This cluster describes the focus of researchers in optimizing environmental impact by adopting recycled or reclaimed material in pavement projects which reduces harmful emissions. Whereas the keyword analysis shows that the main concern was to optimize the consequences of a pavement project with management strategies. Proper management strategies enhance the project efficiency during the operating and maintenance phases which are the most impact causing stages of a project. Pavement management has a significant combination with LCA and LCCA which show the contribution of LCA and LCCA as decision-making techniques to the management of pavement projects.

The fourth influential cluster was yellow nodes around the word “life cycle costing” with eight occurrences, along with “life cycle assessment” and “environmental impact” with seven occurrences both. LCA justifies the environmental impact and provides the required data for LCCA. In the various publication, the integrated LCA and LCCA approaches are adopted to evaluate the economic, environmental, and social impact of a pavement project with the inclusion of environmental and social costs. In addition, a significant term “uncertainty analysis” of 5 occurrences was used since the data required for processing LCA and LCCA is expected to face data uncertainty. The term uncertainty has close connections to the term “sensitivity analysis” with three occurrences, which is used to resolve uncertainty.

4. Analysis of The Extracted Publication

In this section, the chosen publications were analyzed and the results were interpreted. First, the publication targeting the LCA was stated following by the publication focusing on the LCCA in the pavement projects. In the last, the publication which focuses on the integration of LCA and LCCA to achieve economic, social, and environmentally sustainable project was interpreted.

4.1. Assessment of Pavement Performance with LCA

In this section, the publication focused on the LCA were interpreted. LCA was adopted to assess the material selection and impact of materials at various phase of the life cycle of a pavement project.

4.1.1. Phases of LCA

The LCA consists of various phases, such as materials production, transportation, construction, use phase, maintenance and rehabilitation (M&R), and end of life as shown in Table 1. The first phase in the construction process is to extract raw materials used to manufacture the product linked with Green House Gases (GHG) emissions. The second phase is the transportation of the extracted materials and machines to the construction site and then transported to waste disposal from where the construction activities of the project, such as the construction of new pavements, maintenance, reconstruction, and renovations, progress. On the construction site, utilization of equipment may account for GHG pollution. In the M&R phase of LCA, emissions of GHGs are to be considered because of traffic delays caused by construction and maintenance. Then comes the use phase, where the fuel consumption and emission of GHG due to deteriorating pavements are to be calculated. At the end of life phase, pavement materials are to be demolished and then deposits or recycle, where the demolition and recycling or transporting of the demolished materials causes harmful emission. GHG emission analysis is highly important in all phases and was considered by many researchers in all extraction, manufacturing, transport, production, use and end-of-life activities [12]. The construction phase had the highest (62.0%) impact on the environment, followed by the end life phase (35.8%), and then the M&R phase (1.7%) [107]. This impact only considers the construction, maintenance and demolition activities, whereas the user's activities are omitted which changes the results drastically. Liu, et al. [108] considered the material production, transportation, construction, and use phase of a permeable asphalt (PA) pavement compared to dense asphalt (DA) pavement, whereas the research has some limitation that did not consider some environmental factors for a permeable pavement, which needs to be focused on in the future. Most approaches overlook M&R phase assessments, which may be very useful in maximizing the effects of the M&R phase. However, the service and performance level of pavement changes dynamically where the environmental impact depends on it. Batouli and Mostafavi [109] analyzed the scenario and adopted Service and Performance Adjusted LCA (SPA-LCA) where it was concluded that the increasing demand for pavement leads to increase environmental impact which could be overcome with the improvement of current management practices in the use phase. Moreover, it was also suggested that increasing the investment for M&R could significantly improve the network performance and sustainability.

Similarly, the use phase of a project has more impact on the environment as the traffic and vehicle related emissions cover the use phase consequences [110]. In the LCA usage phase, Haslett, et al. [111] observed a 6.4% rise in energy demand and GWP when incorporated the realistic traffic conditions, whereas in some practices the impact of the usage periods was ignored while some did not mention clearly.

4.1.2. Pavement Materials Assessment with LCA

The material endorsement evaluation in the pavement project is one of the key parameters to consider for a sustainable environment. Different considerations such as cost and environmental effects should be examined in the estimation of material selection. In addition, its impact on survivability and performance on a project should be taken into consideration when making decisions about the materials. LCA is a standard approach that promotes the overall use of materials for a pavement project. Various researchers undertook LCA for the materials assessment in the pavement project. Where some researchers focused on virgin materials, some focused on recycled while some assessed the combination of both. Although some researchers did not clarify the nature of the material. In a case study, Heidari, et al. [66] analyzed the impact of concrete and asphalt on a project and discovered that the concrete pavement would increase the cost of the projects by about 35%, although eliminating pollution by around 2,000,000 tons per year and reducing the use of energy by 700,000 GJ. Similarly, a 26% reduction was measured for hot mixed asphalt (HMA) pavement compared to the plain concrete pavement. It identifies that the smart selection of materials should be assessed with LCA to measure sustainable measures.

LCA is the methodology for measuring the environmental impact of a given pavement project during its life cycle, from the processing of raw materials to the final recycling phase. The environmental impact of pavement projects was measured through analyses of environmentally sustainable materials and recycled materials. The relative energy, Global Warming Potential (GWP) and cost decreased with increased recycled content, as observed by Yang, et al. [22] by comparing 10 blends with 25–60% asphalt binder ratio (ABR) to a virgin dense-graded mixture. Similarly, Araújo, et al. [24] analyzed the different type of recycled materials and with 50.0% recycled asphalt pavement (RAP), energy consumption was reduced by 3% and gaseous emissions were reduced by 14% for CO_2, 23% for SO_2, and by 15% for CH_4, N_2O, and NO.

In many countries, the recycling of concrete paving has been a common practice. While the material properties and structural efficiency of pavement substituted by recycled concrete aggregates with virgin concrete were extensively identified. However, relatively little focus was given to determine their possible advantages on sustainability with LCA. Some of the researchers focused on the recycled materials, where the impact of recycled materials was found minimum as compared to the virgin materials such as hot mix asphalt with reclaimed (HMAR) asphalt achieve best social and economic performance compared to hot mix asphalt with an additive warm mix (HMAW) asphalt, which achieves more environmental performance [112]. Similarly, 25% clinker hydraulic road binders minimize GHG emissions by more than 50% while fly ash also decreases GHG emissions with 50% cement material [23]. Although clinker and fly ash reduce CO_2, the performance of pavement was not assessed when using clinker and fly ash.

The pavement project requires a huge number of materials as the development is growing at a high rate. Assessing the recycled material is a valuable alternative for sustainable construction, where the relative energy, GWP and cost decreases with the increased recycled content, compared to virgin materials. Recycled materials such as RAP and recycled asphalt shingle (RAS), which can partly replace virgin asphalt binding and aggregate mixtures, are widely identified as one of the most frequently used sustainable techniques for asphalt pavement [22]. The trend of recycled concrete is becoming very common where material performance and properties were emphasized very largely although little consideration was given to the sustainability perspective. Keeping in view, Shi, et al. [21] conducted an LCA comparison of plain cement concrete (PCC) pavement with recycled concrete aggregate mixed with plain cement concrete (RCA-PCC) pavement where it was observed that RCA-PCC saves 35% of the cost, utilizes 18% less of energy, generates 23% fewer air emissions and 17% fewer gas emissions, uses 25% reduced ground, releases 26% fewer pollutants, and is 15% less mobility, while saves 34% in water runoff. A detailed summary of publication about adaptation of materials and impact of pavement during life cycle phases are demonstrated in Table 1 where the symbols "✔" and " - " represent the availability and the absence of reviewed items, respectively.

Table 1. Publication summary of Life Cycle Assessment (LCA) of pavement materials.

S. No	Article	Material		Phases						Remarks
		Recycled Materials	Virgin Materials	Material Production	Transportation	Construction	Use	M&R	End Life	
1	Li, et al. [107]	✔	-	-	-	✔	-	✔	✔	The construction phase has the highest environmental impact (62.7%), followed by the demolition (35.8%) and maintenance phases (1.7%). Steel has the highest proportion of environmental impact in the construction phase (55.5%).
2	Liu, et al. [108]	-	-	✔	✔	✔	✔	-	-	Life cycle economic cost of PA is 26–27% higher than that of DA The environmental impact under each impact categories is about 20–65% lower than that of DA
3	Heidari, et al. [66]	-	-	✔	-	✔	-	✔	✔	Compared to asphalt pavement concrete pavements increase 35% costs, 2,000,000 tons of carbon emissions reduction and 700,000 GJ reduction in energy consumption annually.
4	Shi, et al. [21]	✔	✔	✔	✔	✔	✔	-	✔	RCA-PCC pavement saves 35% of the cost, utilizes 18% less energy, generates 23% fewer air emissions and 17% fewer gas emissions, uses 25% reduced ground, releases 26% fewer pollutants and is 15% less mobility, while saves 34% in water runoff.
5	Haslett, et al. [111]	-	-	-	✔	-	-	✔	-	In the LCA usage period, a 6.4% rise in energy demand and GWP has resulted in the incorporation of realistic traffic conditions.
6	Liu, et al. [25]	-	✔	✔	✔	✔	✔	✔	✔	The RCA-PCC pavement is slightly less sustainable compared to the plain PCC pavement during the use phase.
7	Batouli and Mostafavi [109]	-	-	-	-	-	-	✔	-	Rise in M&R expenditure ensure the network's efficiency and environmental impacts significantly.
8	Zheng, et al. [112]	-	-	✔	✔	✔	✔	✔	-	The best economic and social performance was achieved by HMAR and the best environment performance was achieved with HMAW.
9	Anastasiou, et al. [23]	-	✔	✔✔	✔	✔	✔	✔	✔	The 25% clinker hydraulic road binders minimize GHG emissions by more than 50% while fly ash also decreases GHG emissions with 50% cement material.

Table 1. *Cont.*

S. No	**Article**	**Material**		**Phases**						**Remarks**
		Recycled Materials	**Virgin Materials**	**Material Production**	**Transportation**	**Construction**	**Use**	**M&R**	**End Life**	
10	Yang, et al. [22]	✔	✔	✔	✔	✔	✔	✔	✔	The relative energy, GWP and cost decreased with an increased recycled content were observed in comparing 10 blends with 25–60% ABR to a virgin dense-graded mixture.
11	Yu, et al. [26]	✔	-	-	-	-	-	-	✔	8.2–12.3%, 5.9–10.2% in energy and GHGs and a reduction in overall costs
12	Araújo, et al. [24]	✔	✔	✔	✔	✔	✔	✔	✔	With 50.0% RAP, energy consumption was reduced by 3% and gaseous emissions were reduced by 14% for CO_2, 23% for SO_2 and 15% for CH_4, N_2O and NO.
13	Batouli, et al. [20]	✔	✔	✔	✔	✔	✔	✔	-	Compared to the FDOT design and the ACPA rigid floor design, the HMA flexible pavement created 13.2 times and 14.1 times higher GWP.

4.2. Assessment of Pavement Performance with LCCA

The quality and luxurious life of humans depends upon pavement quality, quantity, and efficiency. To maintain the quality and efficiency of the pavement project it should be maintained properly throughout its life. The proper functionality and safety of pavement require routine M&R intervention. LCCA is an approach that identifies the M&R intervention of pavements including direct and indirect costs. LCCA approach assists to evaluate optimal M&R approaches for deteriorating structures over a specific time. After reviewing the included articles, a detailed summary of the articles was demonstrated in Table 2 which were then interpreted. The symbols "✔" and " - " in Table 2. represent the availability and the absence of reviewed items, respectively.

4.2.1. Cost Function

Construction analysis provides a face value mostly with case studies, i.e., the discussion of conscience, comprehensive illustration of the implementation of a modern model or process. The life cycle of the pavement project is fully case based, where the outcomes of the trials are compared in percentage form to determine the better alternatives. In a case study of a pavement project, Kong and Frangopol [113] incorporated cost function with the time variable. Incorporation of time with cost function evaluate the impact of time travel or delays due to pavement performance and serviceability on the user cost. Although, incorporating cost function with other variables, such as the effect of project inspection and scheduled or routine M&R, will improve the maintenance efficiency of pavement deterioration. Introducing cost function in the pavement intervention and reliability enhances the reliability based structure management system. A reliability-based management model can be used for various analyses. A safe and operable approach is required to sustain the deteriorating pavement assets. Mostly pavement management possesses detailed LCCA to allocate the funds for M&R optimally. Saad and Hegazy [114] identified the lack of a mechanism to justify the allocation of LCCA details in M&R and incorporated microeconomics theories to justify the decision made based on the LCCA. The concept of marginal utility was used by economists to determine the number of items, the consumers are willing to invest. The microeconomics approach justifies the fund allocation based on consumer behaviors and proved the marginal utility per dollar was equalized.

Table 2. Publication summary of Life Cycle Cost Analyses (LCCA).

S. No	Author	Purpose	Methodology	Type of Projects	LCCA Dependencies						
					Time	Inspect Cost	User Cost	Environmental Hazards	Safety Performance	Agency Cost	Cost Function
1	Kong and Frangopol [113]	Deterioration analysis	Reliability-based structure management systems	-	✔	-	✔	-	✔	✔	✔
2	Saad and Hegazy [114]	Deteriorating infrastructure	Microeconomic	Pavements	-	-	-	-	✔	✔	✔
3	Sajedi and Huang [115]	Analyzing Corrosion associated cost	Reliability-based life-cycle-cost comparison	Bridges	✔	-	-	-	✔	✔	✔
4	Akadiri and Olomolaiye [116]	Material selection	Questionnaire	Pavement	✔	-	✔	-	-	✔	✔
5	Gao, et al. [37]	New construction materials	Stochastic Multi-Objective Optimization	Bridge deck	✔	-	-	-	-	✔	✔
6	Salinas, et al. [117]	Interface bonding	Comparative analysis	Tack Coat	-	-	-	-	-	-	✔
7	Li, et al. [118]	Highway decision making	multi-commodity minimum cost network (MMCN)	Tollway project	✔	-	-	-	-	-	✔
8	Li, et al. [119]	Safety risk	Fault tree analysis (FTA) is	Highway	-	-	-	-	✔	✔	✔
9	Jha, et al. [120]	Maintenance time management	Optimization model	Highway	✔	-	-	-	-	✔	✔
10	Huang and Huang [121]	Maintenance time management	Concurrent maintenance	Bridges	✔	-	-	-	-	✔	✔

Table 2. *Cont.*

S. No	Author	Purpose	Methodology	Type of Projects	LCCA Dependencies						
					Time	Inspect Cost	User Cost	Environmental Hazards	Safety Performance	Agency Cost	Cost Function
11	Macek and Snížek [122]	Maintenance and renovation	Bridge pass application	Bridge	✔	-	-	-	-	✔	✔
12	Farran and Zayed [123]	Pavement rehabilitation	Genetic Algorithm and Markov chains.	Pavement	✔	-	-	✔	-	-	-
13	Shahtaheri, et al. [124]	Pavement sustainability	SIMPLE-Design	Pavement	-	-	-	-	-	-	✔
14	Hasan, et al. [6]	Integrated LCCA	Review Analysis	Road network	✔	-	✔	-	✔	✔	✔
15	Al-Chalabi [125]	Total Ownership Cost (TOC)	MATLAB	Road tunnel	-	-	-	-	-	-	-
16	Babashamsi, et al. [126]	Pavement LCCAs	Critical Review	Pavements	✔	-	-	-	-	✔	✔
17	Heidari, et al. [66]	Pavements Alternatives	DP, MCS and TOPSIS	Pavements	-	-	✔	✔	-	✔	✔
18	Senaratne, et al. [127]	Maintenance and renovation	Net Present Value (NPV)	Harbor bridge	✔	✔	-	✔	-	✔	✔
19	Okte, et al. [128]	Incorporating user cost	International roughness Index (IRI) progression model	Tollway road	-	-	✔	-	-	-	✔
20	Praticò, et al. [129]	Risk level of the highway design	Fault tree analysis (FTA)	Highway	-	-	-	✔	-	✔	-
21	Hameed and Hancock [130]	Integration of environmental and economic factors	Integrated life cycle analysis approach (ILCA2)	Pavement	-	-	✔	✔	✔	✔	✔

Table 2. *Cont.*

S. No	Author	Purpose	Methodology	Type of Projects	LCCA Dependencies						
					Time	Inspect Cost	User Cost	Environmental Hazards	Safety Performance	Agency Cost	Cost Function
22	Salem, et al. [131]	Pavement rehabilitation alternatives	survey of the US and Canadian statetransportation agencies	highway	-	-	✔	-	-	✔	-
23	Wang, et al. [132]	Integration of environmental and economic factors	Environmental incorporated-LCCA model	Bridge	-	-	-	✔	-	✔	✔
24	Janbaz, et al. [133]	Estimate the capital and annual costs of a UFT system	Regression model	UndergroundFreight Transportation (UFT)	-	✔	✔	-	-	✔	✔
25	He, et al. [134]	Integration of environmental and economic factors	Athena Pavement LCA and MOtor Vehicle Emission Simulator	highway	✔	✔	✔	✔	✔	✔	✔
26	Hasan, et al. [135]	LCC-based identification of geographical locations	Probabilistic Hazard Analysis	Reinforced concrete girder bridges	✔	✔	-	✔	✔	✔	-

4.2.2. Agency Cost and Users Cost

The LCC of pavement consists of Agency and User Costs over an appropriate period of analysis. The Agency's costs include the initial construction costs and the M&R costs incurred during the analysis period. User costs occur during the serviceability phase and M&R phase when the working zone is present. Normally in LCCA with traditional practices, the agency costs were considered whereas the users operating cost was ignored, which is more important for accurate calculation of LCC. Okte, et al. [128] investigated the resurfacing of the Illinois Tollway project to evaluate the vehicle operating cost (VOC) as user cost and found that the VOC should be considered in LCCA as it is reliable for the international roughness index (IRI) progression model. IRI is the strategy used in the pavement design which impacts the VOC directly. The integration of user costs into design and decision-making systems immediately from the planning phase of the project would enable transport departments to remain customer-oriented and minimize the total impact of the project [131].

4.2.3. Operation and Maintenance Management Cost

For pavement design, cost-optimal solutions are required that not only affect the life cycle cost but also enhance the management strategies to ensure safety performance [119]. Pavement design and maintenance management have considerable interaction among them such as good designed and properly maintained pavement minimize the life cycle cost of the whole project. Whereas, there was a lack of consideration of maintenance management costs noticed in the design phase, thus increasing the life cycle cost of the project [120]. The M&R tasks on the operating pavement are very important, whereas M&R activities increase the users' cost by causing traffic jams and detours. A concurrent M&R methodology was introduced into the maintenance management of existing bridges infrastructure which helps in integrating the maintenance timing of the bridge elements hence reducing the user cost and total life cycle cost [121]. The same methodology can be adopted for on land pavements to optimize the users' cost. The model optimizes the life cycle cost of the bridge by incorporating the user cost as well as the agency cost, but the deterioration cost was not considered which needs to be incorporated in future. Moreover, an economical construction strategy for bridges was highlighted and it was evident that the bridges project management consist of investment cost as well as appropriate operating cost because of extended service life. Moreover, an innovative computational model was presented, which links the pricing databases into two sets such as the operational and maintenance cost calculations based on the expert database, whereas the replacement cost of the components was linked to the designer price database [122]. Mostly the M&R methods for pavement projects were reported for a specific type of project such as pavements, bridges, etc. Farran and Zayed [123] developed a generic model for M&R planning of public pavement that helps in determining the optimal M&R decision-making analysis by using the genetic algorithm and Markov chains. The model helps in overcoming the computational calculation whereas the model was only valid for four alternative decisions. Similarly, in railway infrastructure, the operational cost equates to 25–30% per annum. The railway track needs to be inspected and maintained annually. Senaratne, et al. [127] selected Sydney Harbour Bridge as a case study to evaluate the maintenance and ongoing operation of railway infrastructure considering timber transoms. The transoms used has shorted life span and height chances of degradation; therefore, the issue was analyzed by exploring sustainable alternative such as fiber composite with the implication of LCCA and found it more financially stable. Thus, the M&R during the operational phase affect the project significantly which needs to be assessed during decision making where LCCA was found considerable approach for best decision making.

4.2.4. Material Selection with LCCA

In complex pavement projects, the materials need routine maintenance, repair, and rehabilitation to ensure safety and maintaining the interconnected structure to overwhelm the associated cost. Moreover, deterioration management strategies should be adopted for the selection of suitable materials during repair or utilizing materials having deteriorated resistant properties that help to optimize the LCC. In research, long term cost-effectiveness was analyzed for various groups of materials in the design and repairing phase and a time dependent reliability LCC model was developed [115]. Moreover, Hasan, et al. [135] introduced a new method that incorporates the hazard correlated with airborne chloride with the Carbon Steel and Stainless Steel reinforcements into the probabilistic LCC estimate of the RC bridge to manage the corrosion hazards. The model asses the practitioners to assign an appropriate geographical location for the girder bridge to optimize the maintenance cost. While to improve the performance and productivity for sustainable pavement, usually, new materials are adopted at the project level and network level, where LCCA plays a significant role in material selection [116]. Though, because of the limited data implementation of newly adopted materials, the reliable estimate of the life cycle cost becomes a challenge. Therefore, a bottom up LCCA framework was presented which analyzes conventional as well as new construction materials at the project level and network level. Efforts presented to incorporate various cost factors such as years, users, and social cost, as well as a stochastic tackling of uncertainties, were included. The purpose was to approach the reasonable estimate for the future performance of the newly adopted materials or techniques [37]. Similarly, a convenient method to analyze the optimized tack coat for the pavement layer is LCCA, which will help to ensure cost-effective optimum tack coat application in the field [117]. Moreover, project selection has a significant impact on fulfilling the scope of a project. Thus, a Multi-Commodity Cost Network (MMCN) model was introduced to assist project selection and evaluation by estimating the LCCA. Although the model plays a significant role in the selection of an optimal solution. Whereas, a huge amount of data was required, which makes the use of the MMCN model limited [118].

4.3. Integrated LCA and LCCA

The environmental efficiency of the pavement system is based on complex transitions in service level and pavement performance. LCA describes the environmental impact for the lifetime of a material or project and, by quantifying environmental obligations, providing the required data for LCCA. Some studies argued that the agency cost, user costs, and the environmental cost for preventing environmental damage should be allocated to a project. Adopting an LCA and LCCA approach in the design and decision-making phases will help and identify the most economical and environmental options, that can be utilized by all the parties involved in the planning to analyze sustainable alternatives [111]. Implementing an integrated LCA and LCCA methodology in the pavement approach could enhance road infrastructure management which will consider all the associated cost along with environmental protection cost. A detailed summary of the articles is shown in Table 3, where it was illustrated that some publication adopted LCA and LCCA individually and some of the publications were focused on an integrated LCA and LCCA approach. In addition, the sustainability indicators highlighted by the publications were also indicated.

Table 3. Publication summary of Integrated LCA and LCCA.

S. No	Authors	LCA	LCCA	Environmental Indicators									
				Energy Emission	SO	Particulate Matter	SO_2	CO	Pb	VOC	CO_2	N_2O	Ch_4
1	Kendall, et al. [136]	✔	✔	-	-	✔	✔	✔	✔	✔	✔	✔	✔
2	Zhang, et al. [137]	✔	✔	-	✔	✔	✔	✔	✔	✔	✔	✔	✔
3	Liljenström, et al. [138]	✔	-	-	-	-	-	-	-	-	✔	-	-
4	Tokede, et al. [139]	✔	-	-	-	-	-	-	-	-	✔	-	-
5	Liu, et al. [108]	✔	✔	-	✔	✔	✔	-	-	-	✔	-	✔
6	Heidari, et al. [66]	✔	✔	✔	-	-	-	-	-	-	✔	-	-
7	Shi, et al. [21]	✔	-	-	✔	-	-	-	-	-	✔	✔	✔
8	Haslett, et al. [111]	✔	-	✔	-	-	-	-	-	-		-	-
9	Liu, et al. [25]	✔	✔	-	✔	-	✔	-	-	-	✔	✔	✔
10	Yang, et al. [22]	✔	✔	✔	-	-	-	-	-	-		-	-
11	Yu, et al. [26]	✔	✔	✔	✔	✔	✔	✔	-	✔	✔	✔	✔
12	Araújo, et al. [24]	✔	-	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
13	Batouli, et al. [20]	✔	✔	-	✔	-	-	-	-	✔		-	-
14	Giustozzi, et al. [140]	✔	-	✔	-	-	-	-	-	-	✔	-	-
15	He, et al. [134]	✔	✔	✔	-	-	-	-	-	-	✔	-	-
16	Nascimento, et al. [141]	✔	-	-	-	-	-	-	-	-	✔	✔	✔
17	Li, et al. [142]	✔	-	-	-	-	-	-	-	-	✔	-	-
18	Park and Kim [143]	✔	-	-	✔	-	✔	-	-	-	✔	-	✔
19	Zheng, et al. [112]	✔	✔	✔	-	-	-	-	-	-	✔	-	✔
20	Umer, et al. [144]	✔	✔	-	✔	✔	-	-	-	✔	✔	✔	✔
21	Santos, et al. [145]	✔	✔	-	-	-	-	-	-	-	-	-	-
22	Batouli and Mostafavi [109]	✔	-	-	-	-	-	-	-	-	✔	-	-
23	Inti, et al. [146]	✔	✔	-	-	-	-	-	-	-	✔	-	✔
24	Gschosser and Wallbaum [147]	✔	✔	✔	-	-	-	-	-	-	✔	-	-
25	Santhanam and Gopalakrishnan [27]	✔	-	-	✔	-	✔	-	-	✔	✔	✔	✔

Mostly in the life cycle evaluation, the environmental damage costs were ignored. An extensive LCA technique in the field of pavements was used in the analysis to estimate the marginal cost of damage to different emissions and an algorithm was developed to align the LCA with the LCCA model. In comparison with usual traffic activities, the congestive module accounts for extra fuel usage and air pollution during construction and M&R cycles. Analysing the results of the LCA and LCCA implementations, streamlined maintenance schemes costs were decreased by 5.9–10.2% and the holistic costs relative to previous optimization schemes by 8.2–12.3%, compared with the influence of energy and GHG assessments [26].

Zhang, et al. [137] studied a pavement system with an LCA and LCCA integrated Life Cycle Optimization (LCO) model, where an energy savings of 5–30%, Reduction of 4–40% GHS pollution, while concrete costs decreased by 0.4–12%, was reported. Moreover, with the recycled materials adaptation approach, such as 50.0% RAP, energy consumption was reduced by 3% and gaseous emissions were reduced by 14% for CO_2, 23% for SO_2, and 15% for CH_4, N_2O, and NO [20]. In many of the studies, LCA and LCCA were adopted where user cost, agency cost, and environmental impact are considered, whereas less attention was given to incorporate the environmental cost [20,26,112,136,137], which is the cost utilized for the depletion of the harmful impact of the environment.

Pavement projects affect the economic, environmental, and social aspects directly or indirectly, whereas it was recommended that the pavement agencies must review these parameters in the planning stage of a project [133]. A decision-making system introduced by integrating sustainability criteria and economic criteria, developing a model which utilizes LCA and LCCA for pavement management and selection of best alternatives between asphalt concrete pavement (ACP) and plain cement concrete (PCC) pavement. The results evaluated from the analysis demonstrated that ACP was more economical than PCC pavement although its carbon emission was highest. Thus LCCA implementation in pavement selection is very important, as a case study, indicates that choosing concrete pavement increases the construction cost by 35% whereas, it will reduce 2 million tons of carbon emission and 0.7 million GJ energy consumption annually [66]. Moreover, Hameed and Hancock [130] developed an integrated life cycle approach (IILCA) that unite the LCA and LCCA by incorporating materials quantities, the environmental impact of materials in term of cost such as carbon footprint and cost of waste materials. Similarly, Wang, et al. [132] incorporated the environmental costs such as structure emissions to air, water and land and developed an environmental incorporated-LCCA model. The model was applied on a bridge to select structural material for bridge girders, taking into consideration direct, environmental, and overall initial costs. Whereas steel girders were found to have lower direct costs and environmental costs due to lower pollution, easier building practices and the higher content recycling rate in the construction phase, demonstrating greater economic and environmental efficiency in the initial level. Further, He, et al. [134] proposed a decision-making framework to integrate the LCA and LCCA to assess highway treatment events which allow to implementation of the most suitable alternative for a project. Project solutions were evaluated utilizing different environmental methods, including asphalt overlay of the warm mix, cold in-place recycling, maximum depth reclamation, intelligent compaction, and precast concrete pavement systems. Using the outcomes of life cycle evaluation with the implemented proposed framework, the professionals may grasp help in the ramifications of project-level actions, conduct what-if analysis to analyze exchange between options and achieve sustainability-related organization priorities and goals. Additionally, the back-and-forth relation among the economic, environmental, and social features of pavement seems very tough for the decision-makers in the design phase. As a result, reducing the initial construction cost, the decision-makers compromise the environmental and social entities. A sustainable infrastructure multi-criteria preference assessment of alternative for early design (SIMPLE-Design) strategy was formulated, which incorporates the indifference curve to assess the decision-makers in dealing with the back-and-forth relationship between different alternatives [125]. Whereas the indifference curve needs to be further extended with the inclusion of more trade-off entities to improve the decision-making in diverse scope. The LCCA, future cash flows, feedback, and incorporating the project performance with sustainability can assess the process of decision making towards the selection of sustainable options for a construction project. Interpreting the principle of LCA with LCCA to demonstrate the sustainability that asses the quality, time, and cost of a project [6], which is very useful for new and repairable systems because, at some point in their life span, their operating and maintenance costs and impact will exceed their acquisition costs [125].In many studies, the researchers developed some models or frameworks that try to minimize the limitation of the existing methodologies for specific parameter or areas. He, et al. [134] developed a Decision support system with the integration of LCA and LCCA which allows the practitioners to evaluate a sustainable project alternative by identifying economic, social, and environmental impact. Similarly, Li, et al. [107] defined the Environmental Impact Evaluation (EIE) Model to analyze each of the processes that contribute to the transport life cycle of projects in which the development stage has the highest environmental impact 62.7%, followed by the demolition 35.8% and restoration stages 1.7%.

Data availability is one of the critical aspects in the process of LCA to evaluate a successful analysis although the acquisition of the data in the assessment was found very confusing and sometimes improper data leads to faulty computations. Park and Kim [143] built an LCA-based Environmental impact Estimate Framework that incorporates existing data during its design process to estimate the environmental impact of an earthwork type road project; however, the established model uses only limited data available in the design stage. Santos, et al. [145] evolved the LCC-LCA model that depends on a hybrid inventory system that enables sub-models to link each other across data sources. This provides for the monetary flows linked to the pavement life cycle structure exchanges that are specifically protected by the LCC model for which data was not accessible.

5. Discussion

The construction industry is one of the most important industries, which has a huge impact on the economy, environmental as well as social life [148–153]. To meet sustainability goals, it is necessary to evaluate the activities over the life cycle of the project. LCA and LCCA are the assessment tools the evaluate the project performance in terms of environmental, social, and economic impact. Implementation of Life cycle techniques for decision-making during the planning and design stage to evaluate all the constraints related to the pavement project may be more cost-effective with a resilient and productive construction over the life cycle of the project.

The AASHTO guidelines stated that pavement engineering is not a precise scientific approach; although, there should be judgment following varying factors such as traffic, weather, recycling, and cost and impact assessment. AASHTO introduced LCC in its infrastructure Construction Guide in 1972 [68,69] according to which, LCC should be adopted compulsory, and defined guidelines for LCCA comprising all expenses and advantages connected with the provision of pavement during their whole life span [41]. Although at that time insufficient knowledge was available, extensive research started to evaluate enhance the proper approach. Moreover, for LCA standard guidelines were adopted in the pavement projects defined by International Standardization Organization ISO 14040/14044. With the increasing interest in sustainability, LCA and LCCA adaptation in the pavement projects gained significant momentum in the field of research. While evaluating the trend in research for LCA and LCCA, Scopus data bases [88] report was analyzed which indicated a less interest in the field of research from 1999 to 2007. Whereas after 2007, the concept of sustainability attracted the attention of researcher towards LCA and LCCA in pavement projects. Moreover, due to the huge amount of pavement development and its impact on economy, environment, and social life, the LCA and LCCA in sustainability became one of the prime interest by the researchers. Although, extensive amount of research was evident, there is still less interest of the pavement stakeholder towards the practical application of LCA and LCCA due to the uncertainties in the results.

LCA deal with the impact of a project on the environment and indirectly the social life of human being. Whereas adopting sustainability strategies, the project faces a cost issue that increases the budget of the project. To consider the economic perspectives of a project along with sustainability, the LCCA methodology got the attention of the researchers and practitioners. Likewise, LCA, the LCCA is perceived by decision-makers to be an effective solution for assessing the economical project with improved sustainability. Moreover, LCCA has a wide range of application, which allow decision-makers to compare and choose a sustainable option in terms of cost. In the process of LCA, the impact of a pavement project was assessed from the materials extraction to the end life of the project, where a detailed inventory is generated and integrated with impact values. The inventory generated a detail of a project which can be further used for cost assessment. In some researches, the pavement project life cycle was assessed with virgin materials, whereas in some places recycled materials were used and compared [107]. Likewise, using RCA in the pavement could save 18% of energy, reduce 23% gaseous emissions, reduce 25% pollutants, whereas, decreases 35% overall cost of the project. However, in the assessment of materials for a pavement project, the environmental impact was considered, whereas the environmental costs were ignored. Moreover, in the majority of the studies, material properties and efficiency of pavement were assessed in term of cost; however, little attention was given to the impact of materials along with the cost of the project. Since the environmental impact could only reduce and cannot be eliminated, which need potential attention to treat; thus, consideration of environmental cost is very important in the LCCA stages. The environmental cost is the cost that could use for the treatment of the damage or reduce the impact. In addition, in several types of research and case studies, the LCA and LCCA were adopted individually, while some focused on the integrated results of LCA and LCCA.

Furthermore, economic and environmental development techniques for road projects were emphasized with proper management. An efficient management approach enhances pavement performance during planning, construction, operation, and maintenance. The LCA and LCCA have a significant relation with management strategies in the decision-making stages. Whereas, there was a lack of consideration of the maintenance management costs during the design process, thereby raising the environmental impact, social stresses, and life-cycle cost of the project [120]. Similarly, maintenance of operating projects is very significant, where the maintenance activities increase the cost of travelers by creating traffic delays and detours that also become a great cause of energy consumption and environmental stresses.

Additionally, the LCA and LCCA were described as the most developed methodology that affects different facets of pavement projects to optimize the cost and environmental impact ensuring a sustainable project. In addition, LCA and LCCA were known to be the important approach used in the planning and design phase by decision-makers to assess the economic, environmental, and social impact of a project [154,155].

Moreover, from the literature, it was evident that the majority of the cases require to access the dataset or software developed for LCA and LCA, which was noticed very restricted for the agencies and practitioners. In addition, the application of LCA and LCCA in road projects are expected to grow and there is a need for improvement in the field of LCA and LCCA assessment to counter the uncertainties in real time project. Furthermore, in real time projects, LCA was less evident as the agencies, keep their data confidential.

6. Conceptual Framework

Based on the literature, a conceptual framework, as seen in Figure 3 has been developed to consider the impact of life cycle evaluation on various aspects of the pavement project and how it impacts the economy, environment, and social life.

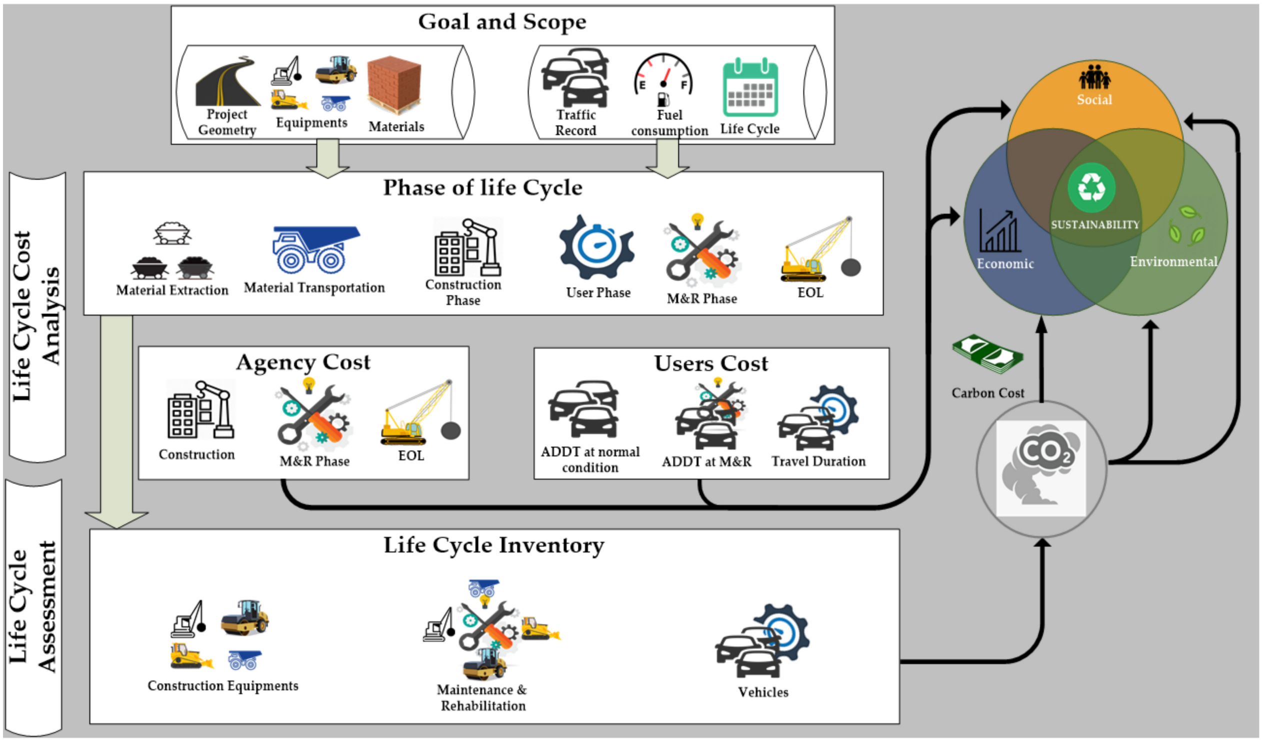

Figure 3. Integrated LCA and LCCA framework and its impact on sustainability.

The use of integrated LCA and LCCA is an obligatory prerequisite to efficiency regarded in pavement planning and management. Initially, LCA and LCCA identify appropriate solutions to the design or M&R strategies. The LCA and LCCA describe initial construction and operation, the M&R activities needed for the future and the coordination of those activities. The life cycle evaluation approach can develop solutions to identify the environmental, economical, and social impact of the products, and services. The economic impact due to capital expenditure is assessed by LCCA. Whereas the LCA assess the impact and potential risks associated with the project. The cost of the overall life cycle, including planning and design, development, service and repair, and disposal, should be included in assessing the agency cost and users' costs, whereas the impact of agency activities and user activities are also the key concern to identify. The embodied impact of materials, transportation of materials, the onsite machinery utilization in the construction and M&R phase as well as the vehicle in the use phase, impact the environment adversely. Comparatively, the use phase of the pavement project is the main part of the project which impacts the economy and environment. Consequently, for a sustainable project, their impact, and the cost to reduce the impact must be considered in the decision making of life cycle evaluation.

Furthermore, the new pavement projects are very costly to execute; thus, it is recommended and practiced to rehabilitate old and existing pavement or assessing recycled material in the construction. The rehabilitation process impacts the environment and economy comparatively low, while the inclusion of M&R costs and impact in life cycle evaluation will enhance the sustainability aspect; moreover, most pavement projects ignore user activities, consequently, adversely affects the user's life. The key parameter such as vehicle expenditure, travelling time, and safety is the important aspects need to be considered in the life cycle of pavement projects. The vehicle utilizes fuel that affects the economy and emits harmful gasses affecting the environment, whereas the fuel consumption and emission of harmful gasses are proportional to the time of travel. Consequently, the social aspect of sustainability is affected as the life of humans depends upon pavement quality, quantity, and efficiency. Thus, adopting an integrated LCA and LCCA approach to incorporate the impact and cost of agency activities and user activities will enhance the constraints of sustainability. Moreover, in the developed framework, the carbon price was incorporated, which will assess the managerial activities to compensate for the harmful impact due to pavement projects. The proposed framework is differentiated from the previous frameworks in the literature [108,134,141,142] with respect to the inclusion of carbon price and assessing the overall impact of LCCA and LCA to enhance economic, social, and environmental factors. In the frameworks proposed previously, the impact of pavement were evaluated along with LCC but there was a lack of consideration of environmental cost such as carbon price. The integration of the carbon price enhances the framework adaptability for delivering a sustainable project.

7. Case Study

Based on the analysis of the literature, a framework was developed, where LCA and LCCA were integrated to evaluate the impact of a pavement project on sustainable constraints, where a carbon cost factor was introduced to hinder the consequences of pavement impact. To validate the developed framework a case study was conducted.

In the design and decision-making phase, the implementation of an LCA and LCCA approach is expected to define the most cost-effective and environmentally sustainable options. The introduction of an advanced pavement LCA and LCCA approach facilitates road infrastructure management, which considers all related costs and environmental mitigation costs. To assess the model, a case study performed with the integrated approach of LCA and LCCA for a newly constructed road in 2020, which consists of two lanes in each direction. The total road length was 22.5 km located in the City of Karak, which is 123 km from Peshawar on the main Indus Highway between Peshawar and Karachi, Pakistan. The road was designed based on the AASTHO standard for 20 years. Moreover, the Average Annual Daily Traffic (AADT) for the following road project was measured 2500 with an annual Transport Growth Rate (TGR) of 8.4%. A higher annual growth rate recorded was due to the impact of the Pakistan–China economic corridor on the development of the northwestern areas of Pakistan. Thus, a higher number of peoples were attracted towards investing in the linked areas with the corridor. Moreover, the functional unit consider for the following study was 1 km section length which for which LCA and LCCA was analyzed. The adaptation of the developed integrated framework for the case study is shown in Figure 4.

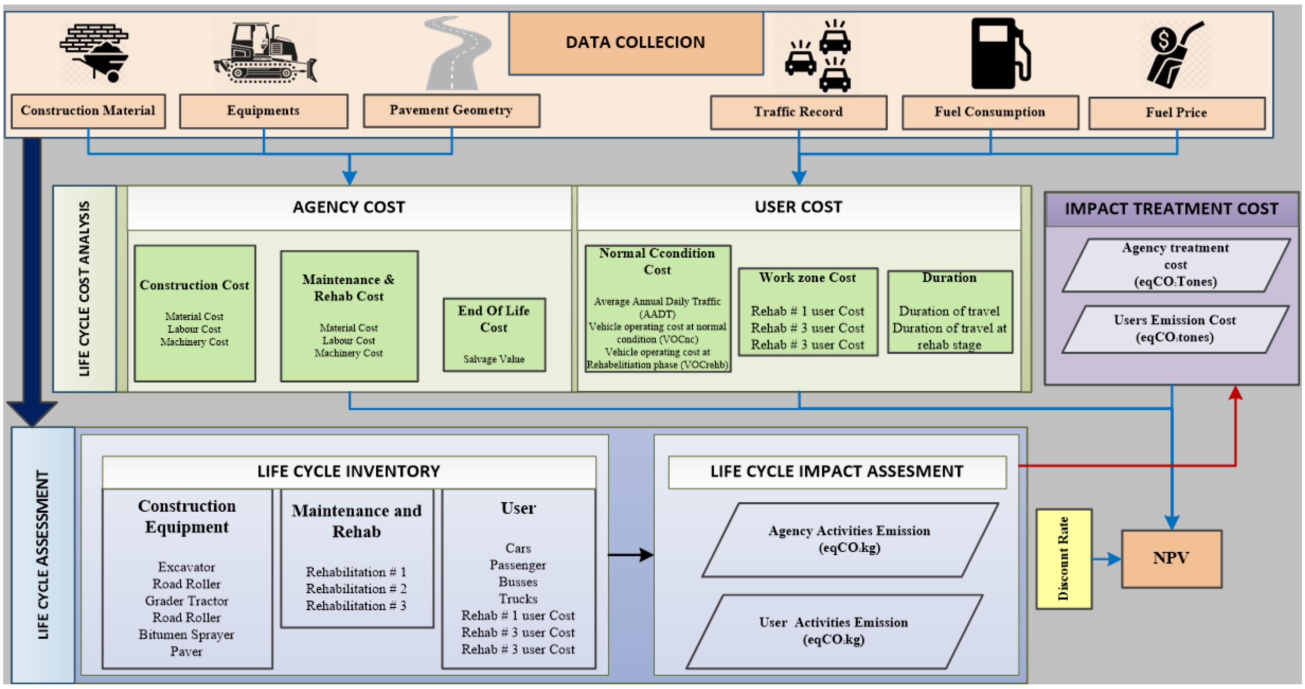

Figure 4. Case study adopting Integrated LCA and LCCA framework.

7.1. Data Collection

7.1.1. Agency Data

The important data regarding the project such as pavement geometry, construction activities, construction materials, on-site equipment used for construction, and related costs were collected from the resident engineer, local contractors, and the Communication & Work (C&W) department of Khyber Pakhtunkhwa, Pakistan [156]. The cost breakdown structure of the construction phase is shown in Table 4.

Table 4. Construction phase cost breakdown.

	Component Activities	Qty	Unit	Total Cost (USD)
1	Clearing and Grubbing by mechanical means	1829.00	m^2	185
2	Compaction of Natural Ground	1829.00	m^2	229
3	Formation of Embankment from Borrow Excavation in Common Material including compaction Modified AASHTO 90% by power roller.	1114.38	m^3	5505
4	Grooving in existing BT road of size 4 × 4 cm @ 2-m c/c.	3657.99	m^2	1167
5	Granular Subbase Course using Pit Run Gravel	278.60	m^3	2508
6	Water Bound Macadam Base Course	746.64	m^3	11,760
7	Bituminous Prime Coat	3657.99	m^2	4350
8	Asphaltic Wearing Course (Asphalt Batch Plant Hot Mixed)	186.10	m^3	21,871
9	Pavement marking in reflective thermoplastic paint with glass beads for line 15 cm width.	1999.39	m	1288
	Total			48,863

During the use phase, the pavement system faces degradation which causes moisture damages, base failure, cracking, and potholes. However, since all of the components of a pavement system cannot provide a definite period, a scheduled rehabilitation is required to sustain the pavement serviceability throughout its lifetime [10–12]. For the current project, the M&R cost was estimated from the reference project in the same area with the help of contractors and project engineers. Where, the pavement designed life was 20 years, for which M&R was scheduled after every 5 years and a fixed price was allocated initially during the design phase to treat the pavement degradation. The M&R cost seems comparatively less than the initial construction cost, as it just includes assessing and restoring delamination, cracking and potholes, as well as ensuring adequate roadway lane markings and striping. The details about the M&R are shown in Table 5.

Table 5. Maintenance and Rehabilitation cost breakdown.

Component Activity	Year	Cost (USD)
M&R # 1	5	10,000
M&R # 2	10	10,000
M&R # 3	15	10,000
Total M&R Cost		30,000

Moreover, the estimation of salvage value or End of Life Value (EOLV) of the project in Pakistan was frequently ignored. In the current case, the EOLV of the asset was calculated −5864 USD based on the ratio of end condition of the pavement multiplied by the initial construction cost using Equation (1).

$$\text{EOLVi} = \left(\frac{\text{PSIni} - 2}{4.5 - 2}\right) * \text{Ci} \tag{1}$$

where EOLVi represents the end-of-life value of alternative i, $\mathrm{PSI}_{\mathrm{ni}}$ is the Pavement Serviceability Index of alternative i at the end of life and Ci is the initial construction cost of alternative i.

7.1.2. Users Data

The cost of the users is the assessment and integration of daily user vehicle cost in normal condition along with the cost of M&R activities. Moreover, due to the M&R activities, different levels of traffic jams are likely to occur in the upstream work area based on traffic volume. To take account of transport delays, speeds of vehicles must be estimated and compared against normal traffic conditions. Whereas the road usage cost does not refer to the construction of new road projects, but rather to the road during its service phase and the repair and enhancement of existing road sections with heavy traffic volumes.

To evaluate the users' cost during normal operation, the AADT recorded 2500 with an 8.4% TGR annually, was obtained by the project engineers measured during the feasibility stage. The VOC for all type of vehicles, i.e., cars, passenger vans, passenger busses and trucks in the 1st year of the project was 497,484 USD, calculated by the distance travelled by the ADDT in the total days of the year multiplied by the unit rate of daily vehicle operating cost as shown in Table 6, using Equation (2). The VOC USD/1000 km was obtained by The National Transplant Resource Centre (NTRC) report Pakistan [157] and fuel consumption from daily fuel rates of Pakistan.

$$\mathrm{VOC} = \mathrm{TD} * \mathrm{AADT} * \mathrm{Time} * \mathrm{OC} \tag{2}$$

where TD is the distances travelled by the vehicle, AADT is the daily traffic, Time is the number of days for which the cost to be calculated and OC is the operating cost per vehicle.

Table 6. Vehicle Operating Cost during normal condition.

Vehicle Type	VOC (USD/ 1000 Km)	VOC (USD/1 Km)	AADT	Duration	VOCn (USD) (1st Year)	TGR	AADTn (20th Year)	VOCn (USD) (20th Year)
Car	317	0.317	800	365	92,629	8.4%	4015	464,869
Passenger	392	0.392	600	365	85,849	8.4%	3011	430,843
Busses	963	0.963	500	365	175,789	8.4%	2509	882,219
Trucks	654	0.654	600	365	143,218	8.4%	3011	718,760
Total		2	2500		497,484		12,547	2,496,690

Moreover, a TGR of 8.4% was observed in the AADT and calculated 12,547 AADTn for the nth years using Equation (3). Whereas the VOC for the duration of the 20 years measured was 2,496,690 USD, which show the major contribution of the users cost to the project.

$$\mathrm{AADTn} = \mathrm{AADT} * (1 + \mathrm{TGR})\hat{}\,\mathrm{n} \tag{3}$$

where AADTn is the daily traffic, n is the number of year and TGR is the travel growth rate.

Compared to the pavement normal condition, the VOC deviates from the normal condition during the M&R activities. The work zone under the maintenance activities affects the users' cost, travelling time and increases the environmental impact. Due to the insufficient data, the user cost was assumed to increase by 20% during the M&R activities. The M&R activities were scheduled after every 5 years with a maximum duration of 15 days. At first, the AADTn for work zone after 5, 10 and 15 years were calculated using Equation (3). After the VOCn for the corresponding year was measured using Equation (2), followed by adding 20% increase in the VOCn. In the last, the $\mathrm{VOC}_{\mathrm{Rehb}}$ was summed up as mentioned in Table 7.

Table 7. Vehicle Operating Cost during Maintenance and Rehabilitation.

Component Activity	Year	AADTn	VOC (USD/1 Km)	Activity Duration (Days)	VOCn	% Increase in VOC	20% Increase in VOCn (USD)	VOC_{Rehb} (USD)
Rehabilitation # 1 Work zone user cost	5	3742	2	15	112,256	20%	22,451	134,707
Rehabilitation # 2 Work zone user cost	10	5601	2	15	168,017	20%	33,603.	201,621
Rehabilitation # 3 Work zone user cost	15	8383	2	15	251,478	20%	50,296	301,774
Work zone user Cost					531,751		106,350	638,101

7.2. Life Cycle Assessment

The first phase of LCA was the identification of the Goal and scope of the project. In the current LCA of pavement only the construction phase, maintenance and rehabilitation phase, and use phase were considered for assessment. The assessment of raw material acquisition and end life are omitted due to the unavailability of appropriate data provided. In the construction phase, the impact of the pavement due to the construction activities and on-site machinery were measured. Similarly, the M&R phase was similar to the construction phase, where the impact of maintenance activities and the machines used were measured. Moreover, the use phase of LCA measures the potential impact of the usage activities such as vehicle fuel consumption and emission. In the following case study, the user impact such as energy depletion and CO_2 emissions due to on-site machinery used for construction and the vehicle and transportation were taken under consideration.

The second phase of LCA was the development of Life LCI which consists of a detailed list of input and out data flow of variables for an asset or a product. The LCI for the case study was developed from the data collection stage. The inventory list contains the potential aspect of a project as shown in Table 8, that impact the environment. The equipment utilized for the construction phase were also expected the same for the rehabilitation phase activities. Similarly, the potential sources of impact in the use phase were different type of vehicles and their emissions.

Table 8. Life-Cycle Inventory.

Construction Equipment	Fuel Type	Unit
	Construction and Rehabilitation Phase	
Excavator	Diesel	L/hr
Tandem Roller	Diesel	L/hr
Road Roller	Diesel	L/hr
Grader tractor	Diesel	L/hr
Road roller	Diesel	L/hr
Bitumen Sprayer	Diesel	L/hr
Paver	Diesel	L/hr
	Use Phase	
Car	Petrol	L/hr
Passenger	Petrol	L/hr
Busses	Petrol	L/hr
Trucks	Petrol	L/hr

The third phase of LCA was the LCIA, which aims to evaluate the potential impact on the surrounding resulting from the variables determined in the LCI. In the case study, only the fuel depletion and CO_2 emissions by the equipment in the construction, M&R phase and the vehicles in the use phase were under consideration. During the construction phase, the daily activity and duration of activity details were provided by the project engineer. The total consumption of fuel was measured as shown in Table 9, by multiplying the hours of activities, the duration in days, and the unit consumption by the machinery. During each activity, the machinery burns the fuel in the result of which the CO_2 is emitted that are harmful to the environment and human health. The burning of 1-L diesel of fuel per hours is equivalent to 2.62 kg of CO_2 [158]. The total consumption of diesel fuel was converted to the equivalent of CO_2 kg followed by converting to eq CO_2 Ton.

Table 9. Construction phase fuel consumption and CO_2 emission.

Construction Equipement	Daily Activity (Hr)	Duration (Days)	Total Hours	Unit Consumption (l/hr)	Total Consumtion (l/hr)	Eq CO_2 Kg	Eq CO_2 Tons	CO_2 Cost (USD/Ton)
Excavator	8.00	5	40	8	320	838	1	29
Tandem Roller	8.00	12	96	10	960	2515	3	88
Road Roller	8.00	10	80	10	800	2096	2	73
Grader tractor	8.00	12	96	6	576	1509	2	53
Road roller	8.00	15	120	10	1200	3144	3	110
Bitumen Sprayer	8.00	10	80	9	720	1886	2	66
Paver	8.00	8	64	12	768	2012	2	70
		Total			5344	14,001	14	490

Similarly, the LCIA for the use phase was measured in which the input from the LCI generated was evaluated with impact output. In the use phase, the vehicle and the rehabilitation phase are the potential sources of fuel consumption and CO_2 emissions. The unit price of the 1-L petrol in Pakistan was taken 0.69 USD. The total fuel consumption of the vehicles was measured by the VOC during the design period, whereas the VOC due to the work zone in rehabilitation was also highlighted being as the VOC and impact of the vehicle increase with the time delays. Then, the total amount of fuel consumption was converted to Kg where 1 litre of petrol is equal to 2.19 eq CO_2 Kg as shown in Table 10. The eq CO_2 was then converted into eq CO_2 Ton.

Table 10. Maintenance and Rehabilitation phase fuel consumption and CO_2 emission.

Component	Year	Energy Source	Total Cost (USD)	USD/L	Litre	Eq CO_2 kg	Eq CO_2 Tons	CO_2 Cost (USD/Ton)
Car	20	Petrol	464,869	0.69	673,723	1,610,198	1610	56,357
Passenger	20	Petrol	430,843	0.69	624,410	1,492,339	1492	52,232
Busses	20	Petrol	882,219	0.69	1,278,578	3,055,802	3056	106,953
Trucks	20	Petrol	718,760	0.69	1,041,681	2,489,617	2490	87,137
Rehabilitation # 1 work zone user cost	5	Petrol	134,707	0.69	195,227	466,592	467	16,331
Rehabilitation # 2 work zone user cost	10	Petrol	201,621	0.69	292,204	698,368	698	24,443
Rehabilitation # 3 work zone user cost	15	Petrol	301,774	0.69	437,354	1,045,275	1045	36,585
	Total				4,543,176	10,858,191	10,858	380,037

7.3. Life Cycle Cost Analysis of Road Project

The relative impact on the results of the study of specific LCCs variables differs between the major and the minor values. The level of detail in the LCCA relates to the level of evaluation on the investment. Little variations in potential expense impact the reduced present value slightly. Even such considerations complicate the study in no way without enhancing the outcome of the analysis tangibly. The difficulty in identifying certain costs makes it less wise, particularly if the impact on LCCA results is at best marginal as mentioned by the Federal Highway Administration (FHWA) report Walls [159]. Following the FHWA manual, certain variables are omitted to get the best marginal outcomes.

In the final stage, the equivalent uniform annual costs (EUAC) of the case study was performed as shown in Table 11, using the NPV approach using Equation (4).

$$\mathrm{EUAC} = \mathrm{NPV}\left(\frac{1(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}}}\right) \tag{4}$$

where NPV = net present value, i = discount rate, and n = years of expenditure.

Table 11. Life cycle cost analysis of road project.

Cost Component Activity	Cost	Discount Rate	Years	P/F	NPV
	(USD)	i	n		
Initial construction Cost	48,863	1	1	0.5	24,432
Construction CO_2 Cost	490	1	1	0.5	245
Rehab #1	10,000	0.7835	5	0.055416	554
Rehab #1 User Cost	134,707	0.7835	5	0.055416	7465
Rehab #2	10,000	0.6139	10	0.008341	83
Rehab #2 User Cost	201,621	0.6139	10	0.008341	1682
Rehab #3	10,000	0.481	15	0.002765	28
Rehab #2 User Cost	301,774	0.481	15	0.002765	834
User cost for normal years	1,858,589	0.3769	20	0.001667	3098
User CO_2 Emission cost	380,037	0.3769	20	0.001667	634
Salvage Value	−5864	0.3769	20	0.001667	−10
		NPV			39,045

All the cost identified were single payment cost which was discounted to NPV. The discount rate for the uniform series cost was considered identified by the FWHA report [159] against each year of the payment occurring. In the process of LCCA, the agency cost and user cost were identified. In addition, considering the carbon price to compensate for the environmental impact such as CO_2 emission cost was calculated. To implement the carbon price the "Cap-and-trade" system and carbon taxes phenomena were considered in LCCA. The carbon tax or the cap and trade are the amounts implemented by the governments on the consumers which they must pay. The carbon price is then utilized to reduce the impact of harmful emissions.

The amount Eq CO_2 kg were converted into tons for which an average cost of 35 USD per ton of emission was calculated as shown in Tables 9 and 10.

After conducting integrated LCA and LCCA for the case study, the impact and costs were evaluated for construction, M&R and use phase as shown in Figure 5.

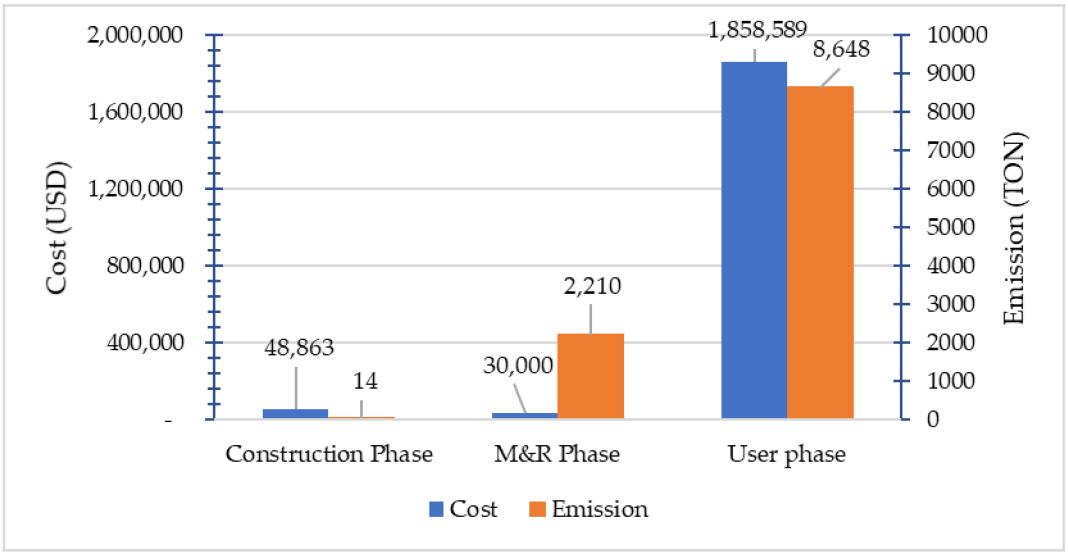

Figure 5. Associated costs and emission with different phases.

The construction phase was the least costly and having the least impact compared to the M&R phase and user phase. In the construction phase, the on-site machinery was responsible for the emission which ends with the completion of the project. In addition, the M&R phase of the project usually cost less because routine maintenance or scheduled maintenance activities are to be performed to sustain the survivability of the pavement. Moreover, the M&R phase had a higher impact compared to the construction phase. The impact of M&R was higher due to the activities during the service phase, which increases the emission and other environmental impacts. In the M&R phase, emissions of CO_2 were summed up individually to indicate a clear impact during this phase. The user phase comparatively to the construction phase and rehabilitation phase was most costly and have a higher impact. During the user phase, the vehicles are responsible for the increases in the cost and emissions, where the vehicle utilizes fossil fuel affecting the economy and discharges toxic emissions affecting the atmosphere. Moreover, during the case study, a higher traffic growth rate was recorded, where traffic growth is directly proportional to the economic growth in the area; therefore, the presented approach can be adopted by any real time project with a less or higher traffic growth rate. Additionally, the use phase of a project lasts longer than the construction phase and M&R phase, whereas the fuel consumption and emission of toxic gasses are proportional to the duration of the project. Thus with the adoption of an integrated LCA and LCCA approach to include and forecast the associated impact and costs during decision making could be very effective and enhance the project sustainability thresholds of the project.

8. Conclusions

A systematic literature review was performed on 55 articles consist of research papers, conference papers, and review papers. PRISMA methodology was adopted for the evaluation of the extracted data from four databases, namely, Scopus, Web of science, Emerald, and Science Direct. The study focuses on the influence of integrated LCA and LCCA in the enhancement of pavement designing and management strategies. Furthermore, environmental and economic developing strategies were highlighted for pavement projects, with significant interconnections in pavement planning and maintenance, including well-designed and well-maintained strategies that reduce costs and impact the entire life cycle of the project. In the extracted publication it was noticed that majority of the publication were focused on LCCA and LCA approach individually, while some of the publications were focused on the integrated LCA and LCCA. In the integrated approach, all the costs associated with a project and the impact were evaluated while the environmental cost was ignored. It has been recommended that the cost of the impact associated with the life cycle of pavements must be included throughout the life of the project which should be used to overcome the negative consequences. In support of the recommendation to incorporate the environmental cost in the integrated LCA and LCCA approach, a framework was developed. To validate the literature and the developed framework, a case study was conducted to evaluate the impact on real time project. The results of the case study indicated that the different phases of the life cycle of a project affect the economy, social life, and environment at different level. Moreover, it was evident that the user phase was the most critical phase which has higher cost and impact compared to other phases followed by the M&R phase.

The conducted case study with integrated LCA and LCC involves costs and impact related to pavement construction, maintenance and rehabilitation and user phase. For the three phases, a detailed LCA and LCA was performed with the inclusion of environmental cost such as CO_2 price, whereas the materials extraction and end life of the project are omitted. Moreover, LCA and LCCA predict the performance of the pavement project, whereas in the case study the M&R cost and schedules are assumed by the project managers. While predication the M&R, there exists uncertainties due to the inflation, materials prices deviation and availability of resources. Thus, the M&R was assumed in the current study. In future, a study should be performed to predict the actual M&R phase, including material extraction and end life of the project to assess the impact and related cost including environmental cost.

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Abbreviations

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transport Officials
ACP	Asphalt Concrete Pavement
ASCE	American Society of Civil Engineering
Ci	Initial Construction Cost
C&W	Communication & Work
CO2	Carbon Dioxide
DA	Dense Asphalt
EIE	Environmental Impact Evaluation
EOLV	End of Life Value
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
GDP	Gross Domestic Product
GHG	Green House Gasses
GWP	Global Warming Potential
HMAR	Hot Mix Asphalt with Reclaimed
HMAW	Hot Mix Asphalt with an additive Warm mix
IRI	International roughness Index
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCO	Life Cycle Optimization
ISO	International Organization for Standardization
M&R	Maintenance and Rehabilitation
MMCN	Multi-Commodity Cost Network
NPV	Net Present Value
OC	Operating Cost
PA	Permeable Asphalt
PCC	Plain Cement Concrete
sss	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PSI	Pavement Serviceability Index
RAP	Recycled Asphalt pavement
RAS	Recycled Asphalt Shingle
SLR	Systematic Literature Review
RCA-PCC	Recycled Concrete Aggregate mixed with Plain Cement Concrete
SPA-LCA	Service and Performance Adjusted LCA
TD	Travel Distance
TGR	Transport Growth Rate
VOC	Vehicle Operating Cost

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