SUSTAINABILITY ASSESSMENT OF ROAD INFRASTRUCTURES PROJECTS: A COMPLETE LIFECYCLE INTEGRATED APPROACH

A thesis submitted in partial fulfillment of

The requirements for the degree of

Masters of Science

in

Construction Engineering and Management

by

Husnain Arshad

(NUST201463343MSCEE15414F)

Department of Construction Engineering and Management

National Institute of Transportation (NIT)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan.

May, 2018

This is to certify that the

Thesis titled

SUSTAINABILITY ASSESSMENT OF ROAD INFRASTRUCTURES PROJECTS: A COMPLETE LIFECYCLE INTEGRATED APPROACH

Submitted by

Husnain Arshad

(NUST201463343MSCEE15414F)

has been accepted towards the partial fulfillment
of the requirements for the degree of
Masters of Science in Construction Engineering and Management

---

Dr. M. Jamaluddin Thaheem

Supervisor,

Department of Construction Engineering and Management,
NIT, SCEE,
NUST, Islamabad

Dedication

*I dedicate this thesis to **my parents** and respected teachers!*

Acknowledgement

I am highly grateful to Almighty ALLAH, The Omnipotent, The Most Gracious and Beneficial Who made me worthy to complete this research work. All my efforts were impossible without support of my parents whose unconditional love, prayers, encouragement and patience remained a source of dedication for me.

I would like to pay debt of gratitude to my advisor Dr. Muhammad Jamaluddin Thaheem, for his profound guidance, and encouragement, to complete this research work. He continually and convincingly conveyed a spirit of adventure in regard to research. Without his guidance and persistent help this dissertation would not have been possible. I am also grateful to the committee members, Dr. Abdul Waheed and Dr. Arshad Hussain for their guidance and encouragement.

I would like to acknowledge all the government officers, industry experts and academic peers for their valuable time in responding to interviews and sharing their opinions, which proved highly important in formation of this research.

Husnain

Abstract

In a national context, economic growth, social well-being and infrastructure development have a strong relationship. This complex relationship is at the core of a nation's development which also includes communication infrastructure. An ill-conceived road infrastructure project may potentially influence the socio-economic development. This enhances the need for a comprehensive assessment and evaluation tool for road infrastructure projects, covering a range of decision criteria to incorporate social and environmental concerns along with financial. Sustainable development encompasses all the criteria which lead the assessment in favor of social well-being. Thus, a Lifecycle Sustainability Assessment (LCSA) based holistic approach is devised for evaluation as well as prioritization of road infrastructure projects. The approach is operationalized in the form of a methodological assessment framework, a model to integrate all the facets of sustainability and a threshold based decision-making framework. A detailed literature review is carried out to identify and configure the methodological attributes of LCSA in the form of a methodological framework. Multifaceted interviews of experienced professionals, senior government decision makers and academic researchers are conducted for pairwise comparison of impact categories and their subjective reasoning. Based on this information, rationalization behind opinions is noted, minimum level of compromise on any impact is assessed and Analytical hierarchy process (AHP) based LCSA integration model is developed. Threshold limits of impact categories are evaluated using statistical analysis and a complete feedback driven decision-making framework is developed and demonstrated through a large-scale case study. The implications of this research are in the form of a comprehensive decision support tool which ensures holistic sustainability in road infrastructure projects.

Table of Contents

List of Figures

List of Tables

Chapter 1

Intorduction

1.1 Background

Infrastructure development plays a crucial role in vitalizing the economy of a country and serve as a building block of a functional society. Physical infrastructure such as road sector provides vital communication links for better local and regional connectivity. Not only it adds directly to the economic prosperity of a country, also indirectly contributes to the functionality of all other types of infrastructure. High-income economies have a well-developed road infrastructure as compared to low income economies (Francois and Manchin, 2013). Infrastructure development has a two-way relationship with GDP or economic growth. One, infrastructure promotes economy, and two, growth in GDP brings about changes in infrastructure which subsequently contributes to economic growth of any country (Grimsey and Lewis, 2007). As an essential foundation for achieving inclusive growth, sustainable infrastructure underpins all economic activity. However, infrastructure is critical to sustainable community development, future well-being and the day-to-day lives of individuals (Roseland, 2000).

Governments are to provide services to the people but they can't always deliver them at cost of their own revenues. Due to limited budgetary resources most of the infrastructure projects are based on heavy loans from the international funding agencies, like IMF, World Bank and ADB, on expensive interest rates (Khang and Moe, 2008). Such infrastructure projects won't be feasible if they are not bringing the socio-economic benefits resulting in economic development (Kallis et al., 2012). A redundant project, which is not bringing any change in the living standards of the people, could not raise their purchasing power and ultimately there would be lesser tax revenues for the government (Grimsey and Lewis, 2007). Such unsustainable infrastructure project would ultimately put burden on the government to pay back the loans, which cause circular depreciation of government revenues. In such way, loan based infrastructure development policy would be ultimate failure.

The infrastructure being built today will shape tomorrow's communities. It has been estimated that till the year 2025, the annual investment in the infrastructure development will reach up to $9 trillion (Economics, 2014). But it is not just a matter of building more. To achieve effective development on a planet stressed by climate change, diminishing natural resources and hindered social development, infrastructure needs to be sustainable. Such a sustainable infrastructure would enhance the quality of life for citizens, increase positive impacts (benefits), help protect the vital natural resources and environment, and promote a more effective and efficient use of financial resources.

In the wake of the global human-environment crises, in light of sustainable development needs, a futuristically responsible mindset is required towards consumption of resources (Finn, 2009). Sustainable road transportation means to efficiently satisfy the natural and reasonable mobility demands of a society to the utmost extent at the least possible social, economic, environmental, and resource cost while realizing harmonious development with other social and economic sectors (Hu et al., 2010). The existing literature establishes a foundational framework for quantifying the environmental impacts, but fails to deliver global conclusions regarding materials choices, maintenance strategies, design life, and other best practice policies for achieving sustainability goals (Santero et al., 2011b).

Decision-making in this situation is unique because the survival of the entire human and animal populace is at stake. When the number of stakeholders in a particular situation are so high, the interpretation of sustainability problem and developing solutions for the same comes with its own complexities and boundaries (Perdan and Azapagic, 2011). The interpretations vary according to stakeholder roles, participation, interests and understanding (Kates et al., 2001).

Thus, the assessment of sustainability requires development of efficient and reliable tools using an interpretation inclusive of environmental and social considerations (Ness et al., 2007). Responding to this demand, researchers and organizational decision makers are putting in considerable effort in developing sustainable solutions for problems at a global level. This has driven a particular interest in deepening the understanding of the human-environment interface and enhancing its resilience (Sachs, 2015). Thus, a collaborative effort has been expended from multiple fields in analyzing the considerations for sustainability integration in decision-making. Resultantly, the concept of sustainability assessment with incorporation of life cycle thinking was generated (Azapagic, 2002).

The complexity of decision-making increases with the project scope. Large-infrastructure construction projects are not only highly vulnerable to delays and project failure internally but also involve high values of externalities. For example, if the impacts of roadway construction, operation, and maintenance were added to the operational energy use and greenhouse gas (GHG) emissions of on-road vehicles, these environmental impacts would be roughly 10% higher than what one would estimate based on vehicle operations alone (Chester and Horvath, 2009). Such considerations are often ignored during the planning stage of the projects. This makes the projects highly susceptible to uncertainties, as it advances on the life cycle. Moreover, the project impacts also vary with time, early mitigation of which involves high level of sophistication at project feasibility level. The main challenge in the assessment of project with life cycle approach is the subjectivity of interpretation and expression of qualitative criteria in objective measures suitable for assessment. Therefore, for effectively guiding the sustainability efforts and quantifying the project sustainability footprints, it is imperative to readdress the functional units, systems boundaries, data quality and reliability, and study scope, whose knowledge base is provided by sustainability domain of research (Hoogmartens et al., 2014).

1.2 Problem Statement

Following this line of argument, sustainability assessment methodology needs to be integrated with the existing feasibility assessment at the project alternate evaluation and project prioritization. Such an integration not only involves rationalization of a methodological framework for decision-makers, but also help develop the sector-specific decision-making framework for project evaluation. The existing relevant body of knowledge has not given sufficient coverage to this particular research need.

For the purpose of this study, the target application area is chosen to be highway sector with particular focus on large-scale freeway/motorway projects of particular interest to national economy. The choice is based on the fact that the research has only scarcely considered the sustainability assessment of road infrastructure projects with holistic considerations.

Therefore, the current study identifies the factors affecting the useful life of road infrastructure throughout its life from production and construction to end of Life (EOL), incorporating factors from all categories of sustainability to develop a decision-making framework for project selection. The developed framework attempts a post-analysis integration of the triple bottom line (TBL) pillars of sustainability involving life cycle assessment (LCA), social lifecycle assessment (S-LCA) and life cycle costing (LCC), providing a detailed insight to decision makers of all the high impacting inventory materials and processes, and corresponding damages during all the phases of a road project's life.

1.3 Research Objectives

i. To develop a methodological framework for the road infrastructure Lifecycle Sustainability Assessment (LCSA).

ii. To develop the integrated LCSA model for road infrastructure.

iii. To develop project comparison and project prioritization decision-making framework for road infrastructure.

1.4 Research Significance

Transportation is an important sector of Pakistan's economy, making up to 10% of the GDP and over 17% of Gross Capital Formation. Pakistan has a vast road network having total 263,942 km of roads and 0.33 km/sq of road density (Govt of Pakistan, 2014). Pakistan Vision 2025 plan is committed to raise the road density to 0.45 km/sq, increasing length of roads to 358,000 km (Govt of Pakistan, 2015). China Pakistan Economic Corridor (CPEC) has $12 billion allocation for projects pertaining to basic infrastructure and is mainly in the fields of roads, rail network, ports, airports and data connectivity (Hameed, 2015).

An efficient and sustainable transport system is a prerequisite for any country to become globally competitive while increasing service levels and decreasing costs. The road network in Pakistan carries over 96% of inland freight and 92% of passenger traffic and is undoubtedly the backbone of the economy (Govt of Pakistan, 2014). Pakistan's future infrastructure development plans in Pakistan Vision 2025 and CPEC persist the huge potential and scope for transportation sector which enables the need to review and reassess the basic framework of sustainability assessment for infrastructure projects. The Pakistan Vision 2025 not only commits to apprehend the sustainable development goals (SDGs) but also the government has already signed a number of regional and global commitments in 2013 and 2014 to achieve environmental protection goals (Govt of Pakistan, 2014).

Transportation sector of Pakistan consumes 35% of the total energy annually and is the recipient of substantial portion of the annual federal public-sector development program (NHA, 2009). This huge amount of energy makes it crucial for sustainability concerns. For achieving SDGs for a country, selection, assessment and development of sustainable alternatives are the need of the day. But since the existing tools present their inherent constraints, it is opportune to integrate the competencies offered by these tools and mitigate their limitations. In this regard, the development goals of Pakistan may benefit from the proposed research in the form of a refined decision-making framework for guiding future project development process.

This framework for sustainability assessment presented by the present study will help decision makers to make optimum decisions based on holistic sustainability concerns. Moreover, the research will also provide an insight to researchers and industry professionals regarding the environmental and social externalities and their quantitative interpretation throughout the life of the road from materials production to the end of life of the facility/ road.

Chapter 2

Literature Review

2.1 Sustainability Assessment

Current generations need to maintain and improve the earth resources for the future generations (Finn, 2009). Sustainable development was recognized in Brundtland (1987) report as the development that fulfills the essentials for the people without affecting the resources enough to harm the future generations, expanding its scope to the environmentally and socially sustainable economic growth (Sachs, 2015). Different stakeholders define sustainability differently because of their roles, participation, interests and understanding (Kates et al., 2001). The analysis of sustainability is a mutual research effort of environmental sciences, economics, social and development studies (Kasemir, 2003). Therefore, the assessment of sustainability has its own challenges and boundaries (Perdan and Azapagic, 2011), posing an important challenge for the researchers and concerned organizations in providing efficient and reliable tools of sustainability assessment (Ness et al., 2007). Moreover, for enhancing the interface of environmental impacts and human activities, researchers integrated the approach of life cycle thinking (Azapagic, 2002), which led to the introduction of the Life Cycle Sustainability Assessment (LCSA).

LCSA provides a broadened and clear picture (Guinée, 2016) based on the TBL of three sustainability pillars; social, environmental and economic (Ciroth et al., 2011; Vinodh et al., 2012). LCSA supports the tradeoff of TBL of sustainability for impacts at all life cycle stages of products and generations (UNEP, 2012). Thus providing an effective guidance to policy-makers regarding sustainable development (Heijungs et al., 2010). In the realm of LCSA, integration of life cycle thinking approach with the facets of sustainability provides three sustainability assessment approaches; economic life cycle costing (LCC), environmental life cycle assessment (E-LCA) and social life cycle assessment (S-LCA) (Ciroth et al., 2011).

The literature lacks the total sustainability assessment of road infrastructure which incorporates all three dimensions of sustainability. Most published research is related to the environmental concerns, for example, (White et al., 2010) and Huang et al. (2009).

2.2 Environmental Life Cycle Assessment (E-LCA)

E-LCA is used as a management tool for quantifying the environmental consumption and its substantial impacts across the life cycle (Lindfors, 1995). The application of E-LCA is not limited to the industry for assessment of designs and process optimization, but research and public policy also employ it for identification and measurement of impacts for exploration and improvements in environmentally sustainable options (Azapagic, 2010). E-LCA defines the structural pathways between economic and environmental issues of a product through a chain analysis (de Haes and Heijungs, 2007). E-LCA explores the system's inputs and outputs to investigate the environmental concerns due to an activity, process, service or product (Baumann and Tillman, 2004). Ideally, E-LCA proposes to include all the processes linked with a product from cradle to grave. Thus, its results provide necessary information for decision-making related to product's eco-efficient design, development, enhancement of the production system and selection of product at user-level (Ness et al., 2007). For substantial improvement in the environmental impacts, a comparative analysis approach between different products and services is recommended (Niekamp et al., 2015).

E-LCA methodological development occurred in the early 90s and now is considered as a tool of environmental management in policy and business decision-making (Guinee et al., 2010). In the development of E-LCA terminologies, framework and methodology, SETAC performed a significant role and published the "Code of Practice" for E-LCA (Swarr et al., 2011). Since

1994, International Organization for Standardization (ISO) is also involved in standardization of methods and procedures for sustainability assessment.

2.2.1 E-LCA Methodology

ISO issued ISO 14040–Principles and Framework, and ISO 14044–Requirements and Guidelines. The methodology is considered as standard and is being widely used. ISO 14040 methodological framework presents four systematic steps: goal and scope, life cycle inventory, impact assessment and results' interpretation (Finkbeiner et al., 2006), as illustrated in Figure 2-1 ISO 14040 LCA steps and framework.

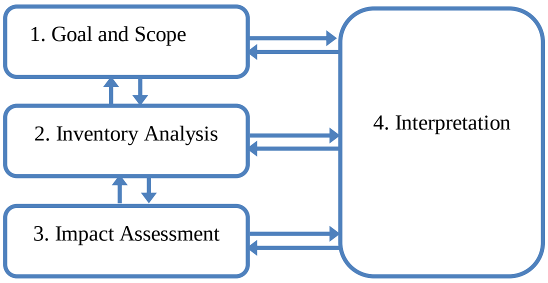


Figure 2-1 ISO 14040 LCA steps and framework

The first step of LCA strongly influences the results (Mithraratne et al., 2007). In this step, the purpose and intended use of study are established through the delineation of the system boundaries of study, selection of functional unit, setting the quality of data required and identifying the assumptions and limits of the study. In the second step, input and output of a process are quantified. For example, energy, materials and chemicals getting into the system and CO_2, SO_2, NO_X, getting out of the system are examined (ISO, 2006). For this purpose, work breakdown structure of the process is established as per the product system specifications and construction plans (Li et al., 2010).

In the third step, impact categories are formed by assembling the system output emissions and other environmental indicators. I the impact assessment phase, ISO (2006) recommends two steps, classification, and characterization. The classification is based on the accumulation of environmental burdens which are emissions and resource consumption, different categories of environmental impacts are formed (Menoufi, 2011). The process of quantitative allocation of the burdens and resources to the impact categories is characterization. A characterization model quantifies the potential contribution from each inventory emission to the environmental impacts by computing the substance-specific characterization factors. Further, category indicator in a common unit for all contributions are obtained by multiplying these characterization factors with inventory data (Hauschild et al., 2013), for example, CO_2 eq./kg for gaseous emissions. A number of impact assessment and characterization methods exist which vary in modeling approaches, impact indicators, variety of substances and spatial diversity of data (Pant et al., 2010). Menoufi (2011) has presented a detailed review of the life cycle impact assessment (LCIA) approaches; midpoint, endpoint, hybrid and other specific.

Midpoint LCIA approaches are problem-oriented and present the results as primary environmental changes in natural environmental aspects and contribute to different environmental issues such as ozone depletion and GWP. Example methods are CML and EDIP methods (Jolliet et al., 2004). Similarly, endpoint LCIA approaches are damage oriented and present the result as damages to the area of protection such as ecosystems, human health and resources. Example methods are Eco-indicator 99 and EPS (Bare et al., 2000). Combination of these two approaches is the hybrid approach, examples of such methods are Impact 2002+, RECIPE and LIME (Heijungs et al., 2003a; Jolliet et al., 2004). The methods such as cumulative energy demand, cumulative exergy demand, ecological footprint, etc. are kept in the 'others' group by Menoufi (2011).

2.2.2 A review of E-LCA of roads

E-LCA in roads was first performed in the 1990's and since then a substantial research has been reported. E-LCA of road infrastructure can be performed for a road component, complete road section, or a complete road project (H Stripple and Erlandsson, 2004). LCA studies related to single road component are in abundance (Butt, 2014). But, the studies related to road E-LCA at the complete project level are extremely limited and overly generic (Jonsson, 2007; Schlaupitz and Naturvernforbund, 2008). It is primarily because more intricacies arise to address the relevant complexities at every level of decision.

In the component-wise studies, most of the past research is focused on asphalt and concrete pavement comparison for example studies of Yu and Lu (2012), Athena (2006), Park et al. (2003) and Hakan Stripple (2001) were for the comparisons of the emissions for the asphalt pavements and concrete pavements. Evangelista and De Brito (2007) and, Loijos (2011) specifically focused on concrete pavements. Whereas, studies of Huang et al. (2009), Vidal et al. (2013) and Butt (2014) were for the environmental emissions of asphalt roads. However, there can be a more diverse application of LCA in the field of roads (Santero et al., 2011b).

A number of studies have been conducted which reviewed the pavement LCA related studies. Muench (2010) discussed the environmental sustainability of road construction and Said et al. (2012) summarized the environmental impacts of road construction and maintenance phases. The study of Carlson (2011) summarizes that the past road LCA studies are difficult to compare because of their varying goal and focus, scope and system boundaries and functional units. Similarly, extensive reviews of the past studies by Santero et al. (2011b) and Santero et al. (2011a) conclude that outcomes of the various pavement LCA studies vary due to use of different pavement design model for LCA studies.

Recent LCA studies have focused on individual road elements or processes. For example, Cass and Mukherjee (2011), and Chowdhury et al. (2010) primarily focused on road pavement layers and surface material selection. Similarly, Birgisdóttir and Christensen (2005) focused on the material recycling, Cass and Mukherjee (2011) focused on the impacts of construction machinery manufacturing and Capony et al. (2013) focused on earthworks in road construction.

A recent comprehensive study by Hammervold (2015) examined two Norwegian highway projects and compared altogether 52 separate road element cases.

In light of these studies, it can be concluded that the literature lacks studies related to the road LCA at the project level. Thus, for sake of exploring the road LCA methodological attributes, following discussion is carried out on LCA methodological attributes; functional unit, system boundaries and impact categories, and synthesized in **Error! Reference source not found.**.

2.2.2.1 Functional Unit

In road LCA, the most crucial issue is the consensus upon a suitable functional unit (Santero et al., 2011b). In past, a number of studies utilized only traffic as a functional unit, for example, Hakan Stripple (2001) used 5000 AADT for analysis period of 40 years and Huang et al. (2009) used 26,000 AADT as a functional unit. Other examples of such studies are Treloar et al. (2004), Athena (2006) and O'Born et al. (2016). But in contrast, there are few studies which applied the length of road as a functional unit, for example Horvath and Hendrickson (1998) and Reza et al. (2014) used a typical two-lane roadway, and Parajuli et al. (2011) and Capony et al. (2013) utilized per Km of road as a functional unit. Main factors for the selection of functional units are goal and scope of study along with spatial features, and local design codes and practices (Santero et al., 2011b). Thus, it can be observed that the studies where functional unit is focusing only traffic, results are at the level of material performance comparison or for the design evaluations, whereas, results of studies which included the length of road in their functional units are depicting a comparison at the project level. In the analysis of road LCA, the input data is related to the physical characteristics such as length, width and thickness. Thus, a section of road per unit length is the simplest and the most representative functional unit (Hakan Stripple, 2001).

2.2.2.2 System Boundaries

The complex web of environmental outcomes cannot be explicitly associated with a single stage of product life (Menoufi, 2011). The system boundary of any life cycle methodology is supposed to incorporate whole of the life, from cradle to grave, and includes both direct and indirect impacts. But, to model accurately and achieve goals effectively, issues like proper understanding of the system and data access constraints in incorporating all life cycle phases must be addressed. A review of the life cycle phases considered in existing road LCA studies is presented in **Error! Reference source not found.** which shows that the most of the existing s tudies have failed to incorporate true cradle to grave approach, except Park et al. (2003) who included all the life cycle phases in their study. The absence of any phase from the E-LCA framework can cause uncertainty in results (Santero et al., 2011a). Park et al. (2003) reported that the extraction phase of construction materials consumes maximum energy, using 1525.8 tons of oil equivalents per 1 km of four-lane highways, while, construction and demolition phases are more energy intensive than the maintenance phase. Moreover, the use phase is also an influential phase of lifecycle due to traffic fuel consumption, concrete carbonation, urban heat island effect and radiations (Li et al., 2010). Thus, the omission of any life cycle phase can interduce a serious discrepancy in LCA results.

2.2.2.3 Impact Assessment

The environmental impacts of roads can be analyzed through a variety of impact categories (Santero et al., 2011b). The review of past road LCA studies, presented in **Error! Reference s ource not found.**, reveal that a variety of impact categories has been used for LCA in existing studies. Also, in past studies, there is no set standard or pattern for selection of impact categories with respect to the focused area of study or objective of performing LCA. However, air emissions and energy are the widely considered impacts in past road studies. The consideration of impacts like water consumption, consumption of raw materials and resource depletion is also relatively low in past studies (Capony et al., 2013; ECRPD, 2009; Horvath and Hendrickson, 1998; Mroueh, 2000; Schenck, 2000). There are very few studies which considered the water emissions or eutrophication impact (Capony et al., 2013; Mroueh, 2000; Schenck, 2000), and hazardous solid emissions (Reza et al., 2014; Schenck, 2000). Also, it is significant to note that almost all the studies have utilized the midpoint impact categories approach.

Table 2-1 A synthesis of lifecycle phases and impact categories in road LCA studies

Sr. No	Life Cycle Phases						
	Author	Materials	Construction	Use	Maintenance	EOL	**Impacts considered**
1	Häkkinen and Mäkelä (1996)	✓	✓	✓	✓		Emission in air, raw materials, noise, energy.
2	Horvath and Hendrickson (1998)	✓					Emission in air, raw materials, water use, water releases, hazardous waste, energy
3	Mroueh (2000)	✓	✓	✓	✓		Energy, emissions in air, raw materials, water use, leaching, noise
4	(Schenck, 2000)	✓	✓	✓		✓	GWP, Ozone Depletion, Acidification, Eutrophication, Smog, carcinogenic, non-carcinogenic, Resource Depletion
5	(Hakan Stripple, 2001)	✓	✓		✓		Energy, emission in air, raw materials
6	(Park et al., 2003)	✓	✓		✓	✓	Energy, emission in air
7	(Treloar et al., 2004)	✓			✓		Energy
8	(Zapata and Gambatese, 2005)	✓	✓		✓		Energy
9	(Athena, 2006)	✓	✓		✓		Energy and emission in air
10	(Chan, 2007)	✓	✓		✓		GHG, emission in air, energy, VOC and carcinogens
11	(Muga et al., 2009)	✓	✓		✓		Emission in air, VOC, GWP
12	(Huang et al., 2009)	✓	✓				Energy, emission in air
13	(ECRPD, 2009)	✓	✓		✓	✓	Energy, raw materials, emission in air
14	(White et al., 2010)	✓					GWP
15	(Parajuli et al., 2011)	✓	✓	✓	✓		Emission in air, energy
16	(Yu and Lu, 2012)	✓	✓		✓	✓	Emission in air, energy
17	(Butt, 2014)	✓	✓		✓	✓	Emission in air, energy
18	(Vidal et al., 2013)	✓	✓		✓	✓	Emission in air, energy
19	(Capony et al., 2013)	✓	✓	✓	✓		raw material, energy, GWP, eutrophication
20	(Reza et al., 2014)	✓	✓	✓	✓		Emission in air, Particulates, VOC compounds, Arsenic, Cadmium, Cyanide, Lead, Mercury, Oils
21	(O'Born et al., 2016)	✓	✓	✓		✓	Cumulative energy demand, GHGs

In light of a variety of road LCA studies conducted globally, it can be concluded that substantial amount of knowledge base particular to pavement design and evaluation has been developed. However, no substantial study is reported whose results could be interpreted for supporting the decision-making at project comparison level. Thus, there is a dire need to develop such support framework for the projects comparison and prioritization at the organizational level.

2.3 Social Life Cycle Assessment (S-LCA)

Social Life Cycle Assessment (S-LCA) evaluates the potential negative and positive social impacts associated with a product or system, throughout its lifespan (UNEP, 2009). S-LCA has been established in complementary to environmental LCA for comprehensive sustainability assessment of products or system (Finkbeiner et al., 2010). S-LCA methodological development is still in progress (Sala et al., 2015). However, UNEP/SETAC life cycle initiative issued the S-LCA guidelines (UNEP, 2009) and methodological sheets (Benoît-Norris et al., 2011).

These guidelines inherited the four-phase E-LCA framework of ISO (2006) and recommended to use the same for S-LCA (Sala et al., 2015). S-LCA guidelines presented the social impact categories, identified the stakeholders to be considered and also presented the impacts sub-categories for each stakeholder (Benoît et al., 2010). They suggested considering six main social impact categories: health and safety, working conditions, human rights, cultural heritage, governance, and socioeconomic repercussions. These impact categories are recommended to be assessed over the stakeholders: workers, local community, society, consumers and value chain actors. The methodological sheets presented by UNEP/ SETAC provided the data collection approach and detailed inventory for assessment of impacts sub-categories. Since their publication, the most widely used impact categories and sub-categories are those provided by these guidelines (Di Cesare et al., 2016; Mattioda et al., 2015; Petti et al., 2014).

However, the guidelines and methodological sheets did not provide any impacts pathways and characterization model, rather recommended a linear aggregation of the impacts for S-LCA results' interpretation, till the development of impact assessment methodology (UNEP, 2012). For impact assessment and aggregation, two types of methodological approaches, performance reference point and impact pathways, are reviewed by Chhipi-Shrestha et al. (2015). Reference points are established on the basis of minimum performance levels of indicators agreed by some organization or standards such as OECD guidelines and International Labor Organization (ILO) conventions (Parent et al., 2010). The method of impact pathways considers the cause-effect relationship between the impact categories and sub-categories and utilizes the midpoint or endpoint indicator approach (Parent et al., 2010).

2.3.1 A review of S-LCA

For this review, 172 articles were considered after a thorough screening. Majority of these articles were published in reputable scientific outlets such as *The International Journal of Life Cycle Assessment* (72), *Journal of Cleaner Production* (12), *Sustainability* (11) and *Social LCA in progress, the 4th International Seminar's proceedings* (12). Rest of 65 articles were from the 51 different journals and conference proceedings.

The content analysis of articles for identification of their areas of applications was performed which reveals that 49% of them are not specific to any industry but are focused on either methodology in general or have largely developed framework or model related to the impact categories and indicators. The application of S-LCA is found in a variety of disciplines and industries ranging from manufacturing to construction and agriculture to energy, as shown in Figure 2-2. Most of the application of S-LCA is observed in the agriculture and food industry (20%), followed by product and manufacturing industry (12%), water supply and waste management (10%), biofuel (10%), construction industry (9%) and energy and electricity (8%). Mining and metallurgy, process industries and supply chain, and electronics have less than 5%

of studies related to S-LCA. The 'others' category is comprised of 20% of total S-LCA studies; application areas in this category are chemical and fertilizer, tourism, fisheries, urban and regional planning, etc., each having less than 3% studies.

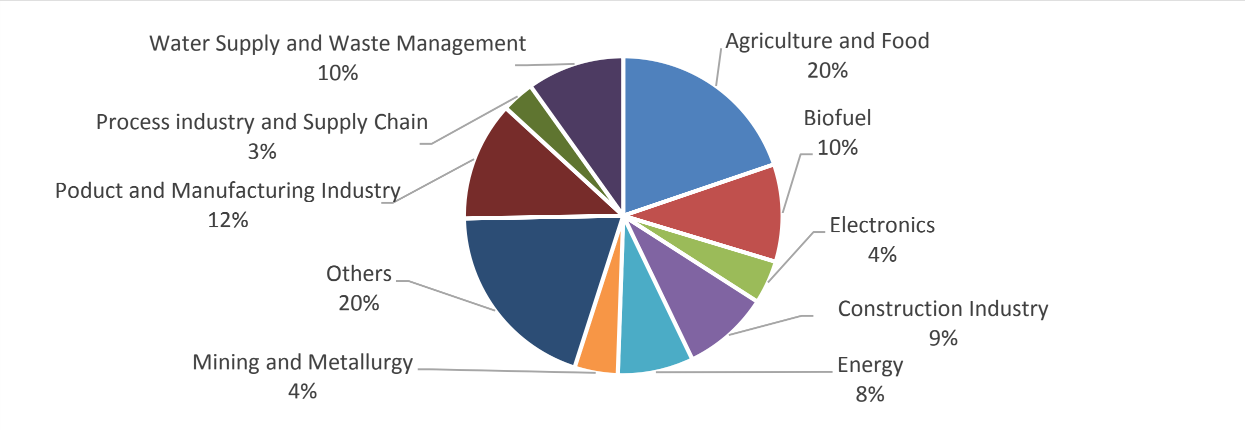


Figure 2-2 Application areas – Mix

S-LCA is relatively a new area of sustainability but significant research has been conducted on it in the last decade, which is evident from the rapidly developing research progression. The evolution over time shows that the rapid increase occurred in relevant studies after the year 2012, which is substantiated by the publication of UNEP / SETAC guidelines in 2011 (Benoît et al., 2010). Total 86 studies were found which have performed case studies, out of which, 44% demonstrate newly developed model or framework, whereas remaining 56% case studies are related to the application of S-LCA for some specific industry, product or process using the existing methodology, models or frameworks.

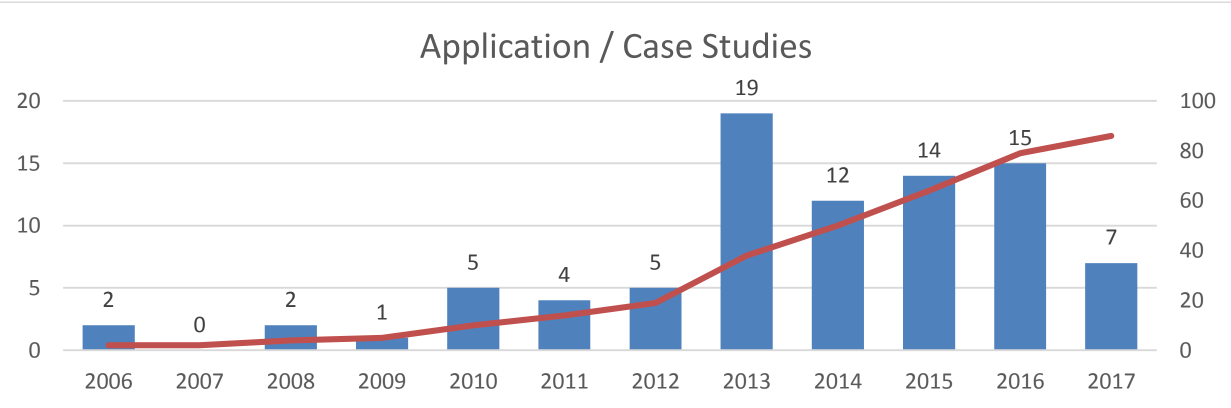


Figure 2-3 S-LCA case studies – Time Series

Most of such case studies are following the UNEP / SETAC guidelines and methodological sheets as their adopted research methodology (Gautam, 2011; Nemarumane and Mbohwa, 2013; Ochoa et al., 2014). Analyzing the case studies on time series, it is found that more than 82% of total case studies were published after the year 2010, which signifies the substantial methodological development till that time, and marks this year as a breakthrough for S-LCA progression in the form of publication of UNEP /SETAC guidelines and methodological sheets (Benoît et al., 2010).

2.4 Life Cycle Costing (LCC)

LCC techniques are mainly applied for decision-making in choosing an economically viable alternative to an investment or product. LCC has wide application in almost every walk of life for decision-making. Government or public institutes perform LCC for decision-making related to procurement of services or projects, to forecast profits and to assess cost and quality tradeoffs (Boshoff et al., 2009).

LCC methodology is intricate and time intensive (Asiedu and Gu, 1998). To address this, a variety of standards and guidelines are developed which support its application, such as, “NS 3454 Lifecycle cost for building and civil engineering work – principles and classification”, “Task Group 4: Lifecycle costs in construction”, “The Green Book by HM Treasury, UK”, “Procurement guide 07: Whole-life costing and cost management” and “ISO 15686:5 (2008) Building and constructed assets – service life planning”. Davis Langdon (2007) has provided a detailed review of these LCC standards and guidelines.

For the selection of road design or evaluation of alternatives, LCC is considered as the main assessment factor (Adams and Kang, 2006; Stenbeck, 2004). It is critically important to evaluate alternatives, due to unavailability of consistent and reliable data and assessment approaches pertinent to roads (Karim, 2008). The lack of methodical approaches for data collection and such continuation in all the life cycle phases cause the failure in investment decisions. Thus, to enhance the objectivity, all the life cycle phases such as design, materials, equipment, operation and maintenance should be considered in the economic assessment of road (Babashamsi et al., 2016). In such a way, an improved investment decision-making can be established by assessing the required funding and evaluating the needful resources allocation between other projects, hence prioritizing the right project (Walls III and Smith, 1998b).

A number of indicators are used for the economic evaluation of construction projects. Out of these, Net Present Value (NPV), Internal rate of return (IRR), Equivalent uniform annual cost (EUAC) and Cost-benefit analysis (CB) are most common (Davis Langdon, 2007). Selection of indicators for the economic assessment depends upon the context of analysis and decision-making level (Babashamsi et al., 2016). Developing countries prefer the IRR due to a high uncertainty of discount rate (K. Ozbay, 2003). However, in literature majority of the financial models related to the construction projects have employed the NPV approach (Davis Langdon, 2007). Also, for financial assessment of roads, NPV is the most common and widely used indicator (Babashamsi et al., 2016; Krutzfeldt, 2012; Walls III and Smith, 1998a; Wolthuis, 2014; Zimmerman et al., 2000). NPV is preferably employed where the comparison of different alternatives and choices is required and options have varying analysis periods (Wolthuis, 2014). The key features and differences between NPV and IRR were highlighted by Agnes Cheng et al. (1994) as:

i. The accounting of present values of all the positive cash benefits and negative expenditures is NPV, whereas, IRR is the discount rate at which value of NPV is zero.
ii. NPV is resulted in absolute terms, as compared to IRR.
iii. NPV determines the surplus amount at the end of project and IRR signifies the no profit no loss project statement.

iv. In NPV, reinvestment of intermediate cash flows is made at cost of capital rate and in case of IRR reinvestment is made at the rate of IRR.
v. Variation in the cash outflow timings would not affect NPV, however in case of IRR result will be negative or multiple IRR.
vi. NPV results will be higher when the initial capital investment is large, whereas IRR strictly focuses the project profitability.
vii. NPV helps in decision making, whereas IRR can make decision-making crucial due to its multiplicity behavior in different scenarios of capital costs and discount rates.

The above comparison clearly establishes the superiority of NPV over the IRR, particularly for the comparison and evaluation purposes.

For performing LCC, a variety of cost component breakdowns are used according to the goal and scope of LCC (Kim et al., 2015; Krutzfeldt, 2012; Ugwu et al., 2005; Walls III and Smith, 1998b; Zoeteman, 2001). Such, cost components include costs of acquisition, construction, operations and maintenance, energy, repair and replacement, salvage value, etc. The American Society for Testing and Materials (ASTM, 2002) provided a generic LCC model as in Equation 2-1, where 'C' is capital costs, 'R' replacement costs, 'A' annual operation and maintenance costs, 'M' damages and repair costs occurring non-annually, 'E' energy costs, and 'S' is salvage.

$$LCC = C + R + A + M + E - S \qquad \textbf{Equation 2-1}$$

This model allows to represent all the cost heads separately, hence varying inflations and discount rates on all the cost items can be employed separately.

Project costs occurring at different times in a project life possess a varying value of money and make project comparison difficult. So, in LCC analysis, all the associated costs occurring in present and future need to be shifted to the same time to incorporate the time value of money phenomena. This makes NPV an essential feature of LCC (Davis Langdon, 2007). NPV is defined as the difference between the present value of costs and the present values of cash inflows, assessed over time for the arbitrated discount rate (Berk, 2014). Accordingly, NPV for a single cost item is modeled as shown in Equation 2-2.

$$NPV = \frac{C_t}{(1+r)^t} \qquad \textbf{Equation 2-2}$$

Following the Equations 2-1 and 2-2, LCC of the project can be performed by summing up NPV of all the cost items in a project, as expressed in Equation 2-3, where 'C_t' is item cost, 'r' is discount rate and 't' is time of cost occurrence.

$$LCC = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \qquad \textbf{Equation 2-3}$$

2.5 Life Cycle Sustainability Analysis (LCSA)

For policy and business decisions, it is imperative to take into considerations all three facets of suitability. However, the assessment results of individual sustainability facets are perplexing, due to the methodological inconsistency of LCC, E-LCA and S-LCA (Hoogmartens et al., 2014). Thus, an integrated approach to sustainability assessment, establishing a tradeoff between the three sustainability pillars, is of utmost desire (Heijungs et al., 2010). This integrated approach to the sustainability assessment is termed as Life Cycle Sustainability Assessment (LCSA) (Klöpffer and Renner, 2008).

The concept of integrated sustainability assessment is not new. A number of proposal have been discussed to explore the possible points of integration of sustainability areas. Initially, after the development of LCC, the debate over the consolidation of sustainability facets into the LCC started (Tupamäki, 1998). Azapagic and Perdan (2000) discussed the set of indicators for total sustainable development and proposed a general framework to carry out a holistic LCA which include the environmental, economic and social indicators. For combining the

LCA with LCC and Social LCA, two approaches were discussed by the Norris (2001). Also, Klöpffer and Renner (2008) critically discussed the possible integration approaches; (1) develop an integrated framework to carry out single LCSA assessment, and (2) perform an individual assessment of each sustainability area and then integrate them. Based on this discussion, it is concluded that the single assessment of all the sustainability areas is constrained due to varying methodological approaches, the origin of impact categories and inconsistencies of results. Thus, a theoretical formulation of LCSA is proposed as given in Equation 2-4.

$$LCSA = LCA + SLCA + LCC \qquad \textbf{Equation 2-4}$$

Accordingly, for a single LCSA assessment approach, few studies conducted detailed discussions to explore the challenges and possibilities of integrating three pillars of sustainability and investigated the mutual points of contact and methodical relationships between sustainability facets. Some studies discussed the normative and empirical aspects of methodological frameworks of sustainability areas and drew a broader picture of possible integration (Guinee et al., 2010; Heijungs et al., 2010). Similarly, Bierer et al. (2013) discussed and proposed a framework for the trans-disciplinary integration of micro and macro environmental, economic, social, physical and technical models. Also, Hoogmartens et al. (2014), in an effort to integrate the LCA, LCC and CBA (cost-benefit analysis), compared their methodologies and concluded that significant connections exist between these three tools. Despite these efforts, assessment of LCSA through a single analysis of all three areas of sustainability is hindered due to their conflicting intrinsic properties, such as focus points, analysis periods, nature of impact categories and representation of results.

In literature, there are also a few studies which adopted the approach to combine the results of individual sustainability area for achieving LCSA. In doing so, studies utilized the normalization and weighting and multi-criteria decision making (MCDM) approaches

(Kucukvar et al., 2014). Such as, Matos and Hall (2007) proposed a landscape theory-based framework to incorporate the interdependencies among sustainability parameters. Kucukvar et al. (2014) performed the multi-objective optimization for evaluation of environmental and socio-economic impacts of two types of pavements and You et al. (2012) developed a multi-objective integrated linear programming tool for sustainability assessment of design and operation of cellulosic biofuel supply chains. However, these studies focused multi-objective approaches of MCDM, which are mainly used for design optimization purposes instead of multi-criteria single objective performance assessment (Chang, 2010).

The studies of Santoyo-Castelazo and Azapagic (2014) and Atilgan and Azapagic (2016) performed the multi-attribute value theory (MAVT) for integration of environmental, economic and social aspects of energy projects using multiple weighting combinations to present the sustainability results at various levels. Similarly, Hermann et al. (2007) developed a tool named COMPLIMENT where analytical hierarchy process (AHP) was performed using weights achieved from distance-to-target method proposed by Seppälä and Hämäläinen (2001).

However, proper LCSA demands a comprehensive decision-making system which could incorporate the scaling of indicators, define their target levels or thresholds, and also incorporate weightings between them (Finkbeiner et al., 2010). Also, for the accumulation of sustainability areas into a single value, weightings are required at three levels; between indicators or subcategories, between the main impact categories and between the sustainability areas.

Through literature review carried out in this chapter, an effort is made to illustrate the current state of methodological approaches of sustainability areas. Also, the level of research related to LCC, E-LCA and S-LCA particular to road infrastructure is discussed to highlight the knowledge gap. This review shows that LCC for road infrastructure is at a sophisticated level, however, the existing E-LCA studies are limited to the pavements only and lack the whole project-level approach. Also, limited literature has encountered all the life cycle phases of roads and impacts' considerations. Issues of standardization of functional unit, inventory scope and agreement on the selection of impact categories for road infrastructure are still open to discussion. Moreover, studies related to the S-LCA of road infrastructure have not been substantially reported. Besides, the literature lacks the standard approach for integrating sustainability areas and hence achieving LCSA. Thus, the current study aims to pave a way to develop a methodological framework for road life cycle sustainability assessment and a decision-making model and framework.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

The discussion and findings of the literature review identify the key characteristics of each sustainability area along with the constraints and knowledge gaps in achieving total LCSA, paving a way towards its methodological approach for road infrastructure. The approach involves MCDM based aggregation of impact indicators along with expert opinion to achieve LCSA of road infrastructure projects.

The multi-objective nature of this study along with interconnected inputs and outputs of various research stages warrant a comprehensive and complex methodological approach. However, to make it lucid and illustrative, the methodology is presented here in a traditional four discrete phases; literature review, data collection, analysis and results' interpretation, and discussion. In the following sections, each phase is briefed individually, marking the output and deliverables of each phase. The detailed methodology is graphically represented in **Error! Reference source not found.**.

3.2 Phase – 1: Literature Review

An extensive literature has been carried out for this study related to E-LCA, S-LCA, LCC and LCSA. The existing standards and up-to-date developed methodologies of all three areas of sustainability were studied. Also, the current state of the extent and most up-to-date application in road infrastructure projects was explored. For doing so, in the first stage research articles related to methodology, its development and application in a variety of disciplines were studied for each sustainability area. Then, in the second stage the selected articles related to roads were studied to identify the applied extent of attributes and hence knowledge gap in each area of sustainability.

For E-LCA, 150 articles were studied initially and then 21 studies particular to road were explored. Similarly, for LCC, 23 articles were selected to study the methodology and then 10 articles related to LCC of roads were studied. S-LCA is comparatively a new area, hence no substantial study of S-LCA related to road projects was found. Thus, a detailed review of 172 articles including 40 case studies was carried to study the S-LCA attributes and most developed methodological approaches. As a result of literature review, suitable methodological metrics and approaches, and impact categories of each sustainability area were evaluated.

3.3 Phase – 2: Data collection

Further, to develop the road infrastructure sustainability assessment model, the weightings of each sustainability impact category had to be assessed. For this purpose, multifaceted scenario-based structured interviews of policy and decision makers consisting of senior civil and public servants, experienced industry professionals and academic peers were carried out.

3.3.1 Interview design

A multifaceted questionnaire was designed to carry out structured interviews. The questionnaire was formulated in two stages; in the first stage, a proposed road infrastructure sustainability assessment framework and selected impact categories of each sustainability areas were presented to the interviewees. Then an open-ended discussion was held regarding the comparison of current project comparison and prioritization practices in vogue and the proposed framework. In such way, the interviewees were appraised about the sustainability parameters and its hierarchy of indicators. The responses and comments about the proposed LCSA methodological framework were noted and necessary changes were made in the proposed framework. Also, the response towards the limitations of in-practice approach was noted in comparison to the proposed total sustainability-based approach.

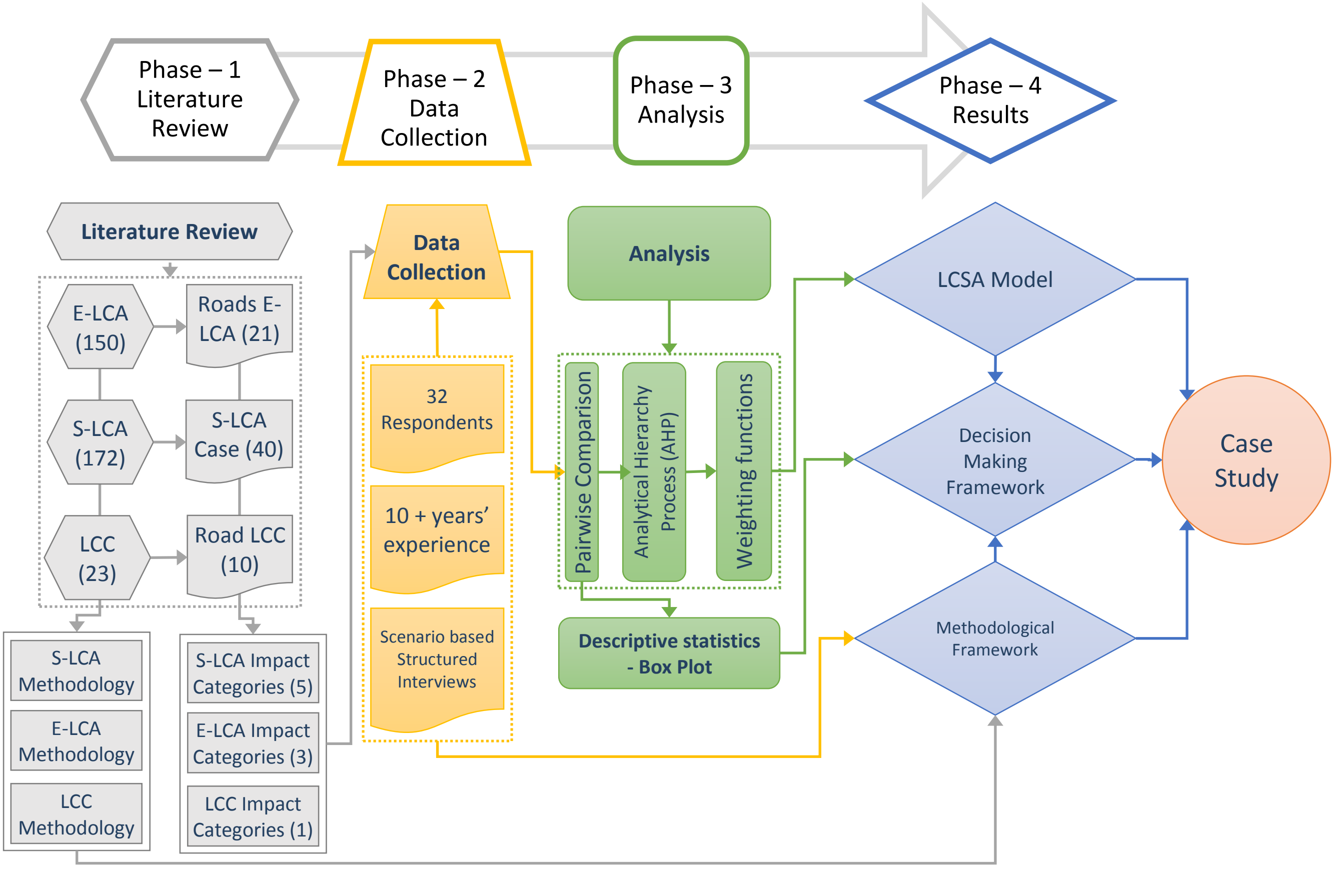


Figure 3-1 Detailed Methodology

In the second stage, the interviewees were asked to make a pairwise comparison of each sustainability area and a pairwise comparison of impact categories within each sustainability area. For this purpose, interview Performa was devised in three sections. In the first section, interviewees were asked to make a pairwise comparison of three sustainability areas; financial, social and environmental. Similarly, in second and third sections, they were asked to make the pairwise comparison of environmental and social sustainability impact categories. It is imperative to note that for the financial sustainability, no pairwise comparison was done in data collection since only one indicator was used for LCC.

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

3.3.2 Demographic features of the sample

The sample size is critical for statistical validation of results and establishing quantitative reasoning. Thus, for an interview-based qualitative research, one to hundred respondents can be adequate. However, Adler and Adler (2011) recommended a sample size of between 12–60 for such qualitative studies. Similarly, Baker et al. (2012) suggested using around 30 interviews for qualitative studies. Owing to the specialized nature of inquiries and unconventional multi-layered structure of this data collection, highly experienced experts from relevant knowledge areas and representing the pertinent decision-making bodies were selected. Participation of interviewees was ensured from all across the country to remove any selection bias in the sample.

As a result, a total 32 interviewees belonging to senior positions in civil and public services, including road infrastructure-related ministries and departments at federal and provincial levels, such as Ministry of Planning, Development and Reform (MoP), National Highway Authority (NHA) and PPP units, consultancies, and academic institutes engaged in research on environment, economics and road construction were involved. The resulting composition of interviewees based on experience and area of relevancy are presented in

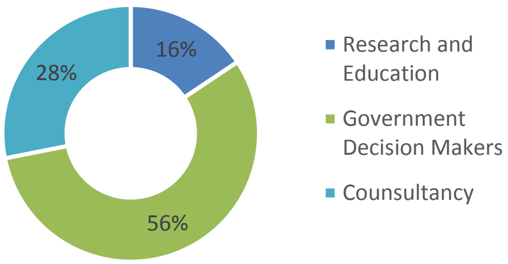


Figure 3-2 Interviewees experience

Figure 3-3 Interviewees work area and **Error! Reference source not found.**.

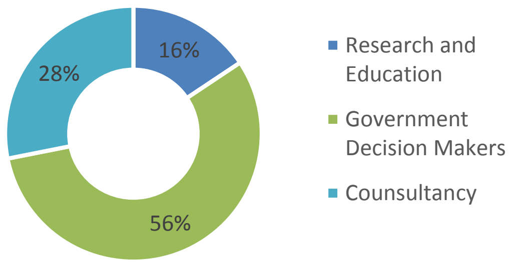


Figure 3-2 Interviewees experience

Figure 3-3 Interviewees work area

3.4 Phase – 3: Analysis

The analysis phase is comprised of two stages. In the first stage, the analysis resulted in the form of sustainability model for project prioritization and comparison. In the second stage, decision-making framework for project prioritization and comparison was formulated.

Three sustainability areas and the impact categories of each sustainability area can be represented in a 2-level hierarchy, as shown in **Error! Reference source not found.**. During t he data collection, a pairwise comparison was carried at both levels, thus generating three groups of pairwise comparison results; sustainability areas, environmental impact categories and social impact categories.

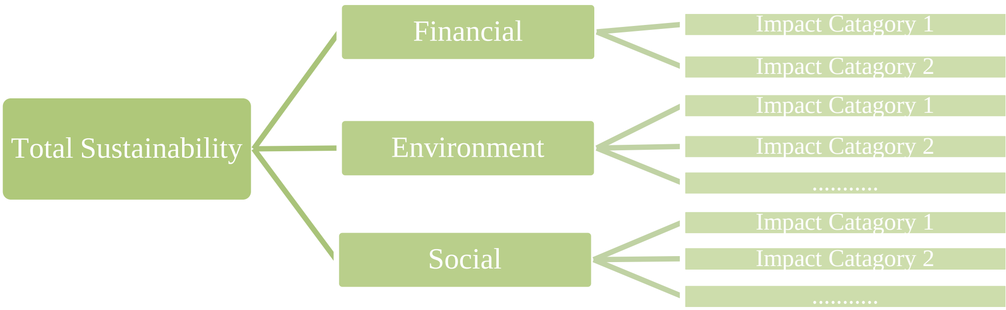


Figure 3-4 LCSA Impact Categories Hierarchy

The pairwise comparison response of each respondent was used to develop a consolidated matrix and AHP was then applied, using customized Excel sheets. The obtained weights from AHP were further formulated into aggregation equations to achieve value functions for each sustainability area and total LCSA. The expression used for the preference aggregation is given in Equation 3-1, where A_j is value function of sustainability area j, w_i is weight of impact category i in that sustainability area and v_i is actual score of impact category i in that sustainability area $\boldsymbol{j}$. This method is most commonly used for aggregation of indicators (Azapagic and Perdan, 2005; Díaz-Balteiro and Romero, 2004).

$$A_j = \sum_{i=0}^{i} w_i v_i \qquad \textbf{Equation 3-1}$$

Further, LCSA integration is achieved using the generic concept of Klöpffer and Renner (2008), which can be expressed as Equation 3-2, where T_s is value function of total sustainability, w_j is weight of sustainability area j, and A_j is the value function of sustainability area j.

$$T_s = \sum_{\mathbf{j=0}}^{\mathbf{j}} \mathbf{w_j}\, A_j \qquad \textbf{Equation 3-2}$$

In the development of decision-making framework, it was found necessary to identify the lower threshold values of each impact category and sustainability area. Thus, the interview results were statistically analyzed using the boxplot and quartile functions to identify this threshold from the lower quartile of distribution. For this purpose, AHP was applied on each respondent's pairwise comparison to obtain the AHP weighs for each respondent. Further, the noted comments and remarks of the interviewees against each response were utilized to formulate the decision-making framework and its boundaries.

Chapter 4

RESULTS AND ANALYSIS

In the first section of this chapter, the established configuration of the LCSA methodological framework for road infrastructure project comparison and prioritization is given. In the second section, detailed results of data collection and the AHP analysis are given to formulate the Road Infrastructure Sustainability Assessment Model. Following this model, a decision-making framework for project selection and project prioritization is developed in the third section of this chapter. Further, for demonstration of the established LCSA methodological framework, project prioritization model and the decision-making framework, a detailed case study has been carried out in the fourth section.

4.1 LCSA Methodological Framework for Road Infrastructure Projects

Following the detailed review of the past studies related to E-LCA, LCC and S-LCA, the methodological attributes of LCSA for road infrastructure projects are evaluated to establish a Sustainability Assessment Methodological Framework. This review of each facet of LCSA provides the direction for selection of appropriate impact categories and inventory indicators, and scope to further configure the complete LCSA methodological framework. Further, this methodological framework was presented to the interviewees for their feedback and comments and necessary improvements were made. The proposed LCSA framework, presented in Figure 4-1, is typically organized in three phases; inventory analysis, impact assessment and interpretation. In following paragraphs, the detailed discussion is carried related to the selected attributes for framework.

For the Environmental Life Cycle Assessment (E-LCA) of road ISO (2006) framework is adopted as a baseline for the inventory analysis and the impact assessment. Further, the literature found not to have consensus on a single fictional unit for performing E-LCA of roads.

However, it can be clearly observed that the choice of functional unit is dependent on the goal and scope of the studies (Capony et al., 2013; Huang et al., 2009; O'Born et al., 2016; Hakan Stripple, 2001). In established framework, the complete project is proposed to be considered as a functional unit for the case of project alternate evaluation. As all project alternatives share a common goal, which is connecting two points, thus the total length of the road becomes significant as its one of the parameter in evaluation. However, for the project prioritization the functional unit must be 'per unit length of road'.

Further, for the selection of suitable impact categories, Table 2-1, reveals that majority of studies are utilizing midpoint impact categories such as energy, GHGs, Ozone Depletion and GWP. However, at the project level, decision makers are hindered to make rationalized assessment while utilizing such variety and range of midpoint impact categories. At such level of decision-making, the endpoint impact categories such as Human health, Ecosystem and Resources have become popular (Menoufi, 2011), which are calculated through the characterization of midpoint impact categories into endpoint impact categories (Heijungs et al., 2003b).

Both midpoint and endpoint impacts have their own merits and demerits. The certainty of estimation and calculation is much higher for midpoint impact categories as compared to the endpoint impact category but endpoint impact categories are more relevant and appropriate for decision support (Bare et al., 2000). Also, for decision support, use of midpoint and endpoint impact categories in parallel is recommended by many researchers (Bare et al., 2000; Dong and Ng, 2014).

The established LCSA methodological framework was presented to the interviewees. About the endpoint and midpoint impact category, most of them felt more comfortable with the understanding and insight of impacts of endpoint categories and suggested to utilize the endpoint impact categories. However, few respondents were interested to have more knowledge of impacts breakdown and hence suggested to use midpoint impact category. Thus, the established LCSA framework uses endpoint impact categories along with the consideration of midpoint impact categories as well.

The review of existing LCC studies reveals that the NPV and IRR are the most widely used methods for project assessment (Babashamsi et al., 2016; Davis Langdon, 2007; K. Ozbay, 2003). However, there can be scenarios when the NPV for one project is better than other but the IRR is better for the other project. In such scenarios, choice of indicator becomes critical for projects selection and prioritization (Osborne, 2010). The comparison between IRR and NPV, presented in literature review section, reveals the insufficiencies in IRR and establishes the superiority of NPV for project comparison (Osborne, 2010). Thus, in established LCSA methodological framework, NPV is proposed as the indicator for LCC.

The review of S-LCA reveals that UNEP/SETAC S-LCA guidelines (UNEP, 2009) and methodological sheets (Benoît-Norris et al., 2011) are most widely used social impact assessment approach. Thus, for the establishing the LCSA methodological framework, use of UNEP/SETAC S-LCA guidelines and methodological sheets are proposed for performing S-LCA.

This established framework was presented to the interviewees for their comment and feedback. In S-LCA impact categories, ‘working condition’ impact category was found irrelevant, least important and confusing with the ‘health and safety’, during the interviews. The first seven interviewees highlighted this issue, that ‘working conditions’ is majorly related to the worker’s health and safety which in their opinion, should be considered in the impact category ‘Health and Safety’. Moreover, particular to road infrastructure, working conditions are mainly related to the construction phase only, which is very short as compared to use phase. Thus, it has a lesser impact on overall social concerns of road infrastructure projects. Therefore, in the proposed LCSA methodological framework, selected S-LCA impact categories are

Socioeconomic repercussions, Health and Safety, Human Rights, Cultural Heritage and Governance.

All the selected impact categories for LCSA are presented in Figure 4-1. Further, for the normalization of the obtained scores of LCSA impact categories, a two-stage normalization is proposed. First the nature of impacts needs to be normalized, such as some impact categories result as benefits which means the ‘more is better’ and some categories result as damages which means ‘lesser is better’. Thus, all the impact categories are harmonized on the same nature scale. Further, for normalizing the order of magnitude of impact categories, Euclidean Vector based normalization has been proposed (Olinto, 2017). The scale of the impact categories results obtained from the LCSA analysis are identified as ratio scale. Thus, for normalizing such ratio scale, a congruence or parallel transformation is required which would produce a normalized version of the results possessing the properties of a vector with length equal to 1 (Magnus and Neudecker, 1988). For this purpose, Euclidean Norm equation, is proposed to be used as presented in Equation 4-1.

$$||v_i|| = \frac{x_i}{\sqrt{\sum x_{ij}^2}} \qquad \text{Equation 4-1}$$

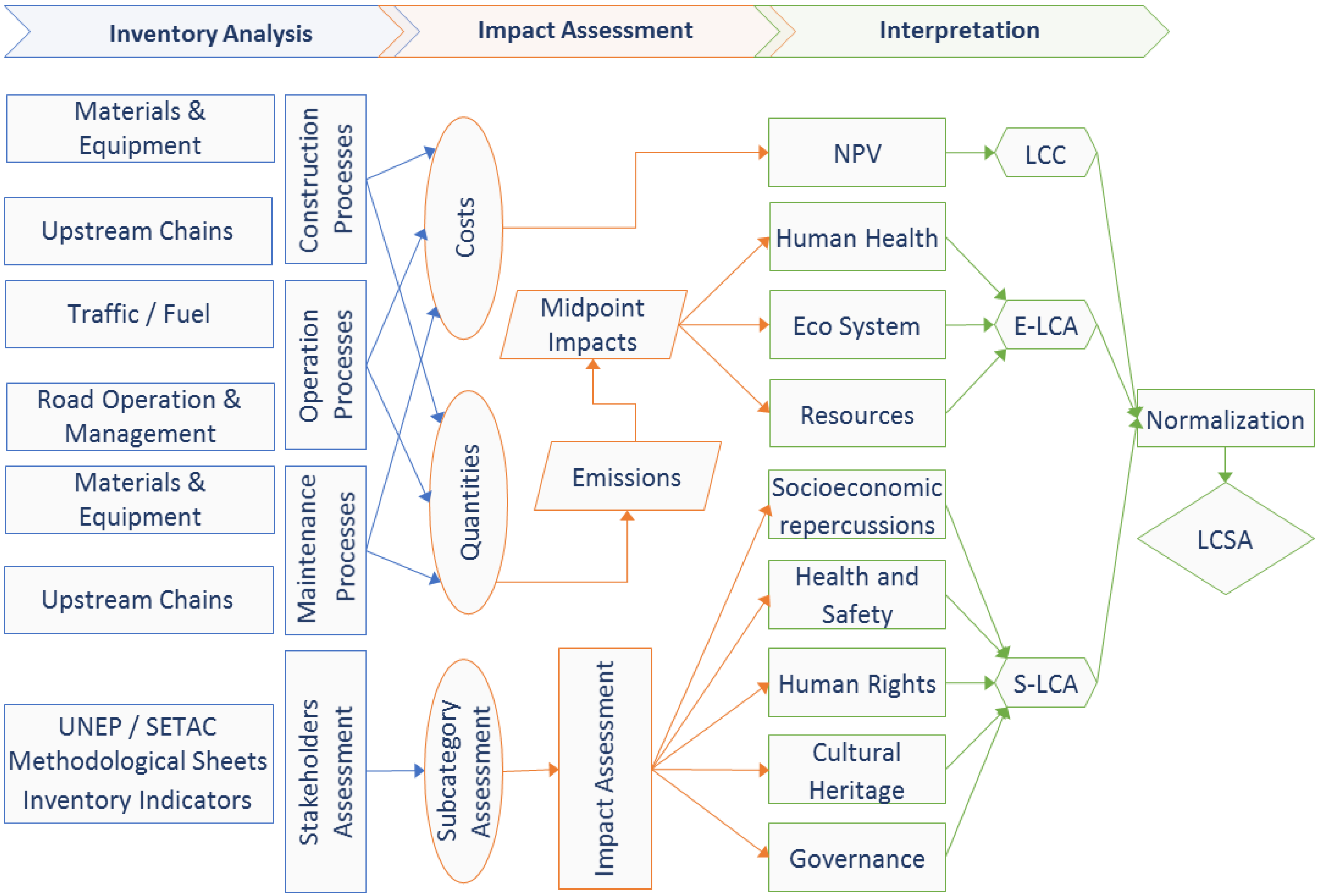


Figure 4-1 Proposed LCSA Methodological Framework

4.2 LCSA Model for Road Infrastructure Projects

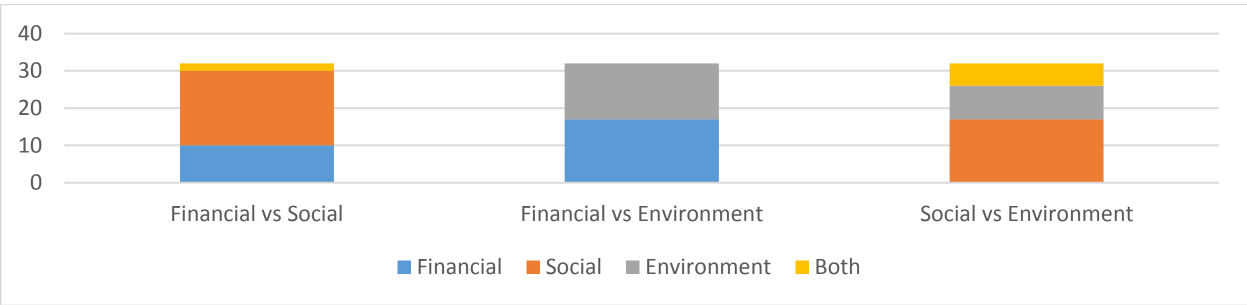
4.2.1 Interview Results and Discussion

For the development of LCSA model, detailed interviews were carried to obtain the priorities among the sustainability areas and impact categories of those sustainability areas. For this purpose, interviewees were asked to make a pairwise comparison of sustainability areas and the impact categories, within each group. The hierarchy of sustainability areas and impact categories, given in methodological framework and shown in Figure 4-1, was followed. In doing so, interviewees gave their opinion of preferences about the sustainability areas and their impact categories. Also, the rationale of every interviewee's choices was noted for each comparison. In following sections, results of each group of pairwise comparison are presented and discussed.

4.2.1.1 Sustainability Areas

Three areas of sustainability; financial, social and environment were compared and interview results are presented in Figure 4-2. In the comparison between financial and social areas of sustainability, 63% interviewees prioritized the social over the financial area. Such interviewees believe that the social concerns have a direct impact over the economy so accounting them would automatically enhance the economic concerns, at least in life cycle terms. One of the interviewees commented that roads are built to entertain the social concerns, thus spending additional money on some extra social benefits is worthy. In the same context, another interviewee mentioned that the inclusive economic growth is not possible if the indirect social impacts are ignored. The interviewees who marginally prioritized the social area of sustainability over the financial area mentioned the boundaries or parameters of their preference, such as, marginal costs can be spent over the significant social benefits and should not be paying billions of rupees for the benefit of minority of people.

Contrary to this, 31% interviewees preferred financial sustainability over social. They argued that, for the developing countries like Pakistan, current need and goal is to deliver infrastructure. However, the budgetary constraints limit the capacity of governments. In such a scenario, the approach is to construct infrastructure at the minimum possible cost, which makes the financial sustainability more important. Also, once an infrastructure is installed, it would deliver to the social sector automatically. Further, there were 6% respondents who believed that both these areas are equally important and cannot be compared without contextualizing.



Financial vs Social		*Financial vs Environment*		*Social vs Environment*	
Financial	31%	Financial	53%	Social	53%
Social	63%	Environment	47%	Environment	28%
Equally Preferred	6%	Equally Preferred	0%	Equally Preferred	19%

Figure 4-2 Sustainability Areas – Pairwise Comparison Results

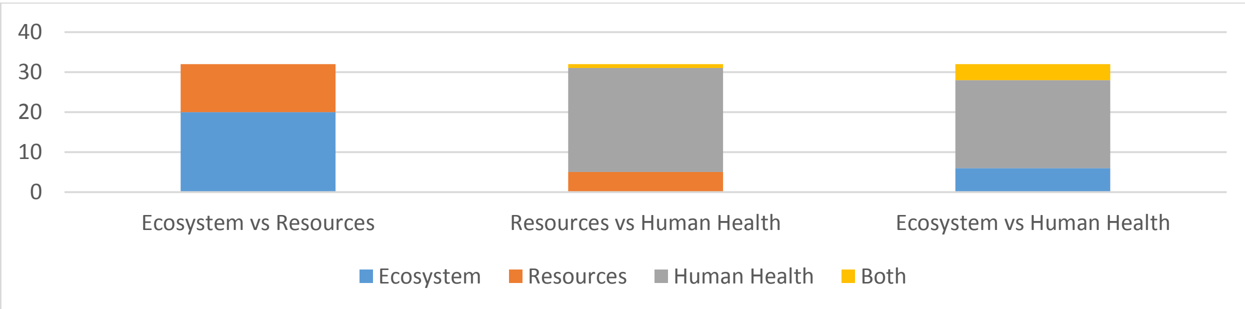
In the comparison of financial and environmental sustainability, 53% interviewees prioritized the financial over environmental area of sustainability and 47% preferred the environmental area over the financial. Respondents who preferred financial sustainability opined that the environmental concerns can be easily mitigated by making a little compromise on the financial part, however, the environmental performance should never be below the minimum threshold. Few respondents commented that the construction of road infrastructure does not have much impact on the environment, thus can be a lower preference as it can be easily managed by minor actions such as planting trees along the highways. Besides, respondents who preferred the environment argued that the environment has a direct impact on the local community, thus should not be ignored.

While making a pairwise comparison of environmental and social areas of sustainability, 53% respondents preferred social over the environment, 28% preferred environment over social and 19% marked both equally important. An interviewee who preferred social sustainability commented that the environment is mitigable and has a lesser impact in case of road construction, thus social must be given more attention. However, an interviewee who prioritized the environment over social was of the opinion that the environmental damage has very immediate and direct impact on the local population, thus should be preferred. There were significant respondents who believed that both the areas of sustainability are equally important as both are directly related to the people, hence no compromise should be made on the quality of life of people.

4.2.1.2 Environmental Impact Categories

In the environmental area of sustainability, endpoint impact categories, human health, ecosystem and resources were proposed in the methodological framework of LCSA. The pairwise comparison was carried over these impact categories to evaluate their weights. Results of this comparison are given in Figure 4-3.

In the comparison of ecosystem and resources, 63% of the respondents preferred the ecosystem concerns over resources. These respondents believe that the impact on ecosystem may cause severe damages in the form of floods and droughts which have a direct impact on humans and economic system of countries. Also, the resource consumption is mainly during the construction phase which is very short in case of roads. Damage to ecosystem is a global concern and has global impacts as compared to resources impacts which are more country-specific, thus ecosystem concerns should be preferred. However, 38% interviewees believed that the concern of resources depletion should be preferred over the ecosystem. They were of the opinion that the excessive consumption of abiotic resource is the main cause of ecosystem damage. Also, one of the interviewees commented that priorities changes demographically, particularly for developing countries. Local issues should be at priority; resource consumption is a local issue and ecosystem damage has global implications.



Ecosystem vs Resources		*Resources vs Human Health*		*Ecosystem vs Human Health*	
Ecosystem	63%	Resources	16%	Ecosystem	19%
Resources	38%	Human Health	81%	Human Health	69%
Equally Preferred	0%	Equally Preferred	3%	Equally Preferred	13%

Figure 4-3 Environmental Impact Categories – Pairwise Comparison Results

In a comparison of resources and human health, 81% interviewees prioritized human health over resources and argued that resource consumption would have a delayed impact, whereas human health is an immediate issue. Further, there cannot be anything which could be prioritized over human life quality. One of the interviewees mentioned that with improving technological advancement and research, there is a shift towards the renewable and more energy efficient resources day by day. Thus, depletion of natural resources should not be our concern. Besides, few other believed that the consumption of natural resources is the main cause of hazardous emissions, which causes damage to human health. Thus, more attention should be given to resource consumptions. There were 16% interviewees who believed that the resource consumption is the root cause of human health damages and prioritized the resources over human health.

For the comparison of human health and ecosystem, 69% interviewees preferred human health over ecosystem. In the opinion of interviewees who preferred human health over ecosystem, the impact of human health is a direct sort of impact and can be observed immediately, thus should be given more attention. Besides, 19% interviewees preferred ecosystem as a more concerning point.

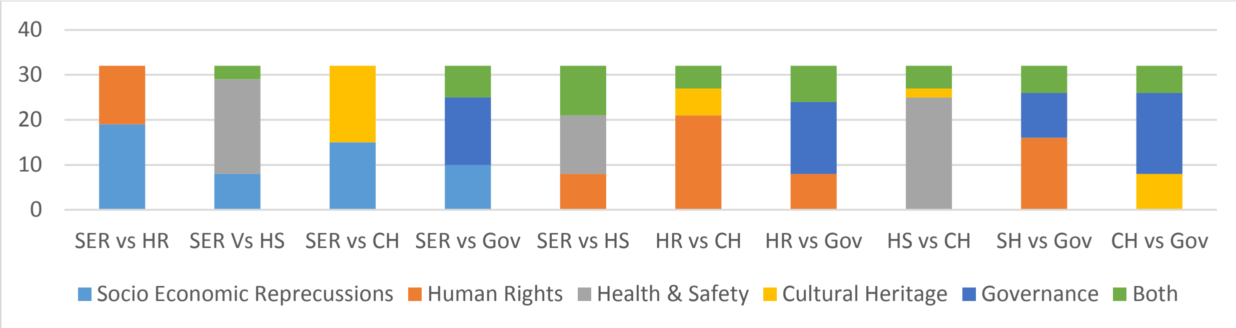
They rationalized their preference by referring to the chain of cause and impact. In their opinion, human health is a major resultant of ecosystem damage; if we save the ecosystem, the human health damage can be prevented. Thus, ecosystem should be more of a concern than the human health. Significantly, 13% respondents made an equal preference for both the impact categories and mentioned that the local and global impact should be equally considered.

4.2.1.3 Social Impact Categories

In the social area of sustainability, impact categories of socioeconomic repercussions (SER), human rights, health and safety, cultural heritage and governance were proposed in the LCSA methodological framework. The pairwise comparison was carried over these impact categories to evaluate their weights. Results of pairwise comparison are given in the Figure 4-4.

In the comparison between socioeconomic repercussions and human rights, 59% interviewees preferred socioeconomic repercussions over human rights. These interviewees argued that better socioeconomic conditions warrant the human rights as well. Few of these respondents commented that the main reason for human rights violation is built into an unfavorable socioeconomic environment. One of the interviewees, who was a consultant and expert in road infrastructure, mentioned that socioeconomic concerns are the primary indicator to check a project feasibility which indirectly covers the scope of human rights as well. Another interviewee was of the opinion that the socioeconomic concern is a matter of masses, however, human rights are a matter of individuals. Thus, impacts related to masses should be preferred over those of individuals. Contrary to this, 41% of the respondents considered human rights as more concerning area as compared to socioeconomic repercussions. These respondents believed that for delivering a road infrastructure projects, human rights cannot be compromised under any circumstances. The law of the land warrants the protection of human rights. Projects violating these rights may face worst scenarios such as protests, stoppage of work and eventual project abandoning. So, in such a scenario, the socioeconomic condition would suffer even more.

Next, in comparison between socioeconomic repercussions and health and safety, 66% interviewees preferred health and safety over socioeconomic repercussions arguing that the project should not be constructed if there is any sort of health and safety concern for the user and the local community. Contrary to this, 25% respondents believed that health and safety is an issue which can be mitigated easily by making some design changes and putting some cost for safety arrangements. Thus, socioeconomic repercussions should be of more concern. There were 9% interviewees which marked both SER and Health and Safety as equally important. In their opinion, health and safety should not be compromised, however, should be managed accordingly while delivering a project with good socioeconomic prospects. While comparing socioeconomic repercussions and cultural heritage, a significant scenario was observed; 53% interviewees preferred cultural heritage over socioeconomic repercussions. They were of the opinion that cultural heritage is not only a national asset but is also of global importance, thus compromising any sort of culturally significant heritage would not be a wise decision, even for a project having a good socioeconomic prospect. One of the interviewees argued that compromising or demolishing any cultural heritage may have severe impacts, such as public protest, legal stays and delay or canceling of the project. Another interviewee mentioned that saving and promoting the cultural heritage can be a source of socioeconomic benefits. Contrary to this, 47% interviewees argued that, for the developing countries, luxuries like saving cultural heritage should not be a consideration. In order to develop infrastructure and promote socioeconomic conditions, cultural heritage can be compromised.



SER vs Human Rights		*SER vs Health and Safety*		*SER vs Cultural Heritage*	
SER	59%	SER	25%	SER	47%
Human Rights	41%	Health and Safety	66%	Cultural Heritage	53%
Equally Preferred	0%	Equally Preferred	9%	Equally Preferred	0%
SER vs Governance		*Human Rights vs Health and Safety*		*Human Rights vs Cultural Heritage*	
SER	31%	Human Rights	25%	Human Rights	66%
Governance	47%	Health and Safety	41%	Cultural Heritage	19%
Equally Preferred	22%	Equally Preferred	34%	Equally Preferred	16%
Human Rights vs Governance		*Health and Safety vs Cultural Heritage*		*Health and Safety vs Governance*	
Human Rights	25%	Health and Safety	78%	Health and Safety	50%
Governance	50%	Cultural Heritage	6%	Governance	31%
Equally Preferred	25%	Equally Preferred	16%	Equally Preferred	19%
Cultural Heritage vs Governance					
Cultural Heritage	25%				
Governance	56%				
Equally Preferred	19%				

Figure 4-4 Social Impact Categories – Pairwise Comparison Results

Similarly, significant comparison of socioeconomic repercussions and governance was found, where 47% interviewees preferred governance over socioeconomic repercussions, 31% preferred the contrary and 22% marked both equally. An interviewee who preferred governance suggested that good governance would bring positive socioeconomic prospects. Those who preferred socioeconomic repercussions argued that for bringing good governance, stable socioeconomic conditions are necessary. Whereas, respondents who marked both equal considered that they are interlinked in forward and backward manner.

Next, in comparison of human rights and health and safety, health and safety was preferred by 41% respondents and 25% respondents preferred human rights, whereas, 34% marked both equally important. The interviewees who prioritized health and safety were of the opinion that there can be no compromise on life of people. An interviewee commented that the arrangements for health and safety are made for a large group of population, whereas human rights is an individual matter, thus health and safety should be preferred. An interviewee who prioritized the human rights was of the opinion that the health and safety can be managed and mitigated however there is no alternative for managing the human rights, thus human rights should be considered at the project feasibility level. An interviewee who marked both as equal believed that both the impact categories are for the people and health and safety is also a sort of human right, thus both should be given equal consideration.

In a comparison of human rights and cultural heritage, 66% interviewees preferred human rights, 19% preferred cultural heritage and 16% gave equal preference to both. The respondents who prioritized the human rights commented that cultural heritage is part of the human right and should not be considered as a priority for the developing countries. Whereas interviewees preferring cultural heritage had an opinion that compromising cultural heritage would have many immediate and severe impacts than violating an individual's rights, which can result in the cancellation of projects too. The respondents who marked both the impact categories equal were of the opinion that sensitivity of cultural heritage is contextual matter, it can be a very serious issue in some project or it may be an easier compromise, also, it depends on the type and extent of heritage itself. On the other hand, there can be no other view that human rights supersede all other impacts. Thus, they prefer giving an equal weight to both of the impact categories.

In comparison of human rights and governance, 50% of the interviewee believed that key to improve human rights is to improve the governance, thus they prioritized the governance over human rights. Contrary to this, 25% interviewees marked human right on top of governance. And 25% of the interviewees preferred to rank both of them equal. In their opinions, human rights are a basic right of the people so can't be compromised, also governance has a larger scope.

In a comparison of health and safety and cultural heritage, strangely health and safety was prioritized by 78% of the interviewees, only 6% interviewees preferred cultural heritage over health and safety and 16% of the interviewees equally preferred. Interviewees who preferred the health and safety were of the opinion that, health and safety is basic human right and cannot be compromised at any cost, also, health and safety is about and present and future however cultural heritage is about past and developing nations cannot afford prioritizing such thing. Interviewees who prioritized the cultural heritage believed that health and safety can be managed through making arrangements or altering the design parameter or spending some cost against it, however, cultural heritage is an asset and identity, thus should not be compromised.

In a comparison of health and safety and governance 50% of the interviewees preferred the health and safety over the governance, 31% of the interviewees preferred the governance over the health and safety and 19% interviewees marked both the equal. Interviewees who preferred health and safety over the governance commented that the safety of people is the basic human right thus should not be compromised at any cost. However, respondents who preferred the Governance over the health and safety were of the opinion that, good governance would govern the health and safety of the society, thus governance should be given priority. Considering the larger scope of governance and depth of the impact on health and safety some interviewees equally ranked both the impact categories.

Next, in comparison of governance and cultural heritage, 56% of the interviewees selected governance on top of cultural heritage. These interviewees gave an opinion that in longer terms good governance can manage the negative impacts produced due to cultural heritage compromise. An interviewee commented that compromise over the cultural heritage for sake of security and law in order like governance issue is justified. In the opinion of another interviewee, a project with positive prospects on governance is worth enough to compromise any cultural assets in its way, because developing countries should focus on the future not past. There were 25% interviewees which preferred cultural heritage. They were of the opinion that compromise on cultural heritage is not an option, cultural heritage is not just a historical asset, it's also about human rights and sometimes it becomes a matter of religious sentiments of people. There were 19% interviewees who equally preferred the cultural heritage and governance.

4.2.2 AHP Results

Analytical Hierarchy Process (AHP) was applied on the consolidated matrix of pairwise comparisons of impact categories to obtain weights of the impact categories and sustainability areas. The results of AHP analysis are shown in Table 4-2.

Table 4-1 Weights of Impact Categories and Sustainability Areas

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

The results reveal that in three areas of sustainability, the weight of social sustainability is considerably high (42.8%), however, environmental (29.5%) and financial (27.7%) areas were comparative with each other. In environmental impact categories, human health (56.6%) was marked as the most significant area of concern. And the impact category of resources was significantly low (17.8%), however, ecosystem weight was 25.6%. For Social impact categories, the weight of Health and Safety was the topmost weighted impact category, having 29.7% weight. The Governance was the second highest weighted social impact category (23.6%) and, Human right, Socio-Economic Repercussions and Cultural heritage weights were 18.6%, 15.7% and 12.4%, respectively. For Financial sustainability as there was only one impact category, thus, 'NPV' weight is considered as 1.0.

The consistencies of AHP results were also checked for each respondent for each AHP analysis. Results revealed that the for AHP analysis of sustainability areas 69%, of environmental impact categories 81% and of social impact categories 84% responses were inconsistent. However, the interviewees which response was inconsistent, rationalized their responses through arguments and reasoning. Also, this is significant to note that the final weights of consolidated responses were consistent, as all were greater than 0.1.

4.2.3 LCSA Model Equations

Using the obtained weights of impact categories and Equation 3-1, the sustainability scores of environmental, social and financial areas are expressed in Equation 4-2, where '$v_{\boldsymbol{Res}}$' is value of resources, '$v_{\boldsymbol{Eco}}$' is value of ecosystem, '$v_{\boldsymbol{HH}}$' is value of human health and $A_{\boldsymbol{Env}}$ is the total value of environmental sustainability; Equation 4-3 where '$v_{\boldsymbol{SER}}$' is value of socioeconomic repercussions, '$v_{\boldsymbol{HR}}$' is of human rights, '$v_{\boldsymbol{HS}}$' is of health and safety, '$v_{\boldsymbol{CH}}$' is of cultural heritage, '$v_{\boldsymbol{Gov}}$' is value of impact category governance and $A_{\boldsymbol{Soc}}$ is the total value of social sustainability; and Equation 4-4 where '$v_{\boldsymbol{NPV}}$' is for the financial area of sustainability and $A_{\boldsymbol{Fin}}$ is total value of financial sustainability.

$$A_{Env} = 0.1777\ v_{Res} + 0.2566\ v_{Eco} + 0.5657\ v_{HH}$$ **Equation 4-2**

$$A_{Soc} = 0.1575\ v_{SER} + 0.1863\ v_{HR} + 0.2971\ v_{HS} + 0.1236\ v_{CH} + 0.2356\ v_{Gov}$$ **Equation 4-3**

$$A_{Fin} = v_{NPV}$$ **Equation 4-4**

Further using Equation 3-2 and the obtained weights of the sustainability areas, the LCSA score can be determined by Equation 4-5.

$$T_{LCSA} = 0.2950\ A_{Env} + 0.4282\ A_{Soc} + 0.2768\ A_{Fin}$$ **Equation 4-5**

4.3 Decision Making Framework for Road Infrastructure Project Comparison and Prioritization

Following the pairwise comparison results, a decision-making framework has been developed for the selection of the most sustainable project alternative proposal. For this purpose, threshold limits of each impact category and sustainability areas are assessed using the box-plot and lower quartile range. Further, based on Yes/No scenario pathways, a response-based feedback process is developed through which project proposals are evaluated.

4.3.1 Minimum Threshold Values

The AHP weightings of each respondent were analyzed to establish the box-plot. The box-plot analysis of sustainability area, presented in Figure 4-5, shows that the mean values for the financial, social and environment areas of sustainability areas are comparative, as 0.30, 0.39 and 0.31, respectively. However, the lower quartile values, presented in Table 4-3, are varying as for social, lower quartile value is 0.26 and for environment and financial lower quartile values are 0.12 and 0.10, respectively.

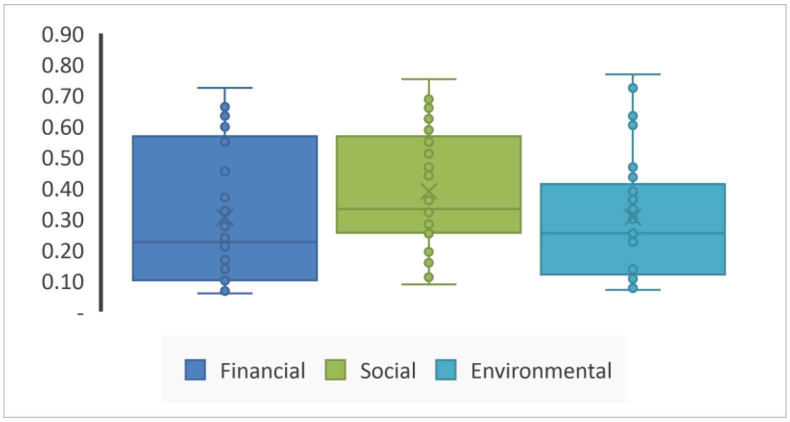


Figure 4-5 Box-plot representation for Sustainability Areas

The box-plot analysis of all the impact categories are presented in Figure 4-6. The mean values for the impact category human health is significantly high (0.51) and for cultural heritage (0.14) and for socioeconomic repercussions (0.17) mean values are lowest. However, for all other impact categories, mean values are comparatively varying from 0.19 to 0.29. Accordingly, the lower quartile values for these impact categories are presenting the same pattern.

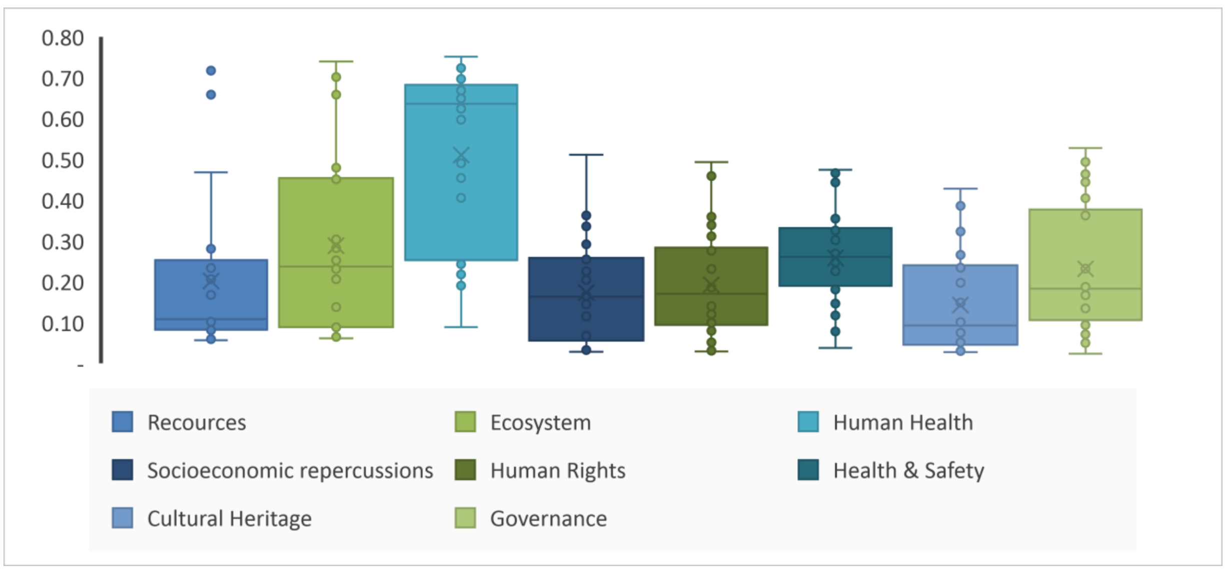


Figure 4-6 Box-plot representation for Impact Categories

This is pertinent to note that NPV, the impact category for LCC, is not analyzed for lower quartile range, as no pairwise comparison was carried out for this single impact category of LCC. Thus, no response for weights was obtained. However, financial area of sustainability and its impact category was brought into discussion during the interviews and responses of interviewees has been previously discussed.

Table 4-2 Minimum threshold limits (Lower quartile values)

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

These lower quartile values for the sustainability areas and impact categories are covering the bottom range of weights given by respondents. This signifies the lowest possible ranges towards any of the sustainability areas and impact categories. Thus, these lower quartile values can be interpreted as the minimum threshold values for the sustainability areas and impact categories which means that a project having value below these threshold is not fulfilling the minimum criteria for sustainability and should not be preferred.

4.3.2 Decision Making Process

In the proposed decision-making framework, the threshold limits are applied to ensure a control system in the feedback framework. Following the defined threshold values, a response-based feedback process is developed for the evaluation of the most sustainable road alternative. The flowchart of the process is presented in Figure 4-7. This decision-making process follows the assessment of all three areas of sustainability to obtain the final values of LCSA impact categories. These values are then compared with their minimum threshold values.

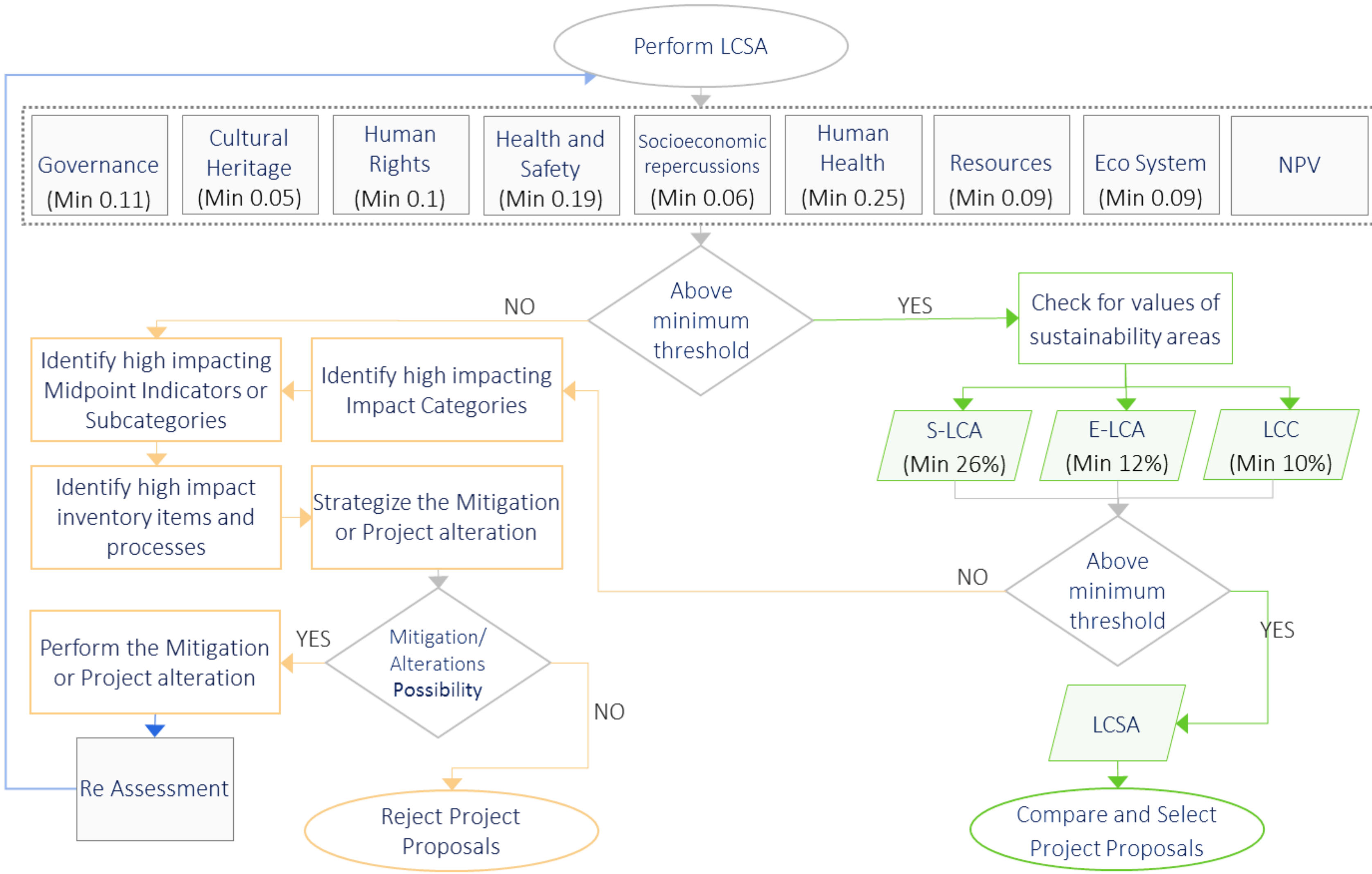


Figure 4-7 Proposed LCSA Methodological Framework

If all the impact categories meet the threshold limit criteria, the projects are further compared for their sustainability areas with minimum threshold limits. If projects meet the minimum threshold criteria at both the levels, the project can be compared on the basis of total LCSA values, and project with the highest LCSA value can be selected as the most sustainable alternative. If any value of LCSA impact category is found below the established minimum threshold value, the subsequent most influential or damaging process, material or linked inventory indicators are identified. For doing so, the high impact midpoint impact categories or subcategories are tracked upstream into the processes and materials.

Once the upstream inventory process or inventory causing the most damage is identified, the corresponding mitigation or project alterations can be made accordingly. If no mitigation or project alteration is possible, the project proposal is rejected. In other scenario, after performing changes according to mitigation or alteration, the project is reassessed for LCSA and revised values of impact categories are considered for the comparison.

It is significant to note that threshold limit of some impact categories may be much lower than international practices. Therefore, such scenario must to be given special attention in the decision-making framework.

However, interviewees labeled this impact category as highly contextual which means that its importance varies situation vise. There can be a scenario when the tangible damages and the attained value of the cultural heritage is quite low but compromising on cultural heritage at cost of people’s sentiments could worsen the situation and may result in abandoning the project. Therefore, such scenario must to be given special attention and damage should be addressed accordingly. Also, in case of NPV, thought there is no evaluated threshold limit, the interviewees argued that the financial should not be compromised beyond the extent of irrecoverable damages.

4.4 Case Study

For the demonstration of the developed LCSA methodological and decision-making framework, a case of a major highway project is presented. The project is located in the province of Punjab in Pakistan. During the feasibility studies, this project had three proposals for different alternate routes, R-1, R-2 and R-3 having lengths 110 km, 94 km and 90 km, respectively. It is significant to mention that existing decision-making is majorly influenced by only financial feasibility of projects, under which R-3 was selected and executed. However, in this study all alternatives have been evaluated to assess the most sustainable alternative based on a holistic LCSA methodological and decision-making framework. Following, the case study is discussed in line with the steps of developed LCSA methodological and decision-making framework.

The system boundaries considered for this case study include construction, operation, maintenance and use phases as well as the upstream processes and materials for each phase. Following the system boundaries, extensive range of materials and processes is covered for the inventory analysis as presented in Table 4-4. The inventory data is taken from the project documents, such as feasibility studies, BOQs and standard construction material rate lists. SimaPro 8.4 software and Ecoinvent 3.0 database is utilized for the inventory analysis and impact assessment to obtain the environmental impact categories.

The upstream processes available in built-in libraries of SimaPro are used, however, processes which are not available in built-in library are modeled accordingly using the inventories of Ecoinvent database. The environmental impact categories results were obtained using the impact assessment method ReCipe 2016 Endpoint (E) V1.00.

Table 4-3 Inventory used for all processes

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

Further, for calculation of financial impact category, lifecycle project costs are estimated using Microsoft Excel. For the impact assessment of social impact categories, the required inventory indicator data as per the proposed framework was not available. However, for this case study, quantitative data for the seven social indicators is extracted from the feasibility studies and records. The obtained indicators are directly characterized into the social impact categories according to their subjective relevance and considering the equal weights. The indicators used for each social impact category are presented in Table 4-5.

Table 4-4 Social inventory indicators

Social Impact Categories	Inventory Indicators
Socio Economic Repercussions	Perspective in Relative Economic Growth, Availability of Area for the development; Acquisition of Land and Re-settlement;
Local Community Health and Safety	Cutting of Trees
Cultural Heritage	Proximity to the Cultural sites of importance (Tombs /Graveyards) etc.; Provision of Sound Barriers to the villages in close proximity
Governance	Area availability for development (ROW); Land acquisition and Re-settlement
Human Rights	Land acquisition and Re-settlement; Crop Compensation

After obtaining the scores for all the impact categories they were normalized according to their nature such as ‘better is good’ or ‘lesser is good’ and for scale of 1 to 0 using the Equation 4-1 of Euclidean norm. Further, following the developed Equations 4-2, 4-3, 4-4 and 4-5, the final LCSA values are obtained. The obtained results of impact categories score, sustainability areas and LCSA are presented in Table 4-6.

The results of LCSA assessment reveal that overall R-2 is comparatively the best option. However, R-3 is performing better in financial sustainability but marginally lack in social and environmental areas. The option R-2 is the least sustainable proposal, having the lowest values in all three areas.

Following, the developed decision-making framework, impact categories having values less than the established threshold limits are identified, as highlighted in Table 6. It can be observed that, though R-2 is the most sustainable proposal, its value of ‘Local Community Health and Safety’ is below the established threshold limit for this proposal. So, before further pursuing this proposal, it needs to be properly addressed by mitigating or altering the concerning inventory. For example, in this case, inventory indicator considered for this impact category is cutting of trees, whose impact can be mitigated through enhancing the provisions of tree plantation across the road and horticulture development. Proposal R-1 is found as the least sustainable while having values below threshold for impact categories human rights and ‘Local Community Health and Safety’.

Table 4-5 Case Study Results

	Normalized Scores			**Weighted Normalized Scores**		
	R1	R2	R3	R1	R2	R3
LCSA Impact Categories						
NPV	0.5404	0.5666	0.6220	0.5404	0.5666	0.6220
Human health	0.5759	0.5809	0.5752	0.3258	0.3286	0.3254
Ecosystems	0.5471	0.5903	0.5935	0.1404	0.1515	0.1523
Resources	0.6027	0.5752	0.5531	0.1071	0.1022	0.0983
Socio Economic Repercussions	0.5145	0.6860	0.5145	0.0810	0.1080	0.0810
Local Community Health and Safety	0.2120	0.6360	0.7420	***0.0630***	***0.1889***	0.2204
Cultural Heritage	0.7071	0.5657	0.4243	0.0874	0.0699	0.0524

Governance	0.5970	0.6965	0.3980	0.1406	0.1641	***0.0938***
Human Rights	0.2722	0.6804	0.6804	***0.0507***	0.1268	0.1268
Sustainability Areas						
Financial	0.5404	0.5666	0.6220	0.1496	0.1569	0.1722
Environment	0.5733	0.5823	0.5760	0.1691	0.1718	0.1699
Social	0.4227	0.6577	0.5744	***0.1810***	0.2816	***0.2460***
LCSA				**0.4997**	**0.6103**	**0.5880**

Further, it is pertinent to note that R-3 is marginally behind R-2, while particularly being below the threshold in impact category ‘Governance’, at the same time R-3 is best in financial area of sustainability. Thus, there can be a potential possibility that improving Governance related inventory through mitigation and by providing other positive provision can improve R-3. Therefore, such a scenario signifies the reassessment of proposals after responding to the impact categories with lowest values through mitigating or altering the corresponding inventory indicators, as highlighted in the developed decision-making framework. Particular to this case study, there is a possibility of change in results after such reassessment, however, reassessment has not been performed for this case study due to limited access to project record and data.

From these findings, it can be sufficiently established that decision-making of this scale cannot solely rely on individual areas of sustainability and a holistic vision is inevitable. The proposed framework and decision-making model points that a proposal with only financial advantage (R-3) has been preferred over the alternative with overall best score (R-2). The long-term implications of such decision-making can be alarming if not entirely disastrous in the form of latent problem and issues pertaining to socio-economic repercussions.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Infrastructure development has a direct relation with economic development of any country (Grimsey and Lewis, 2007). However, the budgetary constraints of countries are hindering the pace of development and thus constrain the economic development. Also, for project evaluation and assessment, the existing tools and techniques are majorly relying upon financial assessment and have the least focus on other concerns of sustainability. This may lead towards the ill-conceived development projects, posing alarming impacts over people. Thus, there is a dire need to revisit the traditional practices of project assessment and evaluation and broaden the scope of assessment beyond the financial analysis.

To assess the viability of the infrastructure as a best resultant towards the benefit of people, lifecycle sustainability addresses and converges all policy aspects. Also, it roots into the social benefits as well as environmental concerns along with the consideration of financial aspects, covering the range of impacts over the ages (Ahmad and Thaheem, 2017). Thus, the proposed methodological framework for the road infrastructure project evaluation and prioritization is based on LCSA, encompassing all the sustainability concerns and enhancing the valuation of people benefits in the project selection.

The significance of sustainability parameters related to the people and their benefits was also highlighted by the results of this study. As social area of sustainability has significantly higher weight than the others, whereas, the financial concern, which is the most widely used parameter for project evaluation in traditional practices, has the least weight. Similarly, the social impacts having direct impact over the people obtained the higher weights, such as 'health and safety' and 'human rights', whereas, cultural heritage was given the least priority. Significantly, though the 'Governance' was quoted to have indirect relation with people, it has obtained the second highest weight and it was being considered by the experts as the key solution for many other impacts over people. The impact categories related to environment represent same pattern, as 'human health damage' got the highest weight and 'resources damage' obtained the least.

The work presented in this study provides the decision makers with a holistic project evaluation tool which appraises the veracious indicators for supporting critical decision-making while prioritizing the people and sustainability. The proposed methodological framework comprehends the methodological attributes for the LCSA impact categories, their impact assessment processes and inventory material and processes. The developed LCSA model integrates all the social, environmental and financial impacts into single parameter for the quantitative evaluation of projects. And the decision-making framework tracking pathways to analyze the most impactful inventory processes and inventory materials, enabling the decision maker to make best fit changes in project and to devise mitigation strategies.

The established threshold limits are the key feature of the decision-making framework. However, decision-making process in not limited to the threshold values of impact categories and also considers the subjective interpretation of the contextual and actual situation of concerning damages. Such as, compromising cultural heritage involves religious and cultural sentiments of the community, thus need to be properly managed and mitigated. Similarly, minimum level of road user and local community safety should be managed according to the road safety standards (Organization, 2015).

5.2 Limitations and future recommendations

This study focuses on the baseline of the sustainability which seems to incorporate all the aspects of decision-making criteria in broader perspective. However, criteria such as technological feasibility aspect and the financial resource availability can be directly considered to appraise the decision-making. Further, the hierarchy of impact categories and other attributes of this research are selected from the existing literature, which is mainly focused on the assessment of project section, material evaluation and material performance. However, for the comparison and assessment of complete project, the attributes and boundaries would be broader and should be evaluated specifically.

For S-LCA, despite the availability of UNEP /SETAC guidelines and methodological sheets (UNEP, 2009;2012), it still lacks the characterization of subcategories into the impact categories. Also, the inventories and subcategories need to be evaluated and screened for the road infrastructure projects in particular.

REFERENCES

Adams, T. M., & Kang, M. (2006). *Considerations for establishing a pavement preservation program.* Paper presented at the Transportation Research Board 85th annual meeting.

Adler, P. A., & Adler, P. (2011). *The tender cut: Inside the hidden world of self-injury*: NYU Press.

Agnes Cheng, C., Kite, D., & Radtke, R. (1994). The applicability and usage of NPV and IRR capital budgeting techniques. *Managerial Finance, 20*(7), 10-36.

Ahmad, T., & Thaheem, M. J. (2017). Developing a residential building-related social sustainability assessment framework and its implications for BIM. *Sustainable Cities and Society, 28*, 1-15. doi:https://doi.org/10.1016/j.scs.2016.08.002

Asiedu, Y., & Gu, P. (1998). Product life cycle cost analysis: state of the art review. *International Journal of Production Research, 36*(4), 883-908.

ASTM, E. (2002). 917-02: Standard Practice for Measuring. *Life-Cycle Costs of Buildings and Building Systems, USA.*

Athena, I. (2006). A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. *Cement Association of Ottawa: Ottawa, ON, Canada*.

Atilgan, B., & Azapagic, A. (2016). An integrated life cycle sustainability assessment of electricity generation in Turkey. *Energy Policy, 93*, 168-186.

Azapagic, A. (2002). Life cycle assessment: a tool for identification of more sustainable products and processes. *Handbook of green chemistry and technology*, 62-85.

Azapagic, A. (2010). Assessing environmental sustainability: life cycle thinking and life cycle assessment. *Sustainable Development in Practice: Case Studies for Engineers and Scientists, Second Edition*, 56-80.

Azapagic, A., & Perdan, S. (2000). Indicators of sustainable development for industry: a general framework. *Process Safety and Environmental Protection, 78*(4), 243-261.

Azapagic, A., & Perdan, S. (2005). An integrated sustainability decision-support framework Part II: Problem analysis. *The International Journal of Sustainable Development & World Ecology, 12*(2), 112-131.

Babashamsi, P., Yusoff, N. I. M., Ceylan, H., Nor, N. G. M., & Jenatabadi, H. S. (2016). Evaluation of pavement life cycle cost analysis: Review and analysis. *International Journal of Pavement Research and Technology*, *9*(4), 241-254.

Baker, S. E., Edwards, R., & Doidge, M. (2012). How many qualitative interviews is enough?: Expert voices and early career reflections on sampling and cases in qualitative research.

Bare, J. C., Hofstetter, P., Pennington, D. W., & De Haes, H. A. U. (2000). Midpoints versus endpoints: the sacrifices and benefits. *The International Journal of Life Cycle Assessment*, *5*(6), 319.

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application*: External organization.

Benoît-Norris, C., Vickery-Niederman, G., Valdivia, S., Franze, J., Traverso, M., Ciroth, A., & Mazijn, B. (2011). Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. *The International Journal of Life Cycle Assessment, 16*(7), 682-690.

Benoît, C., Norris, G. A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., . . . Beck, T. (2010). The guidelines for social life cycle assessment of products: just in time! *The International Journal of Life Cycle Assessment, 15*(2), 156-163.

Berk, J. (2014). *Corporate Finance, Third Canadian Edition Plus NEW MyFinanceLab with Pearson EText--Access Card Package*: Pearson Education Canada.

Bierer, A., Meynerts, L., & Götze, U. (2013). Life Cycle Assessment and Life Cycle Costing-Methodical Relationships, Challenges and Benefits of an Integrated Use *Re-engineering Manufacturing for Sustainability* (pp. 415-420): Springer.

Birgisdóttir, H., & Christensen, T. H. (2005). *Life cycle assessment model for road construction and use of residues from waste incineration.* Technical University of DenmarkDanmarks Tekniske Universitet, Department of Environmental Science and EngineeringInstitut for Miljøteknologi.

Boshoff, L., Childs, R., & Roberts, L. (2009). Guidelines For Infrastructure Asset Management In Local Government 2006–2009. *Department of Provincial and Local Government, REPUBLIC OF SOUTH AFRICA, Pretoria*.

Brundtland, G. H. (1987). *Report of the World Commission on environment and development:" our common future."*: United Nations.

Butt, A. A. (2014). *Life Cycle Assessment of Asphalt Roads: Decision Support at the Project Level.* KTH Royal Institute of Technology.

Capony, A., Muresan, B., Dauvergne, M., Auriol, J.-C., Ferber, V., & Jullien, A. (2013). Monitoring and environmental modeling of earthwork impacts: A road construction case study. *Resources, Conservation and Recycling, 74*, 124-133.

Carlson, A. (2011). *Life cycle assessment of roads and pavements: Studies made in Europe*: Statens väg-och transportforskningsinstitut.

Cass, D., & Mukherjee, A. (2011). Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: case study for pavement operations. *Journal of Construction Engineering and Management, 137*(11), 1015-1025.

Chan, A. W.-C. (2007). *Economic and environmental evaluations of life cycle cost analysis practice: a case study of Michigan DOT pavement projects.* University of Michigan.

Chang, N.-B. (2010). *Systems analysis for sustainable engineering: theory and applications*: McGraw Hill Professional.

Chhipi-Shrestha, G. K., Hewage, K., & Sadiq, R. (2015). 'Socializing'sustainability: a critical review on current development status of social life cycle impact assessment method. *Clean Technologies and Environmental Policy, 17*(3), 579-596.

Chowdhury, R., Apul, D., & Fry, T. (2010). A life cycle based environmental impacts assessment of construction materials used in road construction. *Resources, Conservation and Recycling, 54*(4), 250-255.

Ciroth, A., Finkbeier, M., Hildenbrand, J., Klöpffer, W., Mazijn, B., Prakash, S., . . . Valdivia, S. (2011). Towards a live cycle sustainability assessment: making informed choices on products: United Nations Environment Programma (UNEP).

Davis Langdon. (2007). Literature review of life cycle costing (LCC) and life cycle assessment (LCA). *Management Consulting*.

de Haes, H. A. U., & Heijungs, R. (2007). Life-cycle assessment for energy analysis and management. *Applied Energy, 84*(7), 817-827.

Di Cesare, S., Silveri, F., Sala, S., & Petti, L. (2016). Positive impacts in social life cycle assessment: state of the art and the way forward. *The International Journal of Life Cycle Assessment*, 1-16.

Díaz-Balteiro, L., & Romero, C. (2004). In search of a natural systems sustainability index. *Ecological Economics, 49*(3), 401-405.

Dong, Y. H., & Ng, S. T. (2014). Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong. *The International Journal of Life Cycle Assessment, 19*(7), 1409-1423.

Economics, O. (2014). *Capital project and infrastructure spending Outlook to 2025*. Retrieved from http://www.pwc.com/gx/en/industries/capital-projects-infrastructure/publications/cpi-outlook/about.html

ECRPD. (2009, November). *Energy Conservation in Road Pavement Design, Maintenance and Utilisation.* Paper presented at the WP6 – Life Cycles Evaluation, Centrum dopravniho vyzkumu, Lisenska, Czech Republic.

Evangelista, L., & De Brito, J. (2007). Environmental life cycle assessment of concrete made with fine recycled concrete aggregates. *Portugal Sb07-Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium, Pts, 1*, 789-794.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment, 11*(2), 80-85.

Finkbeiner, M., Schau, E. M., Lehmann, A., & Traverso, M. (2010). Towards life cycle sustainability assessment. *Sustainability, 2*(10), 3309-3322.

Finn, D. (2009). *Our uncertain future: Can good planning create sustainable communities*: ProQuest.

Francois, J., & Manchin, M. (2013). Institutions, infrastructure, and trade. *World Development, 46*, 165-175.

Gautam, P. (2011). *Social life cycle assessment of solid waste management in Kathmandu City Nepal.* Paper presented at the Proceedings of the Life Cycle Management 2011 Conference, Berlin.

Govt of Pakistan, M. o. F. (2014). *Paksitan Economic Survey 2013-14*. Retrieved from www.finance.gov.pk/survey/chapters_13/13-Transport%20final.pdf

Govt of Pakistan, M. o. F. (2015). *Pakistan Economic Survey 2014-15*. Retrieved from http://www.finance.gov.pk/survey/chapters_15/13_Transport.pdf

Grimsey, D., & Lewis, M. (2007). *Public private partnerships: The worldwide revolution in infrastructure provision and project finance*: Edward Elgar Publishing.

Guinée, J. (2016). Life cycle sustainability assessment: What is it and what are its challenges? *Taking Stock of Industrial Ecology* (pp. 45-68): Springer.

Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., . . . Rydberg, T. (2010). Life cycle assessment: past, present, and future†. *Environmental science & technology, 45*(1), 90-96.

Häkkinen, T., & Mäkelä, K. (1996). Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements. *Vtt tiedotteita*.

Hameed, F. (2015). China Pakistan Economic Corridor-Transforming Pakistan's corporate culture. *Institute of Strategic Studies (ISSI) Pakistan*. Retrieved from http://issi.org.pk/wp-content/uploads/2015/07/Final-Issue-brief_dated-22-7-2015.pdf

Hammervold, J. (2015). Towards greener road infrastructure: life cycle assessment of case studies and recommendations for impact reductions and planning of road infrastructure.

Hauschild, M. Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., . . . Laurent, A. (2013). Identifying best existing practice for characterization modeling in life cycle impact assessment. *The International Journal of Life Cycle Assessment, 18*(3), 683-697.

Heijungs, R., Goedkoop, M., Struijs, J., Effting, S., Sevenster, M., & Huppes, G. (2003a). Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level. *Report of the first project phase: Design of the new method VROM report. Online: http://www. leidenuniv. nl/cml/ssp/publications/recipe_phase1. pdf*.

Heijungs, R., Goedkoop, M., Struijs, J., Effting, S., Sevenster, M., & Huppes, G. (2003b). Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level. *Report of the first project phase: Design of the new method VROM report*.

Heijungs, R., Huppes, G., & Guinée, J. B. (2010). Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. *Polymer degradation and stability, 95*(3), 422-428.

Hermann, B., Kroeze, C., & Jawjit, W. (2007). Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *Journal of Cleaner Production, 15*(18), 1787-1796.

Hoogmartens, R., Van Passel, S., Van Acker, K., & Dubois, M. (2014). Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environmental Impact Assessment Review, 48*, 27-33. doi:http://dx.doi.org/10.1016/j.eiar.2014.05.001

Horvath, A., & Hendrickson, C. (1998). Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. *Transportation Research Record: Journal of the Transportation Research Board*(1626), 105-113.

Hu, X., Chang, S., Li, J., & Qin, Y. (2010). Energy for sustainable road transportation in China: Challenges, initiatives and policy implications. *Energy, 35*(11), 4289-4301. doi:http://dx.doi.org/10.1016/j.energy.2009.05.024

Huang, Y., Bird, R., & Bell, M. (2009). A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. *Transportation Research Part D: Transport and Environment, 14*(3), 197-204.

ISO. (2006). 14040: 2006. *Environmental management–Life cycle assessment–Principles and framework*.

Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., . . . Potting, J. (2004). The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *The International Journal of Life Cycle Assessment, 9*(6), 394-404.

Jonsson, D. (2007). Indirect energy associated with swedish road transports. *European Journal of Transport and Infrastructure Research, 7*(3).

K. Ozbay, N. A. P., D. Jawad, S. Hussain, . (2003). Guidelines for Life Cycle Cost Analysis. *Final Report, Report No FHWA-NJ-2003-012, Trenton, NJ*.

Kallis, G., Kerschner, C., & Martinez-Alier, J. (2012). The economics of degrowth: Elsevier.

Karim, H. (2008). *Improved Road Design for Future Maintenance–Analysis of Road Barrier Repair Costs*. Royal Institute of Technology.

Kasemir, B. (2003). *Public participation in sustainability science: a handbook*: Cambridge University Press.

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., . . . Dickson, N. M. (2001). Sustainability science. *Science, 292*(5517), 641-642.

Khang, D. B., & Moe, T. L. (2008). Success criteria and factors for international development projects: A life-cycle-based framework. *Project Management Journal, 39*(1), 72-84.

Kim, C., Lee, E.-B., Harvey, J. T., Fong, A., & Lott, R. (2015). Automated Sequence Selection and Cost Calculation for Maintenance and Rehabilitation in Highway Life-Cycle Cost Analysis (LCCA). *International Journal of Transportation Science and Technology, 4*(1), 61-76.

Klöpffer, W., & Renner, I. (2008). Life-cycle based sustainability assessment of products *Environmental Management Accounting for Cleaner Production* (pp. 91-102): Springer.

Krutzfeldt, G. (2012). Life-cycle costing and risk management: The influence of uncertainties on Dutch transportation infrastructure projects.

Kucukvar, M., Noori, M., Egilmez, G., & Tatari, O. (2014). Stochastic decision modeling for sustainable pavement designs. *The International Journal of Life Cycle Assessment, 19*(6), 1185-1199.

Li, X., Zhu, Y., & Zhang, Z. (2010). An LCA-based environmental impact assessment model for construction processes. *Building and Environment, 45*(3), 766-775.

Lindfors, L.-G. (1995). Nordic Guideline on Life-Cycle Assessment. *Nord 20*.

Loijos, A. A. N. (2011). *Life cycle assessment of concrete pavements: impacts and opportunities.* Massachusetts Institute of Technology.

Magnus, J. R., & Neudecker, H. (1988). Matrix differential calculus with applications in statistics and econometrics. *Wiley series in probability and mathematical statistics*.

Matos, S., & Hall, J. (2007). Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology. *Journal of Operations Management, 25*(6), 1083-1102.

Mattioda, R. A., Mazzi, A., Canciglieri, O., & Scipioni, A. (2015). Determining the principal references of the social life cycle assessment of products. *The International Journal of Life Cycle Assessment, 20*(8), 1155-1165.

Menoufi, K. A. I. (2011). Life cycle analysis and life cyle impact assessment methodologies: a state of the art.

Mithraratne, N., Vale, B., & Vale, R. (2007). *Sustainable living: The role of whole life costs and values*: Routledge.

Mroueh, U. (2000). LIFE CYCLE ASSESSMENT OF ROAD CONSTRUCTION.

Muench, S. (2010). Roadway construction sustainability impacts: review of life-cycle assessments. *Transportation Research Record: Journal of the Transportation Research Board*(2151), 36-45.

Muga, H. E., Mukherjee, A., Mihelcic, J. R., & Kueber, M. J. (2009). An integrated assessment of continuously reinforced and jointed plane concrete pavements. *Journal of Engineering, Design and Technology, 7*(1), 81-98. doi:doi:10.1108/17260530910947277

Nemarumane, T. M., & Mbohwa, C. (2013). Social impact assessment of sugar production operations in South Africa: a social life cycle assessment perspective *Re-engineering Manufacturing for Sustainability* (pp. 711-716): Springer.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2007). Categorising tools for sustainability assessment. *Ecological economics, 60*(3), 498-508.

NHA. (2009). Public Private Partnership Policy and Regulatory Framework. *Public Private Partnership Policy and Regulatory Framework - Private Sector Participation in National Highways, Motorways, Tunnels and Bridge Projects in Pakistan. National Highway Authority.*

. Retrieved from http://nha.gov.pk/wp-content/uploads/2012/08/NHA-PPP-Policy-and-Regulatory-Framework1.pdf.

Niekamp, S., Bharadwaj, U. R., Sadhukhan, J., & Chryssanthopoulos, M. K. (2015). A multi-criteria decision support framework for sustainable asset management and challenges in its application. *Journal of Industrial and Production Engineering, 32*(1), 23-36.

Norris, G. A. (2001). Integrating life cycle cost analysis and LCA. *The International Journal of Life Cycle Assessment, 6*(2), 118-120.

O'Born, R. J., Brattebø, H., Iversen, O. M. K., Miliutenko, S., & Potting, J. (2016). Quantifying energy demand and greenhouse gas emissions of road infrastructure projects: An LCA case study of the Oslo fjord crossing in Norway.

Ochoa, K., Castaño, I., & Alvarez, B. (2014). Social Life Cycle Assessment for Open Pit Gold Mining in Colombia: a case study in Tolima (Colombia). *Social LCA in progress*.

Olinto, A. C. (2017). Invariance and robustness of the ordered inequality of aggregate sustainability indices by vector space theory. *Clean Technologies and Environmental Policy, 19*(2), 587-594.

Organization, W. H. (2015). *Global status report on road safety 2015*: World Health Organization.

Osborne, M. J. (2010). A resolution to the NPV–IRR debate? *The Quarterly Review of Economics and Finance, 50*(2), 234-239.

Pant, R., Bersani, R., Pennington, D. W., & Brandao, M. (2010). ILCD Handbook-Analysis of existing environmental impact assessment methodologies for use in life cycle assessment-background document.

Parajuli, S. P., Naizghi, M. S., Warshay, B., & Arafat, H. A. (2011). A comparative Life Cycle Assessment (LCA) of Using Virgin Crushed Aggregate (VCA) and Recycled Waste Concrete Aggregate (RCA) in Road Construction. *on Water, Energy and Environment 2011*, 312.

Parent, J., Cucuzzella, C., & Revéret, J.-P. (2010). Impact assessment in SLCA: sorting the sLCIA methods according to their outcomes. *The International Journal of Life Cycle Assessment, 15*(2), 164-171.

Park, K., Hwang, Y., Seo, S., & Seo, H. (2003). Quantitative assessment of environmental impacts on life cycle of highways. *Journal of Construction Engineering and Management, 129*(1), 25-31.

Perdan, S., & Azapagic, A. (2011). Measuring sustainable development: an overview. *Sustainable Development in Practice: Case Studies for Engineers and Scientists, Second Edition*, 26-55.

Petti, L., Ugaya, C. M. L., & Di Cesare, S. (2014). Systematic review of social-life cycle assessment (S-LCA) case studies. *Social LCA in progress. FruiTrop, Montpellier*.

Reza, B., Sadiq, R., & Hewage, K. (2014). Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: a case study on paved roads. *Clean Technologies and Environmental Policy, 16*(2), 251-266.

Roseland, M. (2000). Sustainable community development: integrating environmental, economic, and social objectives. *Progress in planning, 54*(2), 73-132.

Sachs, J. D. (2015). *The age of sustainable development*: Columbia University Press.

Said, F., Bolong, N., & Gungat, L. (2012). *Life cycle assessment of asphalt pavement construction and maintenancei a review*. Paper presented at the 10th Seminar Sains and Teknologi.

Sala, S., Vasta, A., Mancini, L., Dewulf, J., & Rosenbaum, E. (2015). *Social Life Cycle Assessment*. Retrieved from

Santero, N. J., Masanet, E., & Horvath, A. (2011a). Life-cycle assessment of pavements Part II: Filling the research gaps. *Resources, Conservation and Recycling, 55*(9), 810-818.

Santero, N. J., Masanet, E., & Horvath, A. (2011b). Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling, 55*(9–10), 801-809. doi:http://dx.doi.org/10.1016/j.resconrec.2011.03.010

Santoyo-Castelazo, E., & Azapagic, A. (2014). Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *Journal of Cleaner Production, 80*, 119-138.

Schenck, R. (2000). Using LCA for procurement decisions: A case study performed for the US Environmental Protection Agency. *Environmental Progress & Sustainable Energy, 19*(2), 110-116.

Schlaupitz, A. H., & Naturvernforbund, N. (2008). Energi-og klimakonsekvenser av moderne transportsystemer. *Effekter ved bygging av høyhastighetsbaner i Norge. Norges Naturvernforbund, Oslo*.

Seppälä, J., & Hämäläinen, R. P. (2001). On the meaning of the distance-to-target weighting method and normalisation in life cycle impact assessment. *The International Journal of Life Cycle Assessment, 6*(4), 211-218.

Stenbeck, T. (2004). *Incentives to innovations in road and rail maintenance and operations.*

Stripple, H. (2001). Life cycle assessment of road. *A pilot study for inventory analysis. 2nd revised Edition. Report from the IVL Swedish Environmental Research Institute, 96*.

Stripple, H., & Erlandsson, M. (2004). Methods and possibilities for application of life cycle assessment in strategic environmental assessment of transport infrastructures. *Building Environmental Assessment CONsensus on the Transeuropean Transport Network (BEACON). ISER Institute*.

Swarr, T. E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. C., & Pagan, R. (2011). Environmental life-cycle costing: a code of practice: Springer.

Treloar, G. J., Love, P. E., & Crawford, R. H. (2004). Hybrid life-cycle inventory for road construction and use. *Journal of Construction Engineering and Management, 130*(1), 43-49.

Tupamäki, O. (1998). Construction Can. *ENCORD's Programme for RTD&ID, The European Network of Construction Companies for Research and Development*.

Ugwu, O., Kumaraswamy, M., Kung, F., & Ng, S. (2005). Object-oriented framework for durability assessment and life cycle costing of highway bridges. *Automation in construction, 14*(5), 611-632.

UNEP. (2009). Guidelines for Social Life Cycle Assessment of Products.

UNEP. (2012). Towards a lifecycle sustainability assessment: making informed choices on products. Retrieved from LC3a2

Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling, 74,* 101-114.

Vinodh, S., Jayakrishna, K., & Joy, D. (2012). Environmental impact assessment of an automotive component using eco-indicator and CML methodologies. *Clean Technologies and Environmental Policy, 14*(2), 333-344.

Walls III, J., & Smith, M. R. (1998a). *Life-cycle cost analysis in pavement design-interim technical bulletin*. Retrieved from

Walls III, J., & Smith, M. R. (1998b). Life-cycle cost analysis in pavement design, FHWA-SA-98-079. *U.S. Dept. of Transportation, FHWA, Washington, DC.*

White, P., Golden, J. S., Biligiri, K. P., & Kaloush, K. (2010). Modeling climate change impacts of pavement production and construction. *Resources, Conservation and Recycling, 54*(11), 776-782.

Wolthuis, L. (2014). *Decision Support System to conduct Life Cycle Cost Analysis for service life road pavement design using an object oriented model.* University of Twente.

You, F., Tao, L., Graziano, D. J., & Snyder, S. W. (2012). Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis. *AIChE Journal, 58*(4), 1157-1180.

Yu, B., & Lu, Q. (2012). Life cycle assessment of pavement: Methodology and case study. *Transportation Research Part D: Transport and Environment, 17*(5), 380-388.

Zapata, P., & Gambatese, J. A. (2005). Energy consumption of asphalt and reinforced concrete pavement materials and construction. *Journal of Infrastructure Systems, 11*(1), 9-20.

Zimmerman, K., Smith, K., & Grogg, M. (2000). Applying economic concepts from life-cycle cost analysis to pavement management analysis. *Transportation Research Record: Journal of the Transportation Research Board*(1699), 58-65.

Zoeteman, A. (2001). Life cycle cost analysis for managing rail infrastructure. *European journal of transport and infrastructure research EJTIR, 1 (4)*.