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Integrating Bridge Maintenance Life Cycle Assessments into Bridge Design for Improved Sustainable Decision Making

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ABSTRACT

Environmental sustainability issues are being considered across many construction sectors, emerging from global concerns on resource depletion and CO_2 emissions. Whilst construction sectors are minimising the environmental impact of their activities and the associated CO_2 and Green House Gas (GHG) emissions, not many of these environmental issues are factored into the early design stage of bridges to facilitate design choices. Consequently, environmental impacts of bridge maintenance activities are not factored into the bridge design process. Doing so can potentially reveal the overall environmental performance of the bridge and enhance design choices. The Life Cycle Assessment (LCA) environmental tool is gaining ground across many construction sectors, because of its capacity to reveal the environmental impacts of process and services. LCA has been only minimally explored for bridges, and its integration into the early design process has not been seriously attempted. In fact, only a small volume of literature has considered LCA application to bridge maintenance activities, and that without considering the scope for influencing sustainable bridge design decisions through stakeholders' input.

The research was undertaken to provide insights and recommendations for incorporating LCA result of bridge maintenance methods at the early design stage to aid sustainable design choices. The study conducted a thorough literature review to understand and explore the environmental aspect of sustainability in bridges and the trend and usefulness of LCA results in the bridge industry. Results revealed that not many environmental matters are considered for bridge design and maintenance, and that LCA application for bridges is limited to comparison of materials, components and structural types. As such, this study launches an LCA analysis of some major maintenance activities of concrete, steel, and masonry bridge, which is mainly assumed for other studies. Results revealed expansion joint and bearing replacement as key sources for high environment impact in concrete and steel bridge, whereas saddling rehabilitation had the most impact for masonry bridge. The overall comparison revealed masonry bridge as the least environmentally impactful bridge on account of the selected maintenance actions.

Through a semi-structured interview, the study presented the derived result to bridge design experts to verify and reveal the usefulness of the result. Experts revealed the emergence of masonry bridge (as the least impactful structure) as the major usefulness of the result. Any industry drive towards masonry bridges is, however, constrained by initial construction cost, span limitation and speed of completion. General findings from the study revealed that LCA incorporation into the design process will be a complex matter, as the design process is already intricate, and environmental concerns are not a major design criterion. The study therefore makes four recommendations that can enhance the consideration of LCA, and consequently LCA of bridge maintenance actions, in the early design process. These are: (1) detailed environmental matters such as CO_2, NO_2 and GHG emissions should be considered as a design criterion; (2) encourage designers to highlight emerging environmental matters within the design brief; (3) LCA awareness should be increased amongst bridge designers; and (4) LCA damage indicators may be factored into bridge design process. The thesis also concludes by making detailed recommendations to policy makers, researchers, designers, and bridge owners.

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LIST OF ABBREVIATIONS

LCA	Life Cycle Assessment
GHG	Green House Gas
UN	United Nations
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
ISO	International Organization for Standardization
WLC	Whole Life Cost
EIA	Environmental Impact Assessment
LCC	Life Cycle Cost
SEA	Strategic Environmental Assessment
BREEAM	Building Research Establishment Environment Assessment Method
EPBD	Energy Performance of Buildings Directive
LEED	Leadership in Energy and Environmental Design
EPA	Environmental Protection Agency
DBERR	Department for Business Enterprise and Regulatory Reform
DECC	Department of Energy and Climate Change
ESRC	Economics and Social Research Council
EU	European Union
SPSS	Statistical Package for the Social Sciences
WCED	World Commission on Environment and Development
CEEQUAL	Civil Engineering Environmental Quality Award and Assessment
BRS	Building Rating System
BRE	Building Research Establishment
HQE	High Quality Environment Standards
DGNB	German Sustainable Building Council
DCLG	Department for Communities and Local Government

SETAC	Society of Environment Toxicology and Chemistry
MRI	Midwest Research Institute
REPA	Resource and Environmental Profile Analysis
ECS	European Construction Sector
IPCC	Intergovernmental Panel on Climate
CC	Climate Change
FD	Fossil Depletion
MD	Metal Depletion
TA	Terrestrial Acidification
FE	Freshwater Eutrophication
OD	Ozone Depletion
GWP	Global Warming Potential
POCP	Photochemical Oxidation Potential
PM	Particulate Matter
EPS	Environmental Priority Strategies
EDIP	Environmental Design of Industrial Products
UNEP	United Nations Environment Programme
EIO	Economics Input and Output
DEAM	Database for Environmental Analysis and Management
ISI	International Steel Institute
HPC	High Performance Concrete
EAF	Electricity Arc Furnace
BOF	Basic Oxygen Furnace
UHPC	Utra-High Performance Concrete
IRP	Ionizing Radiation
ICE	Institute of Civil Engineers
ASCE	American Society of Civil Engineers

FREC	Faculty Research Ethics Committee
APMO	Average Percent of Majority Opinions
EMS	Environmental Management System

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DEDICATION

This thesis is dedicated to my family, my wife Modupeoluwa, my beautiful daughters Elizabeth and Ellen, my parents Engr Teslim Rasheed Olumide Balogun and Mrs Kehinde Teslim Balogun.

CHAPTER ONE: INTRODUCTION AND BACKGROUND TO THE RESEARCH

1. Introduction

The chapter presents the research background, problem definition, rationale for the research, aim and objectives of the study, and a quick overview of methods employed in addressing them, and concludes by presenting the thesis outline and a brief summary of the chapter itself.

1.1 Background to Research

The built environment is the third largest contributor of Green House Gas (GHG) emissions owing to its extensive activities embedded in material extraction, product manufacture, transportation, construction, maintenance, repair and refurbishment and end-of-life (EPA, 2010). Construction works consume 60% of the earth's raw materials, within which the building sector accounts for about 40% (Correia, 2015). In the UK, the building sector alone accounts for approximately 50% of all carbon dioxide emissions, over 30% of landfill waste and 50% of water consumption from its construction, occupation, and maintenance (DBERR, 2007) activities. UK government is, however, committed to reducing carbon emissions by at least 80% below the 1990 baselines by 2050, and to also reduce GHG emissions by at least 34% compared to the 1990 baseline by 2020 (DECC, 2015). A recent report indicates a 17% and 14% reduction in the emissions of GHG during the period from 2013 to 2014 for the residential and energy supply sectors respectively, but only 3% lower in 2014 than in 1990 for the transport sector (DECC, 2016). Though the set target to reduce GHG by 34% in 2020 is on the way, statistics show relatively little overall reduction in the level of GHG emissions from the transport sector, which is an integral part of the built environment (Saxe *et al*., 2016).

Sustainable development has been the focus of the construction industry for the last two decades, which is in response to global concerns, especially on issues of limited resources and climate change. DBERR (2008) recognised that it will be impossible to reduce the environmental impact of buildings and infrastructure if radical change towards sustainable construction is not engendered. Sustainable construction has reached a tipping point within the built environment sector, such that initiatives, guidance, and regulations towards achieving a sustainable practice have been developed (Barlett and Gurthrie, 2005; Ghumra, 2009; Hojjati *et al*., 2016). Examples of sustainability initiatives for buildings are Energy Performance of Buildings Directive (EPBD), Building Research Establishment Environment Assessment Method (BREEAM), and Leadership in Energy and Environmental Design (LEED) that provides ratings for green buildings. Apart from buildings, initiatives are available for highway infrastructure, such as *Best Value* and agenda 2030 which is an update of Local Agenda 21. While the building construction sector has substantively considered sustainability in their processes, highway infrastructure is yet to incorporate this in full (Gervásio and da Silva 2013; Lounis and Daigle, 2007; Du *et al*., 2014). Civil Engineering Environmental Quality Award and Assessment Method (CEEQUAL) is a widely-recognised assessment tool for infrastructure projects, equivalent to BREEAM (Levett-Therivel, 2004). Though CEEQUAL is versatile enough to address any infrastructure project (Ghumra, 2009; CEEQUAL, 2017), it does not provide a adequate means for achieving the required environmental score. Consequently, project managers need to apply their own environmental assessment tool to achieve the required standard to qualify for an award. CEEQUAL can, however, be integrated with any life cycle assessment tool to achieve best practice for infrastructure (Ghumra, 2009).

Highway Infrastructure cannot be ignored in global warming issues, because it embeds roads, bridges, railways and so on (Pollalis *et al*., 2012), crucial for economic development. Bridges play a vital role in highway infrastructure and allow the transportation of goods and services from one place to another (Wilmers, 2012). Not many researches have considered sustainability of bridges (Arya, Amiri and Vassie, 2015), especially from the aspect of life cycle maintenance plans and how they may inform new bridge design. It is more common to investigate sustainability of bridges through a single life-cycle phase such as the design, construction, maintenance, and end-of-life phases (Du *et al*., 2014). Moreover, sustainability in bridge design has only just started arousing interest, compared to sustainability in bridge construction and maintenance (Pang *et al*., 2015).

Design is, however, identified by DBERR (2008) as playing a significant role in achieving overarching sustainable development targets. A sustainable design is that which contributes to the triple bottom line of environmental, social and economic sustainability (DBERR, 2008), and this has not been fully explored for bridges, particularly sustainable design based on life-cycle maintenance methods.

Life-cycle Assessment (LCA) has been introduced to improve sustainability across many built environment sectors (Cabeza *et al*., 2014), but this has not received serious attention for decision making in bridge design. In addition, LCA results present environmental indicators such as climate change, resource use, metal depletion, water consumption and so on, which are rarely considered in the early design stage of bridges. These indicators are now part of urgent sustainable development matters in Agenda 2030 (United Nations, 2015), and will need to be considered for bridges. On this note, the research is focused on contributing to the body of knowledge in the area of sustainable bridge design, by investigating the environmental impact of bridge maintenance methods and how it can possibly affect sustainable design decisions. This stems from the fact that decisions made in the early design process have far reaching environmental impact (Riches, 2003; Collings, 2006; Ainger and Fenner, 2014). Hence, an insight from investigating common bridge maintenance methods – with the hope of implementing their LCA results into bridge design – could potentially yield useful knowledge for improving designers' sustainable decisions in the early design stage.

1.2 Problem Definition

Sustainable design of bridges encompasses the overall life cycle of the bridge and goes beyond issues of safety and initial cost alone (Gervasio and da Silva, 2013). Decisions on structural type, material acquisition, maintenance and repair options normally occur at the design stage of a bridge, and affect the environmental performance of the bridge (Du *et al*., 2014). Until recently, the environmental impact of bridges has been neglected in decision making compared to their economic and safety performance (Du and Karoumi, 2013). Unlike building designers, bridge designers have few or no specific tools for measuring environmental impact of bridges as the design process itself is led by technical and safety issues, with environmental impact issues being generally neglected (Du and Karoumi 2014).

The drive for sustainable structural options is increasing, which is in response to UK's target to reduce CO_2 and GHG emissions by 2020. Studies such as Collings (2006), Lounis and Daigle (2007), and Bouhaya, Roy and Feraille-Fresent (2009) have tried to address the environmental impact of bridges by measuring the CO_2 emission from a specific life-cycle phase of a bridge. More recent studies have attempted to address the environmental impact of bridges using LCA, though the level of application varies. For instance, Du *et al*. (2014) tried to apply LCA at the procurement stage of five different types of bridge design options in order to identify the option with best environmental performance. Pang *et al*. (2015) used LCA to assess five different strengthening techniques of a bridge to identify the one with best environmental performance. However, a study that has fully applied LCA to investigate the environmental impact of maintenance methods with the hope of integrating the result within the design of new bridges is yet to be identified.

In addition, despite the recent use of LCA to evaluate the environmental impact of bridge structural or material options (Thiebault, 2010; Du and Karoumi 2013; Du *et al*., 2014; Pang *et al*., 2015), there is little or no expert opinion on the usefulness of the results during the design of new bridges. LCA results are rarely utilized in the design phase of transport infrastructure (Thiebault, Du and Karoumi, 2013). Hence, the research hopes to fill this research gap. Apart from this, the research plans to explore other limitations associated with the use of environmental impact results of bridge maintenance activities in general. Highlighted below are the current limitations of the topic area.

1. Information on the environmental impact of bridge maintenance activities is limited.
2. Limited effort has gone into identifying the challenges facing the use of LCA in bridge design.
3. There is limited knowledge on the usefulness of and barriers to integrating LCA result into bridge design.

4. The overarching and major limitation is that emerging environmental sustainability indicators are not directly factored into the bridge design process.

1.3 Research Questions

Five research questions emerged from the problems identified above. The research questions were used to structure and tailor the research towards providing deeper knowledge of the subject matter. According to Robson (2011), research questions are used to sharpen the structure of the research towards discovering new knowledge. Hence, research questions were adopted to steer the research towards a holistic discovery of new knowledge pertaining to the subject area. The research questions are;

1. What sustainability criteria are factored into new bridge design?
2. What are the drivers of structural or maintenance solutions?
3. What are the likely environmental impact results of bridge maintenance actions?
4. What is the degree of LCA awareness amongst bridge designers?
5. What is the usefulness of LCA results of bridge maintenance actions within a bridge design process?

1.4 Research Aim and Objectives

The research aims to provide insights and recommendations for incorporating LCA results of bridge maintenance methods at the early design stage, in order to improve the sustainability of bridge design. The objectives are therefore to:

1. Understand and explore environmental aspects of sustainability in infrastructure,

2. Understand the trend and usefulness of LCA results in the bridge industry,

3. Identify the probable environmental impact of concrete, steel, and masonry bridge maintenance activities, using the LCA tool,

4. Explore the stakeholders' perspective on the usefulness of factoring in LCA results of bridge maintenance methods into the bridge design process, and its potential to improve sustainability decisions,

5. Provide recommendations for integrating LCA results of bridge maintenance methods into bridge design.

1.5 Scope of the Research

The purpose of the research is to make recommendations for integrating the LCA results of bridge maintenance methods into bridge design. Although sustainable development encompasses the economic, social, and environmental perspectives, the present research focuses purely on the environmental aspect. The cradle-to-grave life cycle of bridges includes design, construction, maintenance, and end-of-life, whereas the research considers only the design and maintenance phases. The system boundary covered in the LCA analysis only accounts for material, energy, and transportation related to selected bridge maintenance methods.

1.6 An Overview of the Research Design

The philosophical paradigm underpinning the study is pragmatism, which principally aims to answer the research question using a mixed-method approach. The mixed-method approach allows the combination of quantitative and qualitative methods in certain respects (Creswell, 2014). Due to the nature of the research questions and objectives, which were structured to identify new knowledge, an explanatory sequential mixed method was adopted. That is, a quantitative approach was used before a qualitative approach.

A literature review was first conducted in the area of sustainable infrastructure to understand environmental impact and sustainability issues within infrastructure projects. The research narrowed the focus to environmental impact within the life-cycle stages of bridges, and promoted the use of LCA methodology for that purpose. Some commonly used bridge maintenance methods were further considered for environmental impact investigations, using LCA methodology. Methods were selected on the basis of cost, effectiveness and intervals. Material quantities used for these methods were identified in relevant literatures. Based on the explanatory sequential mixed method adopted, the quantities obtained in the literature were verified with bridge experts using an online questionnaire survey. The verification process was used to enhance the reliability of the material quantities derived from the literature. SPSS 22 statistical package was used to analyse respondents' responses on the verified quantities. Subsequently, verified quantities were put forward for LCA analyses.

SimaPro was used to conduct an LCA analysis on selected maintenance methods based on verified data. In line with the explanatory sequential mixed-method adopted, results derived from the LCA analysis were presented to bridge design experts, through a semi-structured in-depth interview, to obtain their views on the usefulness of the results in the design of new bridges. Qualitative data analysis software package (Nvivo 11) was used to analyse the Interviewees' responses, which led to major themes and significant findings. Based on emergent themes and findings, recommendations were developed for integrating LCA results of bridge maintenance methods into new bridge designs.

1.7 Structure of the Thesis

The thesis is organised into nine chapters as shown in Figure 1.1. The content of each chapter is presented below:

CHAPTER ONE: ***Introduction and Background to the Research***

This chapter presents the research background and justification for the research. The research questions, aims and objectives are outlined in this chapter, as well as the overall thesis.

CHAPTER TWO: ***Sustainability in Infrastructure***

This chapter being part of the literature explores the concept of sustainability and sustainable development within the built environment and in relation to the bridge infrastructure. Major and recent assessment tools used to appraise sustainability in infrastructure projects are reviewed. The chapter highlights the slow progress of integrating sustainability into bridge design.

CHAPTER THREE: ***LCA Methodology: Historic Insight, Framework, Application to Bridges and Usefulness of The Results***

The chapter presents a state-of-the-art review on various applications of LCA on bridges in the past two decades and discusses the usefulness of bridge LCA results.

CHAPTER FOUR: ***Research Design and Methodology***

The chapter discusses the design and methodology adopted in the study. It highlights approaches to address the research questions, aims and objectives, and discusses ethical issues to ensure the credibility, reliability, and validity of the research.

CHAPTER FIVE: ***Results and Analysis of Questionnaire Survey***

This chapter presents the verification process conducted to ensure the reliability of the data collected in chapter three of the research.

CHAPTER SIX: ***Inventory Analysis of Maintenance Methods***

The chapter presents the LCA analysis of selected bridge maintenance methods of concrete, steel, and masonry bridges. It presents the Life-cycle impact assessment (LCIA) of selected bridge maintenance methods, and highlights the relative damage they cause to human health and the ecosystem, and their contribution to resource depletion on a European scale.

CHAPTER SEVEN: ***Interview Analysis and Findings***

The chapter presents the analysis and findings derived from the interviews conducted with bridge experts.

CHAPTER EIGHT: ***Discussion of Findings and Development of Recommendations for the Integration of LCA in Bridge Design***

Findings from chapter six and seven are discussed and compared with existing literature to draw similarities and divergence between them. Insights and recommendations are presented for integrating LCA results of bridge maintenance methods into new bridge design.

CHAPTER NINE: ***Conclusions and Recommendations***

The chapter summarises how research objectives were achieved, the contributions to the body of knowledge, as also research limitations, recommendations, and future research areas.

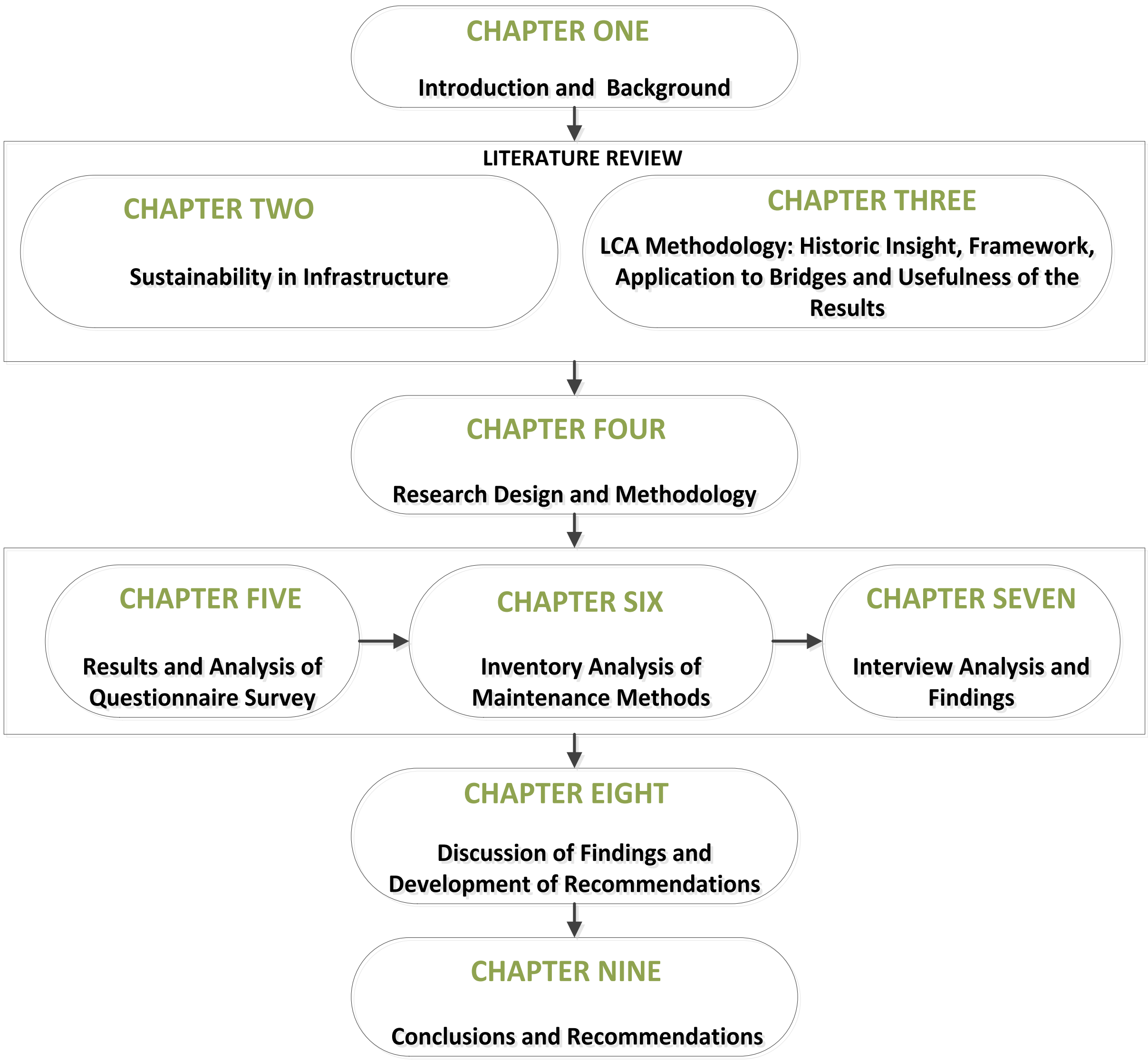

Figure 1. 1 Organisation of Chapters in the thesis

1.8 Chapter Summary

The chapter has presented the introduction and general background to the study. It presented the problems and rationale for the research, research questions, aims and objectives and the methodological design in place to address them, and concludes by presenting the thesis outline. The next chapter discusses sustainability in infrastructure, which introduces the literature review chapters.

CHAPTER TWO: SUSTAINABILITY IN INFRASTRUCTURE

2. Introduction

The chapter provides insight on environmental awareness and the concept of sustainability and sustainable development for infrastructure. It presents and reviews relevant assessment tools available for infrastructure, and concludes by unveiling the extent to which environmental issues are considered for bridge infrastructure.

2.1 Insight on Environmental Awareness and Sustainable Development

Environmental awareness reached new prominence in the 1960s and early 1970s, when environmental damage caused by human activity began to gain momentum (Selmes, 2005). The United Nations General Assembly meeting held in 1984 fostered the 'global agenda for change' – initiated to increase environmental awareness and devise means of curbing abuse – and led to the popular Brundtland report (Gilmour *et al*., 2011). An emergent theme from the Brundtland report was sustainable development (WCED, 1987). However, there were other publications before the Brundtland report, which began the environmental awareness campaign as revealed in Table 2.1. An Earth Summit meeting was again held in Rio de Janeiro, Brazil in 1992 to review progress since the Brundtland report. The review was keen to achieve a strategic balance between economic, environmental, and social needs of present and future generations, and at the same time lay a foundation for common interest, understanding and needs for developed and developing countries. Emerging from the meeting was Agenda 21, which drew global attention. Agenda 21 entails 21 targets envisaged to be met by 2100. Even as many developing countries and industries are yet to implement these targets (Zhang, 2010), agenda 2030 has emerged, from the heads of state and government high representatives' meeting in New York (United Nations, 2015). Agenda 2030 recognises the impact of poverty on the holistic achievement of sustainable development, and devises 17 goals and 169 targets to achieve the three dimensions of sustainable development, which are economic, social, and environmental (United Nations, 2015). According to UNEP (2011), environmental impact is one of the prominent issues of sustainable development, and this study sits well with the environmental concerns of material consumption, climate change, water bodies and terrestrial ecosystem, of the 12th, 13th, 14th and 15th goals of the 2030 agenda.

Table 2. 1 Development of Sustainable Development Concepts. Adapted and revised from Ainger and Fenner (2014) with additional information *(Table used with permission)*

Year	**Title**
Nineteenth century	
	Henry David Thoreau, Ralph Waldo Emerson, John Muir
Twentieth century	
	Aldo Leopold
	Rachel Carson
Modern environmentalism	
1972	*The Limits to Growth, Club of Rome Report*
1974	*James Lovelock's 'Gaia' hypothesis*
Roots of sustainability	
1972	*United Nations Conference on the Human Environment, Stockholm, Sweden*
1972	*United Nations Environment Programme (UNEP)* .
1980s	*Robert Allen's How to Save the World and Lester Brown's Building a Sustainable Society*
Emergence of sustainability	
1983	*The World Commission on Environment and Development*
1984	*The Worldwatch Institute published its first State of the World Annual Report*
1987	*The Brundtland Report, Our Common Future (WCED, 1987)*
1992	*United Nations Conference on the Environment and Development, Rio, Brazil*
2002	*World Summit on Sustainable Development, Johannesburg, South Africa*
2009	*UN Climate Summit, Copenhagen, Denmark* .
2012	*Rio +20 United Nations Conference on Sustainable Development, Rio, Brazil*
2012	*UN Climate Change Conference, Doha, Qatar* .
2012	*World Bank warns that the trend is to a 148C world by 2100*
2016	*UN Heads of state meeting, New York (2015)*

2.2 Sustainability and Sustainable Development Model

'Sustainability' and 'sustainable development' are often misunderstood (Ainger and Fenner, 2014), and sometimes used interchangeably (Gilmour *et al*., 2011). Sustainability is the fundamental goal, whilst sustainable development is the process of achieving the goal through sustainable thinking (Martin, 2004; Gilmour *et al*., 2011). The Brundtland report defines sustainable development as '*the development which meets the needs of the present without compromising the ability of the future generations to meet their own needs*' (WCED, 1987). Sustainable development hinges on three pillars of the Triple Bottom Line (TBL) approach, represented in Figure 2.1a with three intersecting circles of economic, social, and environmental elements (Mebratu, 1998). The triple bottom line supports a fair balance between the economic, social, and environmental elements (Selmes, 2005). However, it failed to recognise the ecological basis of society and economic assets within the limits of our planet (Ainger and Fenner, 2014). The triple bottom line's shortcoming is revised in other models as depicted in Figure 2.1b, reflecting sustainable development from an environmental and socio-economic perspective (Selmes, 2005). The socio-economic model depicts the exchange of resources and waste between the social-economic entity and the surrounding environment. The model denotes that the environmental entity supports the existence of the social and economic entities. In similar vein, Levett (1999) presented a concentric circle model depicted in Figure 2.1c. The concentric circle model presents that the economy exists in society, and society subsists within the boundaries of the environment. This study is therefore underpinned by the later model which suggests that environmental issues should be the primary focus of sustainability studies.

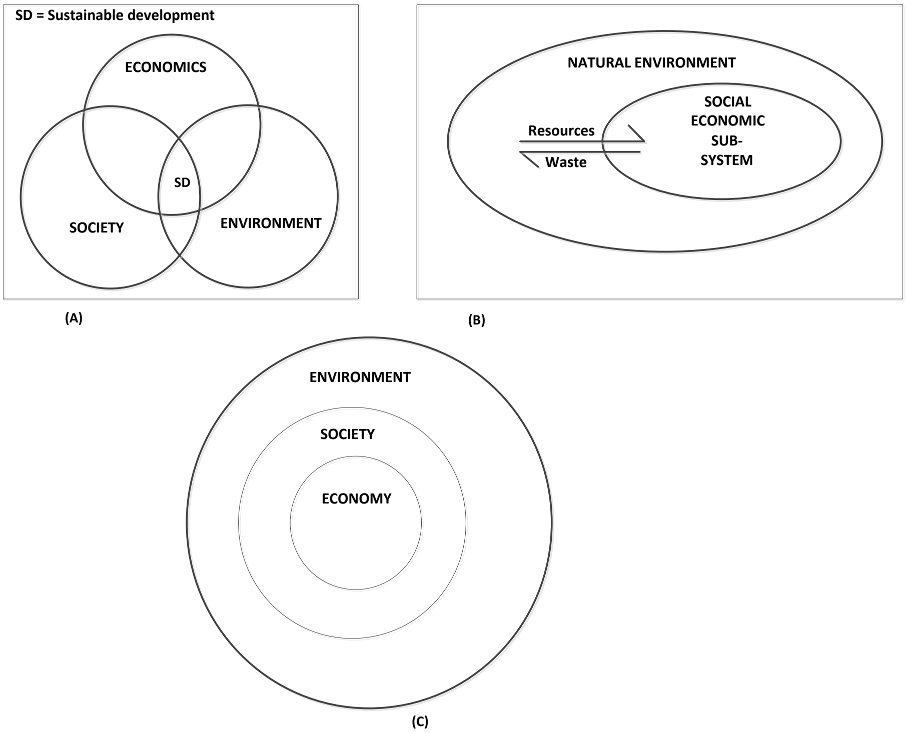

Figure 2. 1 Sustainable development models (a) adapted from Mebratu (1998), (b) adapted from Selmes (2005) and (c) adapted from Levett (1999) *(Images used with permission)*

2.3 Sustainable Development and Sustainability Principles in Infrastructure

The construction of infrastructure requires high energy release, resource use and large amounts of emissions, which are unsustainable (Carvalho *et al*., 2014). Transport infrastructure (including bridges) has great environmental impact during its life cycle stages, stemming from consumption and emissions (Hardy and Fenner, 2015; Trupia *et al*., 2016; Karlsson *et al*., 2017). Strategic planning and sustainable decisions are vital to ensure that infrastructure projects are sustainable (Willets *et al*., 2010; Salling and Pryn, 2015). Such planning may include recommending material alternatives during the design stage to aid sustainable design (Collings, 2006; Zhang, 2010a). Infrastructure projects are mainly driven by cost, time, and quality (Gambatese and Rajendran, 2005; Fenner *et al*., 2006). Although safety and technical issues are vital for bridge infrastructures, the associated impact emerging from exploration, construction, and maintenance activities cannot be neglected, owing to resource use and energy release from and into the environment (Boyle and Coates, 2005; Chandler *et al*., 2008; Kucukvar and Tatari, 2013).

A growing number of highway authorities, companies and government institutions are introducing sustainability principles to meet wider sustainable development goals in their projects (Trupia *et al*., 2016). Among these are infrastructure projects (Gilmour *et al*., 2011; Wessels, 2014; Saxe *et al*., 2016). The application of sustainability principles to infrastructure work has proved difficult for civil design engineers, due to unclear sustainability requirements for infrastructure projects (Arya, Amiri and Vassie, 2015). As a result, not much is heard of "green roads, bridges etc."(Ugwu and Haupt, 2005; Huang and Yeh, 2008; Willet *et al*., 2010), which raises questions of a lack of understanding of sustainability principles for infrastructure (Arya, Amiri and Vassie, 2015). Even so, Barlette and Guthrie (2005) gathered and analysed 17 sustainability documents published from 1996 – 2003 in the hope of producing a set of sustainable principles advocated in these documents. Only one document deals directly with "sustainability and acceptability in infrastructure development (ICE, 1996)", while others focused on buildings. Engineers are, however, being asked to begin implementing sustainability principles in infrastructure through educating and influencing decision makers in the design brief (Willets *et al*., 2010). Similarly, Ainger and Fenner (2014) suggested six ways to improve sustainability practices for infrastructure works, such as:

1. Design with sustainability metrics and climate change in mind (i.e. measure targets against environmental limits).
2. Challenge traditional approaches and design standards (i.e. challenge tradition and encourage change).
3. Explore design-life and reuse options, and 'off-site' implications (i.e. encourage long-term plan).
4. Apply functional components to achieve sustainable systems (i.e. consider integrated needs).

5. Use more sustainable materials (i.e. use material with less environmental impact)
6. Consider biodiversity and wildlife when making detailed decisions about siting and landscaping (i.e. which option has significant environmental impact).

The civil infrastructure sector is believed to be making considerable effort towards developing strategies to achieve sustainable development (Hunts and Rogers, 2005; Willet *et al*., 2010). However, only a handful of studies have presented sustainability principles for infrastructure. For instance, Lim and Yang (2006) presented a conceptual framework for a sustainable infrastructure (Figure 2.2). The framework harmonises the interaction of two important stages (i.e. infrastructural development process and sustainable principles) to achieve an integrated sustainability outcome for infrastructure projects. The framework highlights the significance of sustainability principles in terms of the triple bottom line approach with additional concern for health and safety, and project management.

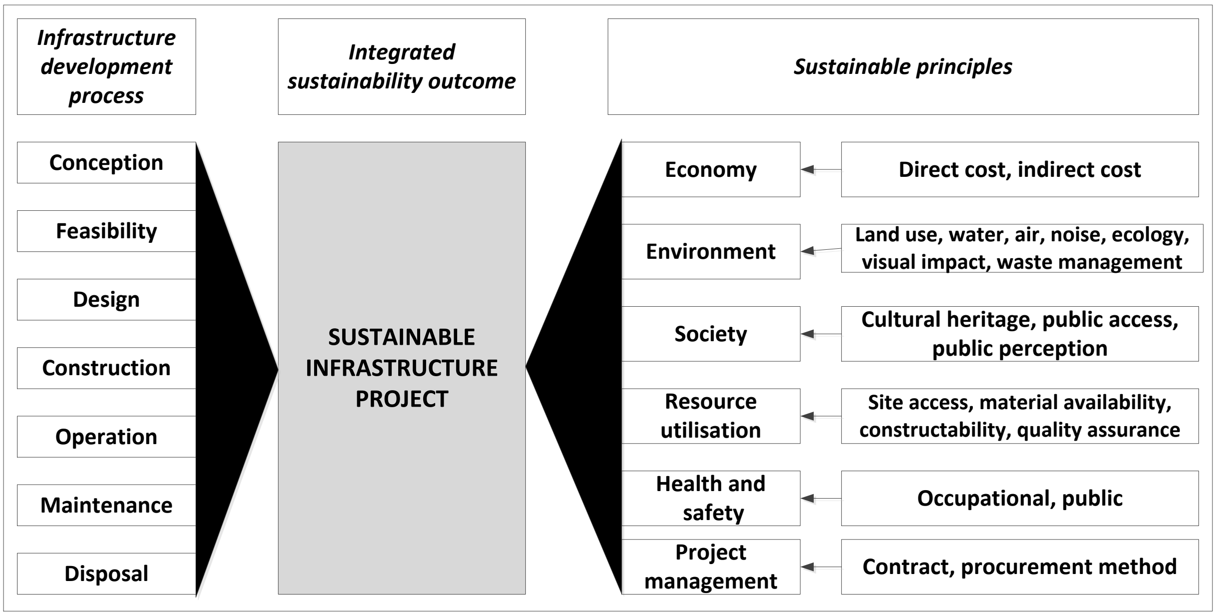

Figure 2. 2 Conceptual framework for a sustainable infrastructure project. *Source*: Adapted from (Lim and Yang, 2006) *(Image used with permission)*

Similarly, Ainger and Fenner (2014) drew from Edward (2005) to develop principles specific to infrastructure projects. Three categories of sustainability principles (absolute principles, operational principles, and individual principles) presented in Table 2.2 are recognised as suiting infrastructure projects. The principles integrate elements of the three pillars in a structured recommendation compared to Lim and Yang (2006) in a conceptualised format (Figure 2.2 above). Willets *et al*. (2010), however, understood the significance of stakeholder engagement with any infrastructure sustainability principle and recommended that:

- Engineers should have far greater involvement in the early engagement of stakeholders.
- Engineers should use their technical skills to educate and influence decision makers.
- Engineers should look beyond project/site specific problems and begin to look at the larger issues and system.
- Planners and engineers should work more closely to develop indicators and bench-markers relating to delivery of sustainable infrastructure.

Table 2. 2 Principles of Sustainable Infrastructure. *Source:* Adapted and revised from Ainger and Fenner (2014) *(Table used with permission)*

Objectives, goals	**Approaches**		
Absolute principles			
A1 Environmental sustainability – within limits	**A2** Socio-economic sustainability – 'development'	**A3** Intergenerational stewardship	**A4** Complex system
Operational principles			
B1 Set targets and measure against environmental limits	**B2** Set targets and measure for socio economic goals	**B3** Plan long term	**B4** Open up the problem space
B1.1 Structure business and projects sustainably	**B2.2** Respect people and human rights	**B3.3** Consider all life-cycle stages	**B4.4** Consider integrated needs
			B4.5 Integrate working roles and discipline
Individual principles			
C1 Learn new skills – competencies for sustainable infrastructure			
C1.1 Challenge orthodoxy and encourage change			

2.4 Assessment Tools for Infrastructure

There are many sustainable assessment tools for infrastructure, but only a handful of these tools tackle the three pillars of sustainable development (Ainger and Fenner, 2014). Assessment tools commonly applied on infrastructural projects are presented in Table 2.3. While these tools present both advantages and disadvantages (Hojjati *et al*., 2016), not many of them have been explored for bridges to aid sustainable design decisions (Spencer *et al*., 2012). In fact, many of them are not specific to a type of infrastructure, though there are several tools specific to building projects; for example, Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and Building Rating Systems (BRS) (Kiker *et al.,* 2005; Gibberd, 2008; Shaw *et al*., 2012). CEEQUAL is commonly used for infrastructure (Levett-Therivel, 2004; Ghumra, 2009; Willets *et al*., 2010; Hojjati *et al*., 2016), but it is not specific to any type of infrastructure. Common infrastructure tools are Halster, SPeAR®, WLC, and LCA, as presented in Table 2.3.

Table 2. 3 Commonly used Assessment Tools

Methods/Assessment	**Application**	**Sustainable development 'Focus'**
Ceequal	Civil infrastructure and buildings	Environment, social, economic
Halstar	Civil infrastructure and buildings	Environment, economic and social, legislation and planning policies
SPeAR®	Civil infrastructure and buildings	Environment, economic, social, and natural resource
WLC	Civil infrastructure and buildings	Economic, and associated environmental impact
LCA	Civil infrastructure and buildings	Environmental impact
EIA and SEA	Civil infrastructure and buildings	Environmental impact

2.4.1 CEEQUAL

CEEQUAL is the civil engineering equivalent of BREEAM (Venables, Venables and Newton*,* 2005; Willets *et al*., 2010). It is designed to reward projects that go beyond legal requirements and consider more detailed environmental, economic, and social aspects of sustainability (CEEQUAL, 2017). Shortcomings identified in early versions of CEEQUAL include not addressing the holistic nature of sustainability and too much emphasis on environmental issues (Willets *et al*., 2010). The new version of CEEQUAL has a widened scope to assess full sustainability credentials of projects and contracts (CEEQUAL, 2017). The new CEEQUAL version involves nine areas of assessment: project/contract strategy, project/contract management, people & communities, land use (above & below water) & landscape, historic environment, ecology & biodiversity, water environment (fresh & marine), physical resources and use & management, and transport (CEEQUAL, 2017). The new version of CEEQUAL promotes the application of appropriate strategies, and the use of environmental and social best practices, but does not operate on a life cycle basis, nor does it extend the benefits of life cycle assessment methodologies to infrastructure. CEEQUAL is also not specific to a particular type of project, and is applicable to a variety of civil engineering projects such as highways, dams, water channels, and so on.

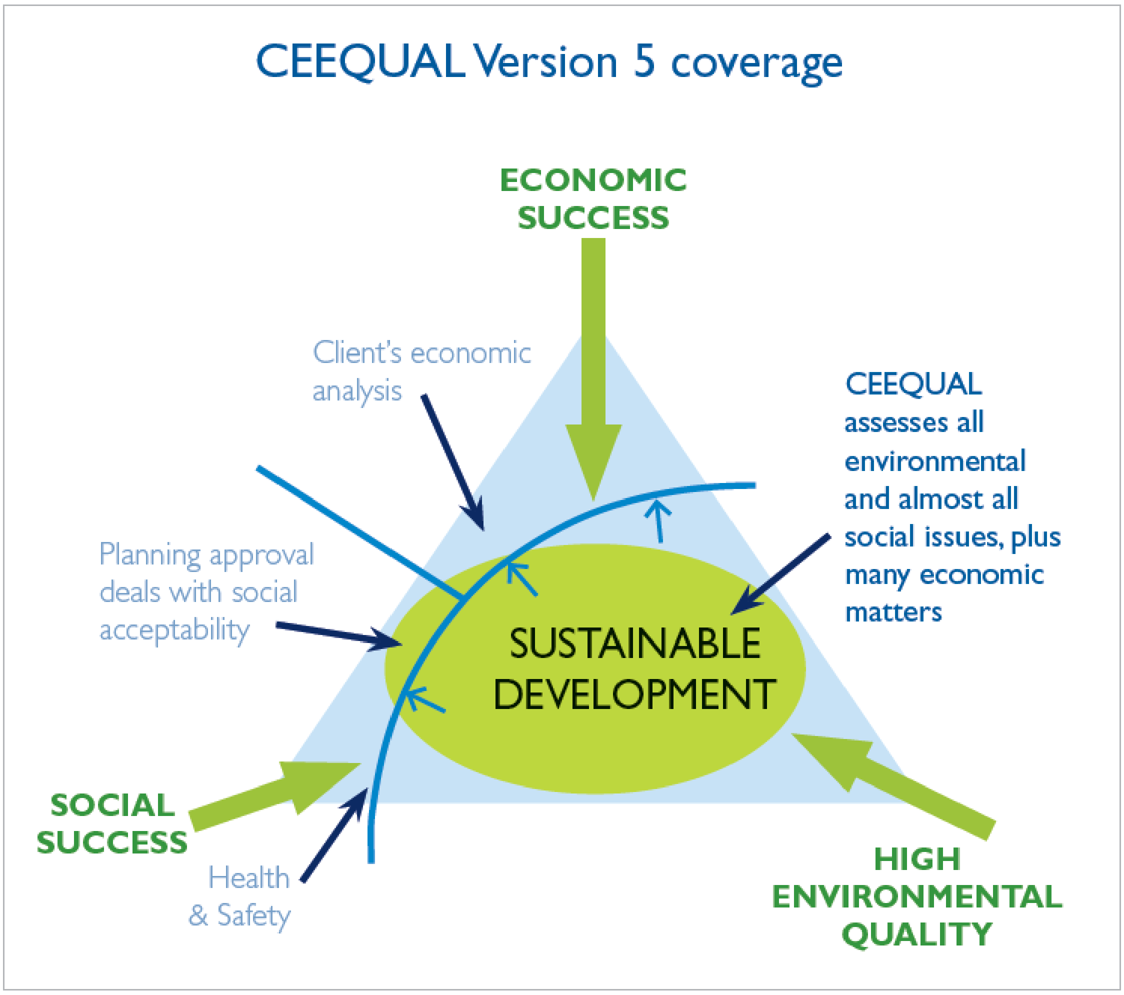

Figure 2. 3 CEEQUAL version 5 coverage. *Source*: Adapted from (CEEQUAL, 2017) *(Image used with permission)*

2.4.2 Halstar

Halstar is a sustainable development tool based on system model (Pearce, Murry and Broyd, 2012). The tool contains a database that embeds 840 sub issues, up to 4200 qualitative criteria and 200 indicators (Hojjati *et al*., 2017). The theoretical basis of Halstar is to aggregate key sustainability factors into a system tool and provide a comprehensive appraisal of factors likely to affect the sustainability of a project (Pearce, Murry and Broyd, 2012). An example of a Halstar result is showcased in Figure 2.4, which reveals major aspects of sustainable development; for example cultural heritage, health and safety, quality and innovation, stakeholder relationship, drainage and flooding, and so on. These aspects cannot be effectively appraised using a single tool, since there are chances of tool fatigue occurring (Holt *et al*., 2010).

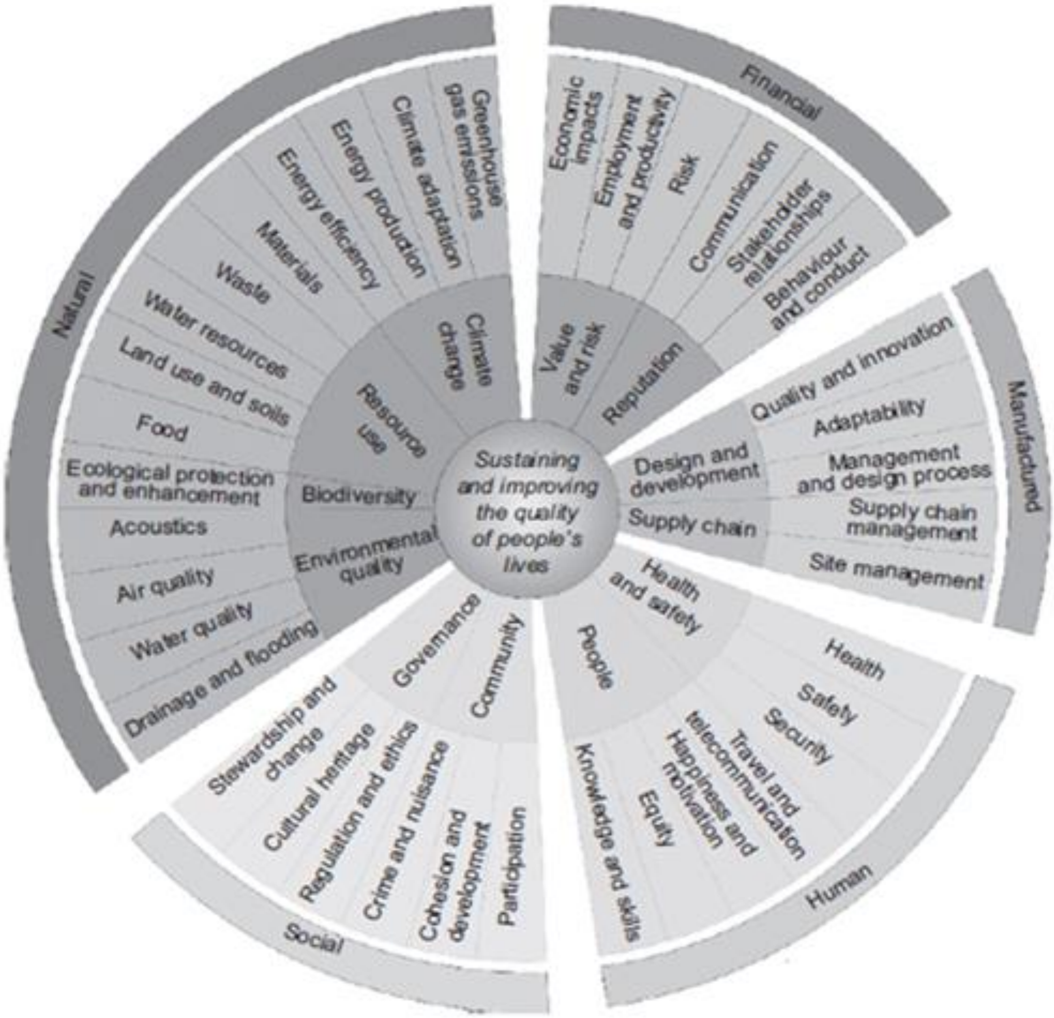

Figure 2. 4 Halstar sustainability wheel. *Source*: Adapted from Pearce, Murry and Broyd. (2012) *(Image used with permission)*

2.4.3 SPeAR®

Sustainability Project Appraisal Routine (SPeAR®) was developed by one of UK's leading consultant groups (Arup Group Ltd) to address economic, social, environmental, and natural resource aspects of sustainable development (Arup, 2017). The tool draws from international best practice guidance on sustainability indicators, such as UK government sustainability indicators, UN sustainable development indicators, UN environmental programme indicator and global reporting initiative G3 indicators (Braithwaite, 2007). SPeAR® is flexible to include new indicators associated with different project contexts (Venables, Venables and Newton, 2005). The SPeAR® diagram depicted in Figure 2.5 reveals sustainability performance of different indicators. Good sustainability performance is reflected by the indicators' closeness to the centre of the diagram and vice-versa. However, SPeAR® is too flexible and oversimplified, besides having broad and generic indicators (Hojjati *et al*., 2017). According to Pearce *et al*. (2010), the flexibility of SPeAR® allowed different versions to emerge, such as GeoSPeAR® for geotechnical engineering projects (Holt *et al*., 2010).

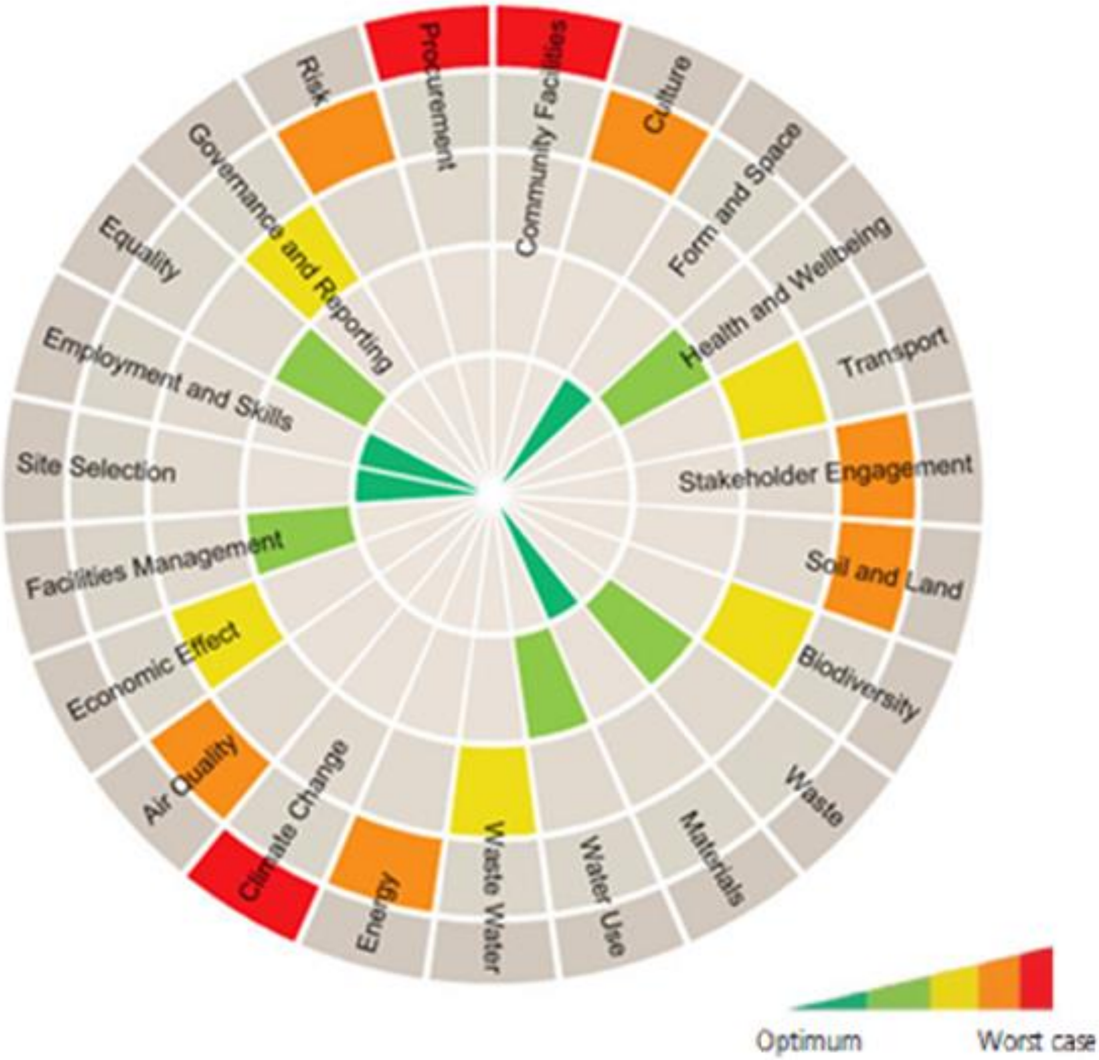

Figure 2. 5 Arup SPeAR® extract. *Source*: Adapted from (Arup, 2017) *(Image used with permission)*

2.4.4 Whole Life Cost (WLC)

WLC covers the lifetime cost of the project, including maintenance cost. Whole life costing is used to make choices between a range of project alternatives, effectively during the early design stage (Ainger and Fenner, 2014). WLC cost is based on Net present value, which assumes that money today would accumulate interest and be worth more in the future. Hence, money is invested today to meet emerging financial needs in the future.

A review of WLC within the construction sector revealed lack of understanding of the technique and the absence of standardised methodology as factors that limit its wider implementation (Olubodun, *et al*., 2010). Although WLC has been applied on infrastructural projects like bridges (Ryall, 2010), potable water service (Savic *et al*., 2008) and trunk sewers (Rahman and Vanier, 2004), its wider use has been limited. Moreover, just like Life-cycle Cost (LCC) and Cost Benefit Analysis (CBA), WLC also is time consuming and requires adequate expertise.

2.4.5 Life Cycle Assessment (LCA)

LCA is an environmental assessment method that quantifies all relevant emissions and resources consumed and provides results on related environmental issues, health damage and resource depletion associated with any product process (Mota *et al*., 2015). LCA reveals the environmental impact of a product or service based on input (energy consumption and materials resources) and output (emissions to air, water, and land) substances (Carvalho *et al*., 2014; Parsons, 2016). Hence, it is based on mass and energy balance principle (Azapagic 1999; Azapagic and Clift, 1999; Finnegan, 2004).

LCA can be used for product comparison, eco-design, eco-labelling schemes, supply chain evaluation and green procurement, while the emergent results could be applied in environmental management, sustainable strategy, and policy making (Guinée *et al*., 2002). LCA can be applied to the whole life of a product starting from material extraction, processing of raw materials, manufacturing, transportation, maintenance, recycling to final disposal (Carvalho *et al*., 2014). LCA has evolved to become an important management tool, which provides opportunities for environmental improvements (Cherubini, Bargigli and Ulgiati, 2009). Apart from this, LCA follows a system approach, which allows it to be integrated with other assessment tools such as Strategic Environmental Assessment (SEA) to improve practice (Björlund, 2012).

LCA has been mainly applied in manufacturing and process industry, to identify life-cycle phases with the most environmental pollution in relation to CO_2, NO_2, SO_2 and other GHG emissions (Ainger and Fenner, 2014). However, LCA is now of global interest, including in the construction industry, which is in pursuit of sustainability and resource conservation (Sharrard, Matthews and Ries, 2005; Kucukvar and Tatari, 2013). LCA has been applied in many construction sectors, such as buildings (Buyle, Braet and Audenaert, 2013; Cabeza *et al*., 2013), bridges (Hammervold, Reenaas and Brattebø, 2013; Du *et al*., 2014), and roads (Huang, Bird and Heidrich, 2009; Giustozzi, Crispino and Flintsch, 2012; Huang *et al*., 2015). In fact, many European construction industries use LCA in research projects and daily practice (Lasvaux *et al*., 2014). LCA methodology underpins most reputable sustainability assessment tools, such as British and Building Research Establishment (BRE) "green guide to specification", French, High Quality Environmental Standards (HQE), and German Sustainable Building Council (DGNB) (Lasvaux *et al*., 2014). However, a tool that accounts for LCA of material used and the associated impact is still required for infrastructure projects (Ghumra, 2009; Spencer, Hendy and Petty, 2012).

LCA methodology presents several challenges, ranging from data availability and data accuracy to data inconsistency (Crawford, 2011; Du and Karoumi, 2014). Moreover, LCA does not address social issues such as noise, dust, and vibration (Ainger and Fenner, 2014). However, it does account for emissions associated with detouring resulting from traffic diversions (Steele *et al*., 2003; Pang *et al*., 2015). Common LCA tools are available in commercial software packages, e.g. Gabi (Spatari *et al*., 2001) and SimaPro (Goedkoop, De Schryver and Oele, 2008).

2.4.6 Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA)

EIA is an early environmental assessment tool. EIA is used to assess the environmental effectiveness of new infrastructure to help decision makers such as planning authorities understand the future environmental implications of such infrastructure (Ainger and Fenner, 2014). EIA is considered a procedure rather than a tool, in the sense that it deals with a broader set of comparisons and places greater emphasis on the decision-making process (Tukker, 2000). EIA outputs are assessed publicly to provide opportunities for feedback. According to Ainger and Fenner (2014), five questions are tackled in EIA:

I. What are the existing characteristics of the environment in the area to be used by the proposed development?
II. What is the nature of the development?
III. What effects will the development have on the existing environment?
IV. What measures can be taken to mitigate any of its adverse effects?
V. What would happen if it did not proceed?

These questions, however, do not address direct impact, cumulative impacts from multiple schemes and alternative design during planning process (Ainger and Fenner, 2014). Therefore, SEA was developed as an improvement on EIA, to strategically provide a framework for assessing the environmental effects of policies, plans, programmes, and strategies (Somevi, 2002). SEA adopts a step-by-step screening process for assessing, mitigating and monitoring environmental effects in alignment with the policy making and planning process (Somevi, 2002). Björlund (2012) argues that LCA, compared with SEA, provides a more comprehensive environmental assessment, though it may not necessarily address other areas covered in SEA, although it could be complimented by other tools. In similar vein, Tukker (2000) explains that there are no fundamental contradictions between EIA and LCA, except the fact that LCA is a more detailed tool used to make specific comparisons, e.g. alternative product systems. The main advantages and disadvantages of EIA and LCA as also other assessment tools discussed above are presented in Table 2.4.

Table 2. 4 Advantages and Disadvantages of common Infrastructure Assessment Tools. *Source:* Adapted and revised from Hojjati *et al*. (2017) *(Table used with permission)*

Tools/Assessments	Advantages	Disadvantages
CEEQUAL	• Ceequal is Evidence-based assessment • A trained Ceequal assessor conducts the assessment • An external verifier reviews and validates the process	• Award-focused • Although focused on environmental concerns, it does not provide adequate means for achieving required environmental score • Applicable to many infrastructural assets without being specific
Halstar	• Adopts a system thinking approach • Contains a comprehensive database of sustainability criteria and indicators	• Addresses many broad issues • Time consuming • Potential for tool fatigue
SPeAR®	• No weighting or scores for indicators • Flexibility and ability to be modified • Not reward-driven	• Oversimplified scoring system • Broad and generic indicator sets
WLC	• Applicable throughout the life cycle of projects • Useful for appraisal of future financial needs of projects • Useful for making choices between alternative projects	• Uncertainty with forecasting future maintenance cost, discount, and interest rates • Requires considerable knowledge and expertise to use • Lack of standardised methodology • Wider application is limited
LCA	• Applicable throughout the life cycle of projects • Applicable for environmental risk management and strategic decision making	• Requires large data input • Time-consuming process • Does not consider social impacts • Availability of data
EIA and SEA	• Adopts a step-by-step screening process • Covers areas like planning process and policy making. • Scope for monitoring	• Procedure is not iterative and does not give feedback into design itself • Lack of quantitative form • Non–technical summaries can be vague and generalised

2.5 Environmental Issues (CO_2 and GHG)

There is a global call to reduce Green-house Gas (GHG) emissions by 35% by 2030, related to increasing concerns with resource depletion and climate change effect (Saxe *et al*., 2016). Construction activities alone contribute nearly 20 to 25% of the carbon emissions (DBERR, 2008). Infrastructure (such as roads, bridges, railways, waterways, canals, and dams) requires large amounts of the earth's resources, given its extraction, construction, maintenance, and disposal activities (Correia, 2015). Most developed countries have triggered the "Zero carbon policies" to publish acts (or mission statements) that emphasise their commitment to reduce carbon and GHG emissions (see Table 2.5). For example, the European Union targets to reduce GHG emission by 20%

by 2020 (EU, 2009). Likewise, the UK government is ambitious to reduce carbon emission by 80% over the 1990 baseline by 2050 (Climate change Act, 2008). However, it has proved easier to achieve these targets with buildings rather than infrastructure (Pan and Garmston, 2012). The UK government, for instance, set policies such as "zero carbon policies" for new homes (DCLG, 2006) and non-domestic new buildings (HM, treasury, 2008). The success of these policies reflects in the 17% and 14% reduction of GHG emission achieved between the years 2013 and 2014 for the residential and energy sectors; whereas only 3% reduction was achieved with the transport infrastructural sector (DECC, 2016). Though zero carbon policies are widely promoted, yet, no published policies specify zero carbon approaches for infrastructure (Pan, 2014). The problem, perhaps, lies in the complexity of infrastructure as outlined in the ICE infrastructure Trajectory Project report (ICE, 2010), or a lack of commitment to it (Pan, 2014). Environmental approaches like LCA are, however, being applied to enhance the scope for mitigating carbon and GHG emissions in infrastructure (Ramesh, Prakash and Shukla, 2010).

Table 2. 5 Targets for reducing GHG emission. *Source:* Adapted from Pan (2014). *(Table used with permission)*

Country	**Policies for reducing GHG emissions**
Australia	Reduce GHG emissions by 80% of the 2000 level by 2050
China	Reduce emission intensity by 40% – 45% from 2005 levels by 2020
EU	Reduce GHG emissions by 20% by 2020
Hong Kong	Reduce carbon intensity by 50% – 60% on 2005 baseline by 2020
UK	Reduce carbon emissions by 80% of the 1990 level by 2050

Integrating detailed elements of the triple bottom into design is probably the biggest challenge for civil designers (Yeang, 2010). Designers are, however, being required to spearhead the effort of overcoming global challenges caused by resource depletion, environmental pollution, climate change and the rest (Ainger and Fenner, 2014). Though designers have a responsibility to understand the environmental consequence of their designs, there is limited information on how this can be achieved. This probably stems from the compromises made on design decisions, which is outside traditional designers' skills (Saxe *et al*., 2016). Undoubtedly, the decisions taken at the outline and detailed design stage of infrastructure determine the overall sustainability outcome (Gilmour *et al*., 2011; Ainger and Fenner, 2014). As such, the holistic assessment of infrastructural projects should fully inform the design team of the long-term environmental success of such infrastructure (Saxe *et al*., 2016). Yeang (2010) argues that the checklists offered in BREEAM and LEED are not comprehensive enough to evaluate a holistic sustainable design. Willets *et al.* (2010) mentioned the same of CEEQUAL. Yeang (2010) however suggests five possible design strategies sophisticated enough to capture relevant environmental issues with infrastructural projects. They are:

- Eco-infrastructure: thinking design as engineering, water management, nature's own utilities and the manmade environment.
- Bio-integration**:** seamless integration of synthetic and natural environments
- Eco-mimesis**:** design inspired by the processes, structure, features, and functions of ecosystems
- Design considering the restoration of impaired environments
- Adopting a self-monitoring ecodesign and to regard designed systems as a series of interdependent environmental interactions, whose constant global and local monitoring is necessary to ensure global environmental stasis.

Civil infrastructure exhibits different characteristics compared to building (Zhang, Amaduddin and Canning, 2011). A system approach that investigates relevant process for environmental issues, e.g. carbon and energy, was suggested by Pan (2014). The system approach will cover the whole life examination of infrastructure concerning environmental issues right from conception to design, construction, operation, and maintenance activities (ICE, 2010). However, consideration of embodied energy in infrastructure, especially with emission from the operation and maintenance phase, presents a methodological challenge (Pan, 2014). LCA is a system approach and has been applied to infrastructure on that basis (Ramesh, Prakash and Shukla, 2010). Though LCA can be applied to different life-cycle phases, interpretation of result varies with context, and more complications arise when the results are applied to real life design decisions and policy making for infrastructure (Pan, 2014).

2.6 Environmental Issues (CO_2 and GHG emissions) for Bridges

Bridges are one type of infrastructure, the environmental impacts of which are rarely considered despite being an integral part of the highway transport system. While considerable effort is being made to reduce carbon dioxide emission and energy for buildings, attention is rarely paid to bridges. The slow recognition of environmental impact within the bridge industry is traceable to a lack of comprehensive guidance or recommendations for sustainable design and construction of bridges (Martins, 2004). Environmental awareness has increased in the past 20 years, drawing the attention of engineers and designers to issues of resource depletion, fossil fuel depletion, carbon dioxide and GHG emissions (Willets *et al*., 2010; Saxe *et al*., 2016). However, environmental issues are hardly ever considered during bridge design (Du and Karoumi, 2014). It is only recently that some carbon calculators and environmental assessment tools for bridges have begun to emerge; e.g. sustainability index (Spencer, Hendy and Petty, 2012). Only a few researches evaluated CO_2 and GHG emissions within the life-cycle phase of bridges (e.g. Collings, 2006; Zhang, Amaduddin and Canning, 2011). Whilst Collings (2006) found that CO_2 emissions were high for the construction and maintenance phases of some bridges, Zhang, Amaduddin and Canning (2011) found out that CO_2 was high for deck replacement. However, Hammond and Jones (2008) identified typical values of carbon dioxide release (or embodied energy) for most primary and secondary bridge construction materials (presented in Table 2.6), which has been used as input data for a number of studies (e.g. Zhang, Amaduddin and Canning, 2011).

LCA has also been applied to evaluate the environmental impact of bridges. For instance, comparison of different bridge component alternatives (Steele et al. 2003; Martins 2004; Keoleian *et al*. 2005; Collings 2006; Du and Karoumi 2012), comparison of new material with conventional material (Keoleian *et al.* 2005; Lounis and Daigle 2007; Bouhaya, Roy and Feraille-Fresnet. 2009), and comparison of different bridge alternatives (Horvath and Hendrickson 1998; Itoh and Kitagawa 2003; Gervásio and da Silva 2008; Hammervold, Reenaas and Brattebø. 2013; Du *et al*., 2014). However, most LCA bridge studies lack actual maintenance data (Pang *et al*., 2015). For instance, studies like Itoh and Kitagawa (2003) assumed maintenance data based on an inspection manual, while Du and Karoumi (2012) relied on literature data. Bouhaya, Roy and Feraille-Fresnet (2009) assumed no maintenance. Very few studies dealt with environmental issues arising from bridge maintenance activities. For instance, Steele *et al*. (2003) compared concrete saddle construction and anchor bracing, where it emerged that the saddling option had great impact owing to structure closure and traffic diversion. Also, Pang *et al*. (2015) compared four strengthening plans: bonding steel plates to girders and crossbeams; bonding carbon fibre-reinforced polymer (CFRP) plates to girders and steel plates to crossbeams; bonding steel plates to girders and applying external pre-stressing tendons to crossbeams; and bonding CFRP plates to girders and applying external pre-stressing tendons to crossbeams. However, these specific comparisons cannot provide adequate evidence to generally aid sustainable design choice in respect of maintenance. To help designers and decision markers adopt environmentally friendly bridge choices, there is a need to compare commonly used preventive and strengthening maintenance options of concrete, steel, and masonry bridges in detail.

Table 2. 6 Embodied Energy and Embodied Carbon values for typical Construction Materials (Extracted from Hammond and Jones, 2008) *(Table used with permission)*

Materials	**Embodied energy (MJ/Kg)**	**Embodied carbon (KgCO_2/Kg)**
Asphalt	2.41	0.14
Bitumen	47	0.48
Concrete (general)	0.95	0.130
Epoxy resin	139.30	5.91
GRP	100	8.10
Galvanised steel	39.00	2.82
Prestressed concrete	2.00	0.215
Steel bar and rod	24.60	1.71

2.7 Chapter Summary

The chapter provides insight into environmental awareness, and how it developed into global issues of sustainability and sustainable development. Limitations and challenges faced by designers and engineers for implementation and application of sustainability are discussed. It discusses common tools and assessment methodologies for infrastructure, and points out their advantages and disadvantages. Amongst these tools, LCA focuses on environmental matters using a quantitative approach, compared to other tools which tend to investigate the three pillars, making the process confusing. Although LCA has its limitations (e.g. time consuming), it is proven to adequately reveal environmental impact associated with the life-stages of infrastructure. However, its application to bridge life-cycle stages, especially the maintenance phase, has been limited. The next chapter will investigate the extent to which LCA has been applied to bridge infrastructure, and the combination of relevant environmental indicators previously applied. This investigation can lead towards understanding the usefulness of LCA results within the bridge industry.

CHAPTER THREE: LCA METHODOLOGY: HISTORIC INSIGHT, FRAMEWORK, APPLICATION TO BRIDGES AND USEFULNESS OF THE RESULTS

3. Introduction

The chapter discusses the historic insight on LCA methodology, and the shortcomings and criticism associated with its general application. It reviews LCA application to bridges and the usefulness of the LCA results, and concludes with a summary of the whole chapter.

3.1 Historic Insight on LCA Development

Life cycle assessment emerged between 1960 and 1970. The US Society of Environment Toxicology and Chemistry (SETAC) pioneered the development of LCA within the states and across Europe (Klöpffer, 2006). LCA was, however, only mentioned in the Notch, Vermont workshop in August 1990 (Fava, 1994). Midwest Research Institute (MRI) – sponsored by Coca-Cola Company in 1969 – were the first to use LCA to determine the execution of resources, emission loadings and waste flow for different containers, called Resource and Environmental Profile Analysis (REPA) (Hunt and Franklin, 1996). LCAs conducted between 1969 and 1972 only accounted for solid waste, while relevant emissions and energy were omitted (Bauman and Tillman, 2004). LCA practitioners at the time lacked a clear consensus on LCA methodology, even though the approach was based on a 'cradle-to-grave' environmental assessment method (Bousted, 1996; Oberbacher, Nikodem, Klöpffer, 1996; Fink, 1997). SATEC published several aspects of LCA between 1990 and 1993 (SATEC, 2003). These include;

- A Technical Framework for Life-Cycle Assessment
- Life-Cycle Assessment
- Conceptual Framework for Life-Cycle Impact Analysis
- Conceptual Framework for Life-Cycle Data Quality and

- Guideline for Life-Cycle Assessment: A 'code of Practice'

The International Organisation for Standardization (ISO) came on board shortly after SATEC's publications, and paved the way for harmonisation of methods and procedures in LCA practice, which led to ISO 14040's first publication in 1997 (ISO, 14040, 1997):

- ISO 14041: Life-Cycle Assessment Goal and Scope definition/Impact analysis Phases
- ISO 14042: Life-Cycle Impact Assessment phase
- ISO 14043: Life-Cycle Interpretation phase

The ISO 14040 (1997) has now been superseded by Principles and framework ISO 14040 (2006) and requirements and guidelines ISO 14044 (2006), which are currently the standard documents for conducting LCA, although different LCA approaches are being utilised within the construction sector (Buyle, Braet and Audenaert, 2013). The European Construction Sector (ECS) in conjunction with the European Committee for Standardization, and ISO Technical committee (TC), have developed a unified approach for conducting LCA on building, called EeBGuide (Lasvaux *et al*., 2014). However, there is still no unified approach for conducting LCA on infrastructure, including bridges.

3.2 LCA FRAMEWORK

A generic application of LCA methodology involves an iterative process between four phases, which includes: goal and scope definition phase; inventory analysis phase; impact assessment phase; and interpretation phase (ISO 14040, 2006). The interactions between these four phases are represented in Figure 3.1.

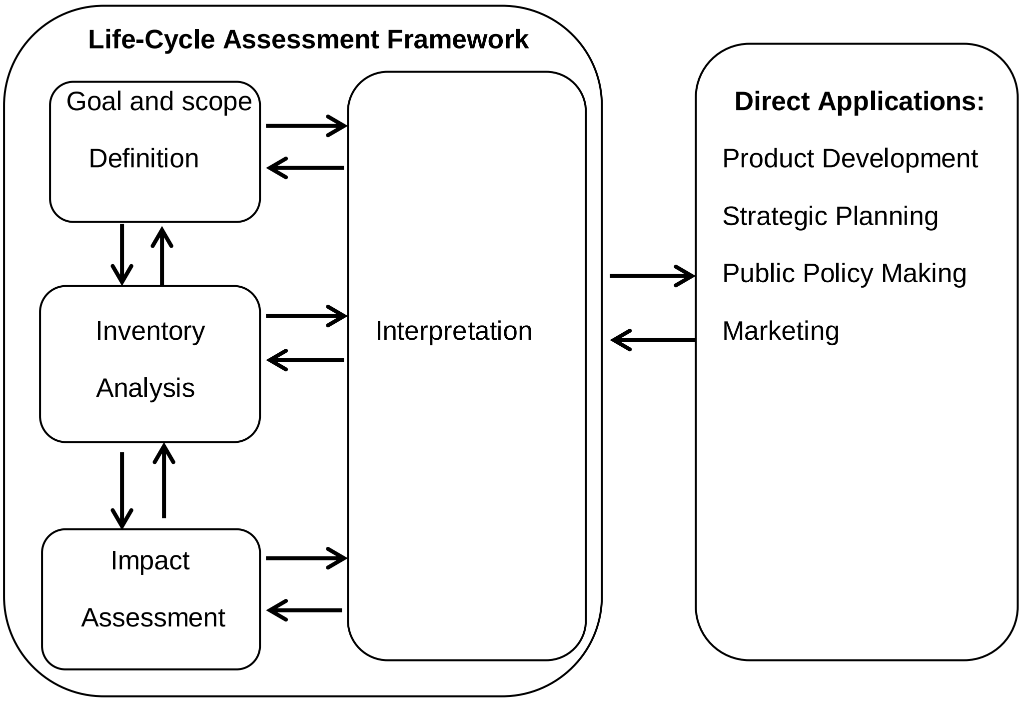

Figure 3. 1 Life-cycle assessments Framework. *Source:* Adapted from ISO 14040 (2006) *(Image used with permission)*

3.2.1 Goal and Scope Definition

The first phase of an LCA is the goal and scope definition phase. The goal and scope phase defines the purpose, goals, scope, data quality and functional units of the study (Cowell, 1998; Rebitzer *et al*., 2004; Ortiz, Castells and Sonnemann, 2009). Similarly, system boundaries, assumptions and limitations are stated, to avoid any misunderstanding concerning the application of the result (Cowell, 1998). However, the goal and scope definition phase permits system boundary expansion to accommodate further investigations (Azapagic, 1999).

3.2.2 Inventory Analysis

The inventory analysis phase takes into account all the inputs and outputs related to a unit product and quantifies the environmental burdens (Pennington *et al*., 2004). The burdens are emissions to air and water, and solid waste (Baumann and Tillman, 2004). The inventory phase reveals the quantified inputs and outputs across the system boundary, which suggests that system boundaries under investigation should be adequately defined at the goal and definition stage (Cowell, 1998). The inventory analysis phase is time consuming and data intensive (Rebitzer *et al*., 2004). A system extension approach involving the separation of a system – under study – into a foreground and background system was introduced to limit the time-consuming process of collecting primary inventory data (Clift *et al*., 1998). Foreground system requires site-specific data for operation or processes, whereas background system supplies necessary material and energy to the foreground systems through a homogenous market, where individual plant processes and operations are unidentifiable (Clift *et al*., 1998). Reliability of the LCA result depends on the quality of inventory data collected (Trusty, 2004). Inventory data can, however, be obtained from factories, government, commercial databases, and scientific journal sources (Du and Karaoumi, 2014). Apart from this, there are widely available commercial inventory databases. An overview of LCI databases commonly used in the construction field is presented in Table 3.1. Material information within these databases depends on processing activities and manufacturing technologies, which differ from region to region (Du and Kauromi, 2014).

Table 3. 1 Available Databases. *Source:* Adapted and revised from Du and Karoumi (2014) *(Table used with permission)*

Database	**Applications**			**Place of Origin**	**Accessibility**
	Building	**Road pavement**	**Others**		
BEES (Building for Environmental and Economic Sustainability)	✓			USA	Free online
BRE (Building Research Establishment)	✓			UK	Free online
Life Cycle Inventory of Asphalt Pavements spread sheet		✓		IVL	Internal use
Portland Cement concrete	✓		✓	Portland Cement Association	Free online
World steel LCI			✓	International Institute of Steel Inventories (IISI)	Free online
(ELCD) European reference life cycle database			✓	European Commission	Free online
US LCI database			✓	US National Renewable Energy Laboratory (NREL)	Free online
SPINE database		✓		Chalmers University of Technology. Sweden	Not Free
Ecoinvent v2.2			✓	The Swiss centre for Life Cycle Inventories	Free
University of Bath database	✓			UK	Not Free
MEXICANIUH			✓	MEXICO	Not Free
DBRI (Danish Building Research Institute)	✓			Denmark	Free
Others: Can be used for product comparison					

3.2.3 Impact Assessment

Impact assessment is the third phase of an LCA study, which drives sustainable decisions. The impact assessment phase identifies associated emissions from the inventory phase and converts them into damage indicators to reveal the major consequences (Jolliet *et al.,* 2003; Pennington *et al*., 2004). It reveals the resulting environmental impact from emitted substances (CO_2, CO, NOx, etc.) and resources (water and land use) consumed (Finnveden *et al.,* 2009). Impact assessment identifies environmental burdens at two main points (that is, midpoint and endpoint). The midpoint and endpoint levels include mandatory stages (of classification and characterisation), and optional stages (of normalisation, grouping or weighting).

Classification Stage

Classification stage categories inventory emitted substances and resources used (Bare, 2010). Classification stage involves two activities. The first step is to select impact categories, which are combinations of emitted substances (CO_2, NO_2, SO_2) and resources and energy used. Impact categories include acidification, eutrophication, global warming, ozone depletion, photochemical oxidation (Heijungs, Guinée and Huppes, 1997). These impact categories are consistently used in LCA studies (Bare, 2010). Other impact categories such as fossil fuel depletion, metal depletion and particulate matter have recently emerged (Goedkoop *et al*., 2012), and have been applied to LCA bridge studies (Du *et al.*, 2014). Impact categories are described below;

- **Acidification (AP)**

Acidification causes impacts on soil, water resources, organisms, and ecosystem due to increased acid content of SO_X, NO_X and NH_X in soil. Sulphur makes the biggest contribution, followed by nitrogen. Both are mainly emitted from burning fossil fuels.

- **Eutrophication (EP)**

Eutrophication, sometimes called 'nutrient enrichment', is when levels of nitrogen and phosphate are raised in the ground, stimulating the growth of algae in aquatic ecosystems. Elevated biomass production in marine environment can deplete dissolved oxygen concentration and cause death of organisms (Wayman, Crodell and Houghton, 2009). Heijungs *et al*. (1992) developed a stoichiometric method for assessing substance potential to produce organic matter (basically phosphate, PO_4), which helps to reveal the impact of Eutrophication in impact assessment methodologies.

- **Global Warming Potential (GWP)**

Global warming or climate change is a resulting phenomenon attributed to the radiative forcing of the atmosphere. Radiative forcing causes the earth's temperature to rise significantly to cause global warming effect. The adverse effect of global warming on human health, animals, terrestrial and aquatic ecosystems, and biochemical processes is quite significant (Wayman, Cordell and Houghton, 2009). IPCC (2015) predicted an increase in global warming effect in 2050, when population is expected to reach its peak. Projection of average global warming due to increase in concentration of atmospheric GHG is linked to economic growth and anthropogenic – human activities – effects (Pollalis *et al*. 2012).

- **Ozone Depletion (OD)**

The ozone (O_3) layer naturally filters the sun's ultraviolet (UV) radiation and prevents the sun's direct impact from reaching the earth. Ozone layer is thinned from increased release of certain anthropogenic emissions such as chlorofluorocarbons (CFCs) and other ozone-depleting substances (Wayman, Cordell and Houghton, 2009). As such, the atmosphere allows higher levels of UV radiation to reach the earth, causing detrimental effect on human health, animals, terrestrial and aquatic ecosystems, and biochemical processes. Adverse effects on human health include skin cancer, cataracts, and weakened immune systems.

- **Photochemical Oxidation (POCP)**

Photochemical oxidation is the formation of harmful atmospheric chemicals by the reaction of sunlight with certain air pollutants such as nitrogen oxides (NOX) and carbon monoxide (Wayman, Cordell and Houghton, 2009). The combination of nitrogen oxides and carbon monoxide in the presence of UV sunlight results in summer smog. Smog is harmful to human health, ecosystem, and crops.

- **Particulate Matter (PM)**

Particulate matter (PM_{10} and $PM_{2.5}$) is an important environmental factor contributing to human diseases (Frischknecht *et al*., 2016). Particulate matter accounts for most respiratory problems in humans, resulting from vehicle use and other types of pollution (McManus, 2001).

The second step is to select suitable category indicators. Category indicators include CO_2, NO_2, SO_2, NO_X, CH_4 and so on. Third step involves selecting impact assessment methods; these include impact 2002+, CML 2007, EDIP, Traci, Eco-indicator 99, EPS 2000 and ReCipe. The impact assessment methods embed relevant midpoint and endpoint impact categories. Midpoint and endpoint orientation of common methods are presented in Table 3.2. Existence of many impact assessment methods led to inconsistency in impact assessment results (Frischknecht *et al*., 2016). For instance, Owsianiak, Laurent and Bjorn (2014) compared the results of impact 2002+, ReciPe 2008 and EDIP. There were large discrepancies between the results of the different methods, even though a common metric score was applied. Clear guidance on impact assessment results is therefore imperative, particularly for LCA practitioners (Rack, Valdivia and Sonnemann, 2013; Frischknecht *et al*., 2016). Selected impact assessment for this study is presented in chapter four.

Table 3. 2 Impact Assessment Methods

Method	Characteristics	Impact category indicators	Midpoint/Endpoint orientations
CML 2007	• This method is an update of the CML 2002 method. • This version is based on the spreadsheet version as published on the CML web site.	Abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation	Midpoint level
Eco-indicator 99	• Widely used impact assessment methods in LCA • A succession of Eco-indicator 95 • Environmental impact assessment load is expressed in single score • A weighting method specifically designed for product design	Greenhouse effect, ozone layer depletion, ionising radiation, respiratory effects, carcinogens, regional effect on vascular plant, local effect on vascular plant species, acidification, eutrophication, and surplus energy for future extraction	Endpoint level
Impact 2002+	• Some midpoint categories were derived from existing characterising methods of (Eco-indicator 99 and CML 2002). • Midpoint scores are expressed in units of a reference substance, and link all types of life cycle inventory results to four damage categories: human health, ecosystem quality, climate change, and resources.	Carcinogens, non-carcinogens, respiratory inorganics, ionising radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid, land occupation, global warming, non-renewable energy and mineral extraction	Midpoint/endpoint level
ReCiPe	• An improvement on CML 2001 and Eco-indicator 99 • Contributors to ReCiPe include: Pré consultants, Centre of Environmental Science, Leiden University (CML) and Dutch national institute for public health and the environment (RIVM), Radboud University • Users can decide at which level to interpret results (either at midpoint or endpoint level)	Fossil depletion, metal depletion, water depletion, natural land transformation, urban land occupation, agricultural land occupation, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, marine eutrophication, freshwater eutrophication, terrestrial acidification, climate change ecosystems, ionising radiation, and particulate matter formation	Midpoint/endpoint
TRACI	• Tool for the Reduction and Assessment of Chemical and other Environmental inputs (TRACI) has 10 impact categories • Developed by US Environmental Protection Agency (EPA)	Global warming, acidification, carcinogens, non-carcinogens, human respiratory, eutrophication, ozone depletion, ecotoxicity, photochemical smog and fossil fuel depletion	Midpoint level
EPS 2000	• Environmental Priority Strategies • Damage-oriented method • An update of 1996 method	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance, crop growth capacity, wood growth capacity, fish and meat production, soil acidification, irrigation water, depletion of reserves and species extinction	Endpoint
EDIP	• The EDIP method (Environmental Design of Industrial Products, in Danish UMIP) was developed in 1996.	Global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, eutrophication, ecotoxicity, human toxicity, persistent toxicity, hazardous waste, nuclear waste, slag and ashes, bulk waste, and resource depletion	Endpoint

LCA Tool (software)

The workability of LCA methodology and data compilation is better enhanced with LCA software. LCA is a time-consuming process, and relies on practical or industry data, which are often difficult to obtain (Heijungs and Guinée 1994). LCA software promotes less complicated analysis, although it runs the risk of being abused (Crawford, 2011). A suitable software tool will include databases for inventory inputs and impact assessment methods. A description of commonly used LCA software (with embedded databases) within the construction domain is presented in Table 3.3. The use of software, however, does not guarantee reliable results unless the right knowledge or expertise is applied (Crawford, 2011). According to McManus (2001), disadvantages in the use of software include:

- **Misunderstanding the Process**

High tendency for people without knowledge (or training) of LCA process to generate inaccurate results.

- **Black Box Problem**

A false impression of result can be given to users on account of the results being easily generated. As such, users may think the results are correct, when they are actually wrong.

- **Data Quality Assurance**

The fact that software can produce results quickly implies that any data inputted will produce a result, even though inaccurate. As such, data required for LCA should be gathered with diligence.

Table 3. 3 LCA Tool with Databases

LCA tool +Databases	Applications			Place of Origin	Accessibility
	Building	Road pavement	Others		
Athena	✓			Canada	Free
Boustead			✓	UK	Not free
CMLCA			✓	Netherlands	Not Free
Economic Input-Output			✓	USA	Not free
EDIP PC Tool			✓	Denmark	Not Free
EPS 2000 Design System			✓	Scandinavia	Free
PaLATE		✓		California (USA)	Not Free
Gabi			✓	Germany	Free
Optimise	✓			Canada	Free
SimaPro	✓		✓	USA	Not free
TEAM				France	Not free
Others: Can be used for product comparison in any industry					

Characterisation Stage

Characterisation involves the multiplication of LCI emissions or substances (e.g. CO_2, CH_4) that contribute to an impact category by a unique characterisation factor – usually a reference substance – that expresses the relative contribution of the substance to the impact category. Characterisation factors are usually based on DALY (Disability Adjusted Life Years) and PDF (Potentially Disappeared Fractions) of species over an area for a period of time (Goedkoop *et al*., 2012). The characterised results themselves only represent the relative contribution of the impact indicator and not the magnitude of the indicators themselves.

Normalisation

Normalisation reveals the magnitude of an impact category from a reference point (ISO 14044, 2006). It reveals the extent to which a category indicator contributes to the overall environmental problem from a reference information (Bare, 2014). Reference information can be the yearly environmental load of a country or continent (Bare, 2014). For example, the average European inhabitants over one year is measured with reference to the average number of human deaths due to disability and disease, or the average disappearance of species due to toxic substances released into water and atmosphere (Goedkoop *et al*., 2012). Normalisation reveals the deleteriousness of the emitted substance on human health and ecosystem, and the resource depletion it causes, as indicated in Table 3.4.

Table 3. 4 Classification of Environmental Impact Substances into Damage Categories

Damage categories	**Impact categories**	**Substances**
Damage to human health	Damage to human health caused by climate change	CO_2, CH_4, NO_X
	Respiratory effect on human health caused by organic substances	VOC, CH_4
	Respiratory effect caused by inorganic substances	PM_{10}, CO, NO_X, SO_X
Damage to ecosystem	Damage caused by the effect of acidification and eutrophication	NO_X, SO_X
Damage to mineral and fossil resources	Damage caused by extraction of minerals	Limestone, ironstone, manganese ore
	Damage caused by extraction of fossil fuels	Coal equivalent, crude oil

Grouping and Weighting

Grouping and weighting is a final step of the impact assessment stage, but optional. It is where the normalised scores are multiplied by a weighting factor that expresses the relative importance of the impact's effect (Finnveden *et al*., 2009). The overall impact results are added up to give a single score value for the overall impact. The single score allows easy comparison of two products' environmental contributions, which is useful for decision making. However, weighting scores cannot be used for comparative assertions if intended for public disclosure, except for results that undergo a peer review process (ISO 14044, 2006). This stems from the fact that different approaches are used to determine weighting factor, varying from country to country (PRé Sustainable, 2015). Examples of such approaches include distance to policy, distance to scientific target, monetisation, and panel weighting (Schmidt and Sullivan 2001).

3.2.4 Interpretation

Interpretation is the final step of an LCA methodology. It involves gathering all the LCA results and putting them into a meaningful context (Skone, 2000). The interpretation stage is used to check the level of confidence of the final results, for results to be communicated in a fair and accurate manner (Skone, 2000). According to ISO 14040 (2006), three steps are involved in interpreting LCA results;

Identify the Significant Issues

Key issues relating to goal, scope, system boundary, functional units, data collection process, data availability, assumptions and limitations of the study are cross checked to ascertain reliability.

Completeness, Consistency, and Sensitivity check

Completeness check is ensuring data collected for the LCA study is sufficient for reaching meaningful conclusions. It involves checking data gap and data acquisition process, and ensuring no aspect of the data collection was exempted. Consistency check ensures all assumptions, methods, and data are consistent throughout the study, as variations may affect the final outcome. Sensitivity check ensures the choices of method and data are relevant to the study.

Draw Conclusions and make Recommendations

Conclusions and recommendations are made after necessary checks are completed. It is, however, unclear whether the conclusion stage is still part of the LCA study itself or it depends on the application context (Saur, 1997). Nevertheless, conclusion is necessary to provide recommendations for improvement.

3.3 Shortcomings of LCA Methodology

LCA is an evolving tool and has attracted a lot of attention in many industry sectors. Though LCA continues to gain ground, major issues are being raised regarding its methodological approaches (Cowell, 1998; McManus, 2001; Crawford, 2011; Parsons, 2016). These include; system boundary selection (or system modelling), lack of proper data, various impact assessment methodologies, uncertainties, functional units, and interpretation of results (Reap, Roman and Bras, 2008). These issues become more complex in LCA of bridges, stemming from a lack of realistic data for analysis (Du and Karoumi, 2014). Critical issues affecting LCA approaches are discussed below.

I. System Boundary Selection

Boundary selection determines the process and activities accounted for in the LCA study. Issues with system boundary selection relate to proper or improper justification of one's boundary selection, which depends on objective, repeatable and resource challenges (Raynolds, Fraser and Checkel, 2000). Problems of not selecting appropriate boundaries will lead to wrong interpretation and comparative results, and generally undermine confidence in the LCA study (Lee, O'Callaghan and Allen, 1995; Reap, Roman and Bras, 2008). However, ISO 14040 recommendations for boundary selection is unhelpful, in the sense that ISO 14040 recommends that elements of the physical system to be modelled should be based on: goal and scope of the study, application and audience, assumptions, constraints, and cut-off criteria (ISO 14040, 2006). The subjectivism of ISO recommendations has been criticised as leading to reduced confidence in comparative LCA studies (Suh, 2004). However, the subjectivism gap is filled when LCA study is conducted in a transparent manner (when all data, methodology and assumptions are clearly stated) and reproductivity is achievable (McManus, 2001).

II. Lack of Proper Data

Lack of realistic data is a challenge in LCA study (Crawford, 2011). The quality of inventory data is significantly dependent on the processing activities and regional technology involved (Du and Karoumi, 2014). As a result, inventory data for the same material could produce varying results (Du and Karoumi, 2014). Similarly, life cycle stages, geographic area and time horizon involved in system boundary depend on data (Reap, Roman and Bras, 2008). If the wrong database is applied, LCA result will be compromised. However, one inventory database cannot cover all material types, processes, and procedures at the same time (Du and Karoumi, 2014). Therefore, a consistent and internationally agreed database for major industry sectors is required.

III. *Various Impact Assessment Methodologies*

Deficiencies with earlier impact assessment methods led to development of alternative ones (Cowell, 1998). Unfortunately, one of the greatest problems of LCA is the existence of different impact assessment methods (Du *et al*., 2014). Studies like Landis and Theis (2008), and Owsianiak, Lauren and Bjorn (2014) compared CML 2007, Eco-indicator 99, EDIP, IMPACT 2002+, TRACI and ReCiPe. These comparisons revealed that certain impact categories may be significant in one method and negligible in another method, which therefore weakens the strength of LCA as a decision-making tool in a comparative study (Selmes, 2005). On this ground, Landis and Theis (2008) revealed that there is no right impact assessment method, although it may be better to utilise the newest methods in practice (Du and Karoumi, 2014). ReCiPe is a newer method and embeds the latest impact categories such as PM_{12}, fossil fuel depletion and metal depletion.

IV. *Uncertainties*

LCA studies are generally exposed to uncertainties. Uncertainties emerge from lack of clarity in the true value of quantities (Björkland, 2002). These uncertainties can mislead a decision maker if not plainly interpreted. According to Parsons (2016), LCA uncertainties are classified as parameter uncertainties, model uncertainties and uncertainties due to choices. For instance, uncertainties emerging from input parameters of inventory database, impact assessment methods and boundary selection should be quantified to reveal the significance of any parameter changes (Huijbregts 2001; Björkland, 2002). Sensitivity analysis and Monte Carlo Simulations are used to address uncertainty issues in LCA, although more reliable criteria are required to explain the significance of the results obtained (Du and Karoumi, 2014).

V. Selecting a Functional Unit

A functional unit is defined at the scope definition stage of an LCA study. A functional unit provides the basis for quantifying input and output data and promotes the scope for comparison (ISO, 1997). Selecting a functional unit is a major challenge with LCA studies, as ISO 14040 and ISO 14044 only provide general guidance. The ISO guidance explains that a functional unit shall be consistent with the goal and scope of the study, and it shall be clearly defined and measurable (ISO, 2006). Selecting an adequate functional unit is, however, vital for LCA study, as different functional units could lead to different results for the same product system (Hischier and Reichart 2003; Kim and Dale 2006; Panesar, Seto and Churchill, 2017). According to Reap, Roman and Bras (2008), error can stem from three areas when selecting a functional unit. These are:

- When identifying and prioritising functions,
- When defining the functional unit,
- When defining the reference flow.

Selecting a functional unit for multiple systems is even more complex, as there are possibilities of different functional units which may not address all the functions (Cooper, 2003). As such, selecting a suitable functional unit is not an easy task. However, based on Panesar, Seto and Churchill's (2017) investigation on green concrete, it was revealed that a suitable functional unit should capture the system's functional performance metrics specific to its application. On this basis, a suitable functional unit would be that which captures the performance of the system to a large extent.

VI. Interpretation of Results (Normalisation and Weighting)

Both normalisation and weighting are optional stages of the impact assessment phase. While normalisation compares the actual characterisation results with the reference results, weighting depends on monetary, ethical, political, and cultural perspectives (Du and Karoumi, 2014). However, these values will differ from region to region and therefore cannot be widely agreed (Finnveden *et al*., 2009). As a result, weighting values are disregarded for making comparative assertions if results are to be made publicly available, so as to avoid biased conclusions (Pré Sustainable, 2015).

3.4 Current Criticism of LCA

A range of criticism has been directed against LCA applications, besides those revealed in section 3.3. To begin with, a task force group was organised by UNEP and SETAC to ensure the unification of impact assessment methodologies emerging from the outcome of a workshop held in 2013, which revealed the complexity of the LCIA method and associated cost and selection of LCIA category indicators as a prominent challenge (Rack, Valdivia and Sonnemann, 2013). A recent report indicates limited progress has been made, although there may be scope for improvement emerging from the rice case study (Frischknecht, *et al*., 2016). Criticism is also raised about LCA's inadequacy in addressing spatial studies, particularly in terms of relevance, indices of stress, stocks and flows, and integrated valuation of services underpinning ecological and biodiversity concepts (Geyer *et al*., 2010; O' Shea, Golden and Olander, 2013). While this remains an emerging area, there is scope for combining LCA and GIS data to solve most of the problems identified (Karlsson *et al*., 2017).

One prominent criticism of LCA is its inability to recognise the economic and social aspects of sustainability, which tends to limit its capacity to make sustainable decisions (Hertwich, 2005; Reap, Roman and Bras, 2008; Jørgensen *et al*., 2008; Jørgensen, Hermann and Bjørn, 2013; Sala *et al*., 2013). Care should, however, be taken not to convolute LCA in practice and derail its original scope for supporting environmental decision making (McManus, 2001; ISO, 2006). Researchers have tried to integrate economic (LCC) and social (LCS) factors into LCA methodologies (Norris, *et al*., 2001; Sala, Farioli and Zamagni, 2013), yet broader application has been challenging (Hunkeler and Rebitzer, 2005).

3.5 A review of LCA on Bridges

LCA is a quantitative method developed to calculate the life cycle environmental impacts of product design (Ainger and Fenner, 2014). Although it can be applied to complex structures like bridges (Du and Karoumi, 2013), only limited literature is available on LCA of bridges (Keoleian *et al*., 2005), including highways, railways, and waterways. Meanwhile, authors such as Haung, Bird and Heidrich

(2009) and Santero, Masanet and Horvath (2011) have worked on LCA of asphalt pavement. An overview (presented in Table 3.5) of review papers published within the last 8 years for building, road and bridges plainly reveals that not much has been done in regard to LCA of bridges. Bridge LCA has mainly been used for comparison purpose (i.e. comparing different bridge forms, materials, components, and design elements). However, only a small body of literature has compared bridge maintenance methods (Steele *et al*., 2003; Pang *et al*., 2015). A chronological review of LCA application to bridges is presented to fill the gap of limitations in the literature. The review covered bridge design, materials, life-cycle phase, elements, impact categories and impact assessment method considered, and the result of the study.

Table 3. 5 Published LCA Review Papers within the last 8 years on Building, Bridges, and Road pavement

Authors	**Area of focus**	**Applications**			**Paper type**
		Bridges	**Buildings**	**Road pavement**	
Chau *et al*. **(2015)**	LCA, LCEA (Life-Cycle Energy Analysis), LCCEA (Life-Cycle Carbon Emissions on buildings)		✓		A review
Islam *et al*. **(2015)**	LCA and LCC implication of residential buildings		✓		A review
Rashid and Yusoff **(2015)**	LCA method for building industry		✓		A review
Cabeza *et al*. **(2014)**	LCA and LCEA for buildings		✓		A review
Du and Karoumi **(2014)**	LCA for bridges	✓			A review
Buyle *et al*. **(2013)**	LCA for building construction		✓		A review
Santero *et al*. **(2011)**	LCA of pavement			✓	A review
Sharma *et al*. **(2011)**	LCA for buildings		✓		A review
Ortiz *et al*. **(2009)**	LCA of building materials		✓		A review
Khasreen *et al*. **(2009)**	LCA for buildings		✓		A review

3.5.1 Case studies Comparing Bridge Forms, Elements, Components, Materials and Designs

Widman (1998) compared the LCA results of steel I-girder bridge and steel box-girder bridge which were the most common types of bridge in Sweden at the time. The system boundary accounted for raw material extraction till demolition stage of the superstructure, substructure, railings, and pavement. LCI data were gathered from Sweden, Norway, and Finland manufacturers. Impact categories considered were CO_2, NO_X, SO_2 and CO. Traffic arising from movement of materials and products was the most impactful stage, emerging from high emissions (of CO_2 and NO_X). Manufacturing of cement and steel was also another great source of environmental pollution. There was no large difference between the LCA results of the bridges compared, apart from the fact that steel I-girder bridge had more concrete input and therefore produced more CO_2 emissions than the steel box-girder bridge. Moreover, traffic influence also contributed more impacts.

Hendrickson and Horvath (1998) analysed the LCI results of a steel girder bridge and steel-reinforced concrete bridge. The analysis only considered the manufacturing, use or maintenance, and the end-of-life phase. Data were derived from the literature, and many uncertainties were recorded. The Economic Input and Output (EIO) methodology was adopted for the study. Impact categories were not clearly stated, other than the fact that the steel girder bridge will potentially have more impact, considering resources consumed during the manufacturing phase. However, the steel can be recycled and reused compared to concrete which will end in a landfill.

Steele *et al*. (2002) examined three case studies of masonry arch bridge with different design and construction material. A cascade bridge was singled out from the design to compare its maintenance methods. LCI data was obtained from Building Research Establishment (BRE), SimaPro software, Pre4, BULWAL and IDEMAT database. The study covered construction and maintenance phases. The construction phase accounted for mixing of mortar onsite, energy from mixer, and transportation of bricks to site. The maintenance phase accounted for two strengthening techniques (i.e. concrete saddle and anchor installation). SimaPro LCA software was utilised and Eco-indicator 99 was used for the analysis. The impact categories considered were; eutrophication (kg PO_4), solid waste production (kg), energy consumption (MJ), greenhouse gas (kg CO_2), ozone depletion potential (kg CFC11), summer smog impact (kg C_2H_4), winter smog impact (kg SPM), heavy metals (kgPb), carcinogens (kg BP), and acidification (kg SO_2). The anchor technique had less environmental impact compared to the saddle (even with traffic disruption).

Itoh and Kitagawa (2003) compared two alternative girder bridge designs: conventional bridge and minimised girder. The system boundary covered the construction, maintenance and replacement phase and accounted for the superstructure and substructure. Only the site activities and resource consumption were included in the analysis. LCI data was obtained from design manuals and interviews with engineers. Impact category considered was CO_2 and energy demand, same as Widman (1998). Overarching results revealed that the conventional design yielded more CO_2 than the minimised girder.

Martin (2004) compared a steel-concrete composite bridge deck and a pre-stressed concrete bridge deck. A cradle-to-grave approach was employed for the analysis, although the LCA method and life cycle phases considered were not clearly stated. Results indicated that the pre-stressed concrete deck used 39% less energy than the steel-concrete composite and generated 17% less greenhouse gases (GHG) than steel-concrete composite for virgin materials. With recycled materials, the pre-stressed concrete still consumed less energy. However, the steel composite resulted in 30% less emission of GHG on the basis of recycling.

Keoleian *et al*. (2005) compared a bridge with conventional steel expansion joints and a bridge with a link slab concrete design, engineered with a cementitious composite (ECC). The analysis accounted for construction, use and end-of-life stages. Assumptions were made for the maintenance scheme of the bridge, i.e. the conventional joints should be replaced every 30 years, deck resurfacing and joint replacement every 15 years, and repair maintenance every 5 years. For the ECC option, the deck resurfacing should be replaced every 20 years and maintained every 10 years. The study did not consider emissions from traffic flow in the use phase. LCI data was obtained from Portland Cement Association, Ecobilan's Database for Environmental Analysis and Management (DEAM), International Steel Institute (ISI), and some data were collected from industries and manufacturers. The impact categories considered were: material resource consumption, energy consumption and global warming. Results indicated that the ECC yielded more energy saving potential and reduced environmental pollutant emissions, emerging from its resistance to deterioration.

Collings (2006) compared girder, arch and cable stay bridge structural form constructed with common bridge materials (i.e. concrete, steel and steel-concrete composite). The study covered the construction and maintenances phases of the superstructure. LCI data was collected from various industries and manufacturers. Impact categories considered are CO_2 and energy consumption. Analysis revealed that the concrete girder consumed less and yielded less amount of CO_2 emissions compared to other structural forms.

Lounis and Diagle (2007) compared two bridge deck design alternatives. The first was designed as a conventional deck using normal concrete, and the other was designed as a High-Performance Concrete (HPC) using fly ash, slag, and silica fume. The study covered all life-cycle phases from material extraction to material disposal. Impact categories accounted for are CO_2 and construction waste. Results revealed that CO_2 emission was three times higher for the normal concrete than the HPC alternatives.

Gervásio and da Silva (2008) investigated two bridge design alternatives (I-girder steel-composite bridge and a concrete-concrete twin U-girder bridge). The study covered the construction phase, raw material production and super-structure components, although the piers were excluded in the analysis. Two methods of steel production were considered: Basic Oxygen Furnace (BOF) and Electricity Arc Furnace (EAF). Nearly all LCI data was assumed, but the bulk of the cement data was obtained from Portland Cement Association, US. The steel data were obtained from International Iron and Steel Institute. Assumptions were made for the maintenance scheme, i.e. deck repair should be done every 20 years, while pre-stressed box girder should be repaired every 10 years. The impact categories considered were; global warming, acidification, eutrophication, fossil fuel depletion, habitat alteration, criteria air pollutants, human health, smog formation, ozone depletion, ecological toxicity, water intake, and indoor air quality. The emissions considered for these categories were carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NO_X), volatile organic compounds (VOC), carbon monoxide (CO), methane (CH_4), and particulates. Results indicated that concrete, steel, and cement production were responsible for most CO_2 emission, and bridges used up the highest proportion of these materials. Also, the steel-concrete composite had better environmental performance than the concrete-concrete alternative.

Bouhaya, Roy and Feraille-Fresnet. (2009) performed LCA on a road bridge made of wood and Ultra-High-Performance Concrete (UHPC) slab. All life-cycle stages were considered for the analysis, from raw material extraction to the end of life. Assumptions were mostly made for the maintenance of UHPC. The UHPC was assumed to be maintenance free for 100-year service life, while the wooden components would be replaced on an economic balance bridge maintenance scale. The impact categories considered were CO_2 and energy. Three end-of-life scenarios were also considered for the timber component. Firstly, it would be used as landfill, burnt for heating, and recycled. Results indicated that the manufacturing phase used the most energy.

Brattebø, Hammervold and Reenaas (2009) compared steel box-girder, wooden arch, and concrete box-girder bridge. The study covered material extraction, manufacturing, construction, use and end-of-life phase. The study used SimaPro and Ecoinvent database. The construction phase accounted for preparation of foundation, concreting abutments, girder erection, diesel consumption, and transportation of materials and workers to site. The use phase covered painting and routine replacement. The end-of-life phase accounted for recycling of steel. Impact indicators considered were resource depletion, climate change, acidification, eutrophication, ozone layer depletion and photo-oxidants. Results revealed that concrete box-girder bridge had better environmental performance over the wooden arch and steel box girder.

Thiebault (2010) compared two railway steel-concrete bridge designs. The comparison was between a ballasted and a fixed concrete single track. The study covered raw material extraction, construction materials recycling, use and end-of-life. Impact categories considered were abiotic depletion, global warming, human toxicity, photo-oxidants, acidification, and eutrophication. Results indicated that the fixed concrete track imposed 77% less environmental impact than the ballasted option.

Dequidt (2012) investigated a Norwegian bridge (post-tensioned concrete-girder deck of 165m span and 670m length). The study accounted for material production, construction, operation, maintenance and repair and end of life. Material production phase was divided into superstructure, substructure, and subsidiary elements. The superstructure covered concrete deck box-girder, non-structural elements, and sub-structure. The study accounted for transportation to site, energy consumption on the construction site and waste management at the construction phase. Traffic-related emission, traffic growth rate and supply for public lightning were considered for operational phase. The maintenance scheme was divided into visual inspection (every year), main inspection (every 5 years) and asphalt course renewal (every 3 years). The end-of-life phase accounted for reinforced concrete, asphalt, gravel, railings, and parapets. Impact indicator considered was global warming category (GWP), while others were excluded. Results indicated that the superstructure, production phase, maintenance phase, concrete, steel, and asphalt were the major contributors of environmental impact.

Hammervold, Reenaas and Brattebø (2013) compared steel box-girder, wooded arch and concrete box-girder bridge. The study covered material extraction, manufacturing, construction, use and end-of-life phase, and accounted for the superstructure and the preparation of foundation alone. The construction phase covered diesel consumption for activities like site preparation, mounting of bridge, transportation of materials, transportation of workers and wooden form works. A maintenance scheme was assumed, i.e. steel box bridge should be repainted every 20 years and 10% of its parapet should be renewed every 10 years, as is done for other bridge forms. The wooden bridge, however, is assumed to be painted with mordant oil every 15 years, and clearing of water should be done every 10 years alongside general inspection every 5 years. Analysis covered personnel transportation to site and equipment used. The end-of-life phase covered bridge demolition, sorting of materials, treatment of materials and all transportation of materials. SimaPro software was used and Eco-invent 2008 database was employed. The actual analysis was conducted using Matlab (BridgeLCA). The CML impact assessment method was used and six impact categories were considered (acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone-layer depletion potential (ODP), photochemical potential (POCP), and abiotic depletion potential (ADP)). Results indicated that the concrete box-girder had best environmental performance compared to the other two bridges. Additionally, the materials in the load bearing areas of the bridge were mostly responsible for the environmental performance, i.e. steel reinforcement, concrete, glued laminated wood, and copper, while surfacing materials such as asphalt and asphalt membrane played an equally significant part in the whole environmental burden.

Du *et al*. (2014) compared five different bridge designs [Two steel boxes (composite), Two steel I-girder (composite), One pre-stressed (concrete box), Two pre-stressed concrete boxes, and One concrete box girder]. The study covered material manufacture, construction, maintenance and use, and end-of-life phase. ReCiPe methodology was adopted, and impact categories considered were Global warming (GWP), ozone depletion (ODP), human toxicity (HTP), photochemical oxidant formation (POFP), particulate matter formation (PMFP), ionizing radiation (IRP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), non-methane volatile organic compounds (NMVOC), and particles (PM_{10}). Emissions accounted for were CO_2, CH_4, SO_2, NH_3, NO_x, NMVOC and PM_{10}. The maintenance scheme applied in the study was derived from historic statistics and personal communication. Results failed to reveal clear distinctions between the bridges compared, on account of the fact that the indicators selected were not enough to reach a convincing conclusion. There were cases where a bridge design performed well with some indicators and did not with others. Therefore, a clear justification cannot be made on the basis of only a few indicators, as it could lead to biased conclusions.

3.5.2 Synthesis of the Case Studies

The literature above covers areas where LCA had been applied to bridges. It was evident that only the superstructure (deck component) of the bridge was accounted for, mostly, and only a handful considered sub-structural components. Impact assessments principally considered are CO_2 emissions and energy with depletion of abiotic resources, acidification, eutrophication, climate change, ozone layer depletion, and photo-oxidant creation as midpoint category indicators. Impacts like particulate matter, fossil fuel and metal depletion are relatively new. Generally, it can be inferred that results were largely determined by the input parameters of LCI, system boundaries and impact assessment methodologies adopted. Therefore, even the same bridge under a different scenario can yield a different result; more so as there is a high level of uncertainty about the data collected. Although Zhang, Wu and Wang (2016) tried to address uncertainty issues in LCA of bridges through sensitivity analysis, it does not change the fact that data availability is a root cause for most uncertainty problems in bridge LCA studies.

Nearly all case studies accounted for the construction phase, followed by the use, maintenance, and end of life. However, a majority of the case studies assumed a maintenance scheme due to lack of data, with the exception of Steele *et al*. (2003) and Pang *et al*. (2015) who compared different maintenance actions. It is therefore evident that a study that compares preventive and strengthening maintenance options of concrete, steel and masonry bridge is yet to be carried out.

3.5.3 Usefulness of Bridge LCA Results

The case studies revealed that LCA in bridges has only been conducted for comparison purposes. Moreover, only issues of uncertainties, functional units, data availability, system boundaries, methodology and impact assessment categories have been addressed (Crawford 2011; Du and Karoumi 2014; Panesar, Seto and Churchill, 2017). Limited attention is paid towards how interpreted results will support decision making, considering that many of these results are subject to the shortcomings presented in section 3.3. Du *et al*. (2014), for example, struggled to reach a convincing conclusion and asserted that only a comprehensive LCA that considers all impact categories could allow a detailed conclusion to be reached. No bridge LCA study has achieved such a level of detail yet, considering that the choice of what to include in the analysis depends solely on the investigator (Crawford, 2011; Du *et al*., 2014; Pang *et al*., 2015). Therefore, the usefulness of the interpreted result should be investigated and justified for practical relevance. According to Cowell (1998), the usefulness of LCA results is measured on four criteria: accuracy, relevance, being understandable and meaningful, and acceptability as a legitimate form of analysis. While these issues are vaguely addressed in bridge industry and in many other sectors, researchers are beginning to employ stakeholder engagement to tackle some of these issues (Shiels, 2004; Selmes, 2005; Sala, Farioli and Zamagni, 2013). The usefulness of the LCA interpreted may be better clarified by stakeholders who can relate with the result and advice on its capacity to aid decision making. None of the case studies in section 3.5.1 presented the usefulness of the result through a structured approach. Exploring the usefulness of bridge LCA results will potentially aid practical implementation and wider applicability of LCA, considering that its application is still limited within the bridge industry. The limited application can be traced to a lack of knowledge and awareness (Tan, Ofori and Briffett, 1999; Crawford, 2011), and possibly doubts regarding the integrity of the results.

3.6 Chapter Summary

The chapter has presented the historic development of LCA, and evaluates the LCA framework and shortcomings and associated criticism. The review on LCA application to bridges reveals that LCA has been minimally applied to bridge maintenance methods. Similarly, the usefulness of the result has not been greatly explored, and as such the study seeks to apply LCA on common maintenance actions. Findings from such investigations could potential guide designers, client and bridge owners on the most sustainable bridge structural form from a life cycle maintenance view point.

CHAPTER FOUR: RESEARCH DESIGN AND METHODOLOGY

4. Introduction

The chapter presents the overarching methodological framework for the research, and details the philosophical underpinnings, approach, strategy, methods, and the overall design adopted in the study. It reveals various data collection strategies and analytical mediums employed to address the research questions, aims and objectives, and concludes by highlighting ethical rules that were upheld throughout the study.

4.1 Underpinning Methodological Paradigm

A research paradigm can be defined as a theoretical framework or lens through which researchers view events (Fellows and Liu, 2008). It is a set of philosophical assumptions that helps to define the nature of possible research and intervention (Mingers and Brocklesby, 1997). Paradigm issues are philosophical in nature and encompass elements of theories – ontology and epistemology – alongside methods of enquiry (Punch, 2014). Furthermore, paradigm can be pictured as viewing the world through a specialised instrument, such as a telescope, an x-ray machine or electron microscope, where each machine reveals an aspect, but is completely blind to other aspects (Mingers and Brocklesby, 1997 p.492). Hence, paradigm potentially drives the choice of methods.

Some researchers see paradigm as *worldview* (Guba, 1990: p 17; Creswell, 2014: p 6) and *construct* (O'Leary, 2010). While these "terms" are derived from natural science and pure science, it is best to stick to 'paradigm', which is mostly used in construction research (Fellow and Liu, 2008). In addition, Bryman and Bell (2011), Saunders, Lewis and Thornhill (2012), and Rose, Spinks and Canhoto. (2015) have listed broadly different types of paradigm – positivism, interpretivism, social constructionism, relativism, and realism, but Fellows and Liu (2008) have narrowed these down to two – positivism and interpretivism, which are mostly used in construction research.

4.1.1 Positivism

Positivism has been an earlier philosophical view of natural science (Robson, 2011 pp. 20). It is a philosophical phenomenon that tends to apply natural science methods to social sciences (Rose, Spinks and Canhoto, 2015). A positivist research is value-free, usually renowned for avoiding researcher bias – that is, entirely independent of the researcher's view (Bell, 1993; Fellows and Liu, 2008; Punch, 2014). Healy and Perry (2000) describe a positivist approach as a way of gathering facts and observations, and testing independent variables with a dependent variable. In line with this, Rose, Spinks and Canhoto. (2015 pp. 16) describe a positivist approach as that which tends to establish a causal explanation in the form of laws using controlled observations and measurement. Positivism paradigm governs most quantitative research, as it seeks factual data, which are then tested against previous literatures or theory to study the relationships between them (Fellow and Liu 2008; McGraw and Creswell, 2009). In summary, a positivist approach is that which uses values, figures, and numbers to demonstrate the relationship between events or entities and postulates theories towards solving a scientific problem.

4.1.2 Interpretivism

Interpretivism position rejects the positivism assumptions that scientific methods should be applied to social science problems (Saunders *et al*., 2012; Rose, Spinks and Canhoto, 2015). It is argued that there are fundamental differences between objects and human reasoning, which is highly dependent on socio-cultural context (Rose, Spinks and Canhoto, 2015). This translates as, reality is perceived and interpreted differently, depending on how it has been understood (Bryman and Bell, 2011). Interpretivist paradigm governs most qualitative research, as it seeks to give meaning to events (Saunders, Lewis and Thornhill, 2012). In a broad view, the interpretivist approach seeks to understand and draw conclusions based on people's perception of a phenomenon.

4.1.3 Paradigm War

Positivism and Interpretivism are two opposing paradigms, and some groups of researchers tend to believe that their choice of paradigm and methods is superior to others, known as the 'paradigm wars' (Punch, 2014, p.15). However, the status quo is changing, and researchers are beginning to combine methods from different paradigms (Creswell, 2014). This, however, comes with much criticism (Knight and Ruddock, 2008). The selection of a multi-paradigm approach causes concerns due to 'paradigm incommensurability thesis', in terms of philosophical orientation and methodological approach that mandates the researcher to stick to rules governing a particular paradigm (Mingers, 1997, pp.13; Mingers and Brocklesby 1997; Knight and Ruddock, 2008)

4.1.4 Pragmatism - Way forward

Pragmatism is an emerging paradigm, which holds that instead of focusing on the dichotomy of philosophical positions, emphasis should be on understanding the research problems, and using pluralistic approaches to develop knowledge for solving the problems (O' Leary, 2004; Johnson and Onwuegbuzie, 2004; Tashakkori and Teddlie, 2010; Dures *et al*., 2011; Morgan, 2014). Pragmatism recognises the differences between the previous paradigms (that is; positivism and interpretivism), but does not see them as incommensurable, if a positive change is to be made (Kelle, 2006). Pragmatism is the philosophical position underpinning a mixed method approach (mixed method is discussed in subsequent sections) (Greene and Caracelli 2003; Bryman, 2006; Guest, 2013; Creswell, 2014).

4.2 Justification for the Selected Paradigm

The selected paradigm was based on the research question, aims and objectives, developed from the problems and rationale of the research. While both objective one and two sought to understand and explore different phenomena through a literature search, objective three and four sought to identify and explore different phenomena through structured and unstructured means, respectively. For clarity, Table 4.1 presents objectives one to four and possible methods of addressing them.

Notably, these methods have emerged from different paradigms. Hence, a suitable paradigm for this research will be that which allows the flexibility of methods towards addressing the research enquiries. On this ground, pragmatism was selected to underpin the philosophical orientation of the overall research, which allows the flexibility of adopting different methods.

Table 4. 1 Research Objectives and Possible Methods

RESEARCH OBJECTIVES	POSSIBLE RESEARCH METHODS	POSSIBLE PARADIGM
1. To understand and explore environmental aspects of sustainability in infrastructure	Desk top studies; secondary and primary literature sources	Positivism; interpretivism
2. To understand the trend and usefulness of LCA results in the bridge industry	Desk top studies; secondary and primary literature sources	Positivism; interpretivism
3. To Identify the probable environmental impact of concrete, steel, and masonry bridge maintenance activities, using the LCA tool	Questionnaire survey; tailored data collection sheet; LCA methodology; interviews;	Positivism; interpretivism
4. To explore the stakeholders' perspective on the usefulness of factoring in LCA results of bridge maintenance methods into the bridge design process, and its potential to improve sustainability decisions	Interviews; questionnaire survey	Interpretivism; Positivism

4.3 Research Methodologies and Methods

Research methodology is the overarching framework that promotes the underlying principles associated with the specific paradigm for a particular research (O' Leary, 2010). While a research design involves the overall planning and execution of a research project (Punch, 2014), research methodologies offer strategies and grounding to execute the project. Creswell (2014) reveals three common research methodologies and associated methods they (tend to or) typically utilize (see Table 4.2).

Table 4. 2 Quantitative, Qualitative and Mixed Methods Approaches. *Adapted* from Creswell (2014) *(Table used with permission)*

Tend to or Typically…	**Quantitative Approaches**	**Qualitative Approaches**	**Mixed Methods Approaches**
• Use these philosophical assumptions • Employ these strategies	• Positivism/postpositivist • Surveys and experiment	• Interpretivism/ Constructivist/transformative knowledge • Phenomenology, grounded theory, ethnography, case study and narrative	• Pragmatic knowledge claims • Sequential, concurrent, and transformative
• Employ these methods	• Closed-ended questions, predetermined approaches, numeric data	• Open-ended questions, emerging approaches, text or image	• Both open and closed-ended questions, both emerging and predetermined approaches, and both quantitative and qualitative data and analysis
• Use these practices of research as the researcher	• Tests or verifies theories or explanations • Identifies variables to study • Relates variables in questions or hypotheses • Uses standards of validity and reliability • Observes and measures information numerically • Uses unbiased approaches • Employs statistical procedures	• Positions him or herself • Collects participants' meaning • Focuses on single concept or phenomenon • Brings personal values into the study • Studies context or setting of participants • Validates the accuracy of the findings • Makes interpretations of data • Creates an agenda for change • Collaborates with the participants	• Collects both quantitative and qualitative data • Develops a rationale for mixing • Integrates the data at different stages of inquiry • Presents visual pictures of the procedures in the study • Employs the practices of both quantitative and qualitative research

4.3.1 Quantitative Research Approach and Methods

A quantitative approach involves gathering factual data to observe the relationship between the facts. It also involves variables and numbers, which are measured and analysed statistically (Denzin and Lincoln, 2000). Quantitative approach is predominantly used in the field of social sciences to test a specific question or hypothesis for a set of variables (Crotty, 1998; Blaike, 2003).

Quantitative research is attributed to the positivism paradigm and governed by a deductive approach (Robson, 2011; Creswell, 2014). In line with this, Blaike (2007) asserted that the quantitative approach comprises of deductive reasoning, and tends towards working from hypothesis prediction to testing variables. Generally, quantitative research employs strategies like experimental and survey design to collect data, using questionnaires, structured interviews, or possibly structured observations (Saunders, Lewis and Thornhill, 2012).

4.3.1.1 Experimental Design

Experimental design helps to determine causal relationships between variables (Fellows and Liu, 2008). Experimental design involves the manipulation of one or more independent variables to discover the effect on a dependent variable (Rose, Spinks and Canhoto, 2015). In other words, experimental investigations can measure the consequence of manipulating one variable against another variable in a controlled environment. This is true for a normal science research, where cause and effect of independent and dependent variables is demonstrated (Thomas, 2013). However, it is difficult to determine this type of cause-effect changes in a social scientific research where circumstances are prone to change (Thomas, 2013). Experiments can be either true experiments, with random assignment of participants to treatment, or quasi-experiments with naturally occurring treatment (non-randomized) (Punch, 2014). As such, researchers exercise control over the true experiment and no control over the quasi-experiment.

4.3.1.2 Non-experimental Design – Survey Design

Survey design is commonly attributed to the use of questionnaires, even though questionnaires themselves do not define the characteristics of the design (Rose, Spinks and Canhoto, 2015). A survey study produces quantifiable data on the variables of interest for the population under study using predefined structured collection procedures – often questionnaires or other secondary sources (Saunders, Lewis and Thornhill, 2012). Questionnaires are data collection instruments that use a standardised, structured set of questions to measure variables, e.g. attitudes, feelings or thought that are of interest to the researcher (Rose, Spinks and Canhoto, 2015). Questionnaires have varying advantages, including speed of collection, low cost, flexibility, anonymity and so on (Naoum, 2007). However, downsides of questionnaire are variable response rate, partial completion, respondent literacy level (Naoums, 2007). Depending on the sample frame in use, questionnaires are administered through emails, post, self and online.

4.3.2 Qualitative Research Approach and Methods

Qualitative research seeks to comprehend people's perception of the world (Crowther and Lancaster, 2009). A qualitative approach has the ability to clarify the whole context of obvious phenomena (Merriam, 1998). It is an approach that explores the meaning of each individual's understanding of the research problem (Creswell, 2014). Usually, qualitative research is associated with interpretative philosophy (Denzin and Lincoln, 2005; Fellows and Liu, 2008).

A qualitative research adopts a 'constructionist approach', which seeks to construct meanings from participants' understanding of the phenomena (Saunders, Lewis and Thornhill, 2012: 163). Many qualitative researches employ an inductive approach to develop a robust theoretical and conceptual framework. To a large extent, a qualitative research requires studying participants' meanings to definitions to bring about new knowledge (Braun and Clarke, 2013).

According to Creswell (2014), various types of qualitative approaches have been reported since early 1990s till now. Creswell (2014), however, narrows these approaches down to five main types, that is – narrative research, phenomenology, grounded theory, ethnographies, and case studies.

4.3.2.1 Narrative Research

'Narrative' as a word is sometimes used interchangeably with storytelling (Riessman and Quinney, 2005). As such, narrative research belongs to a class of approaches which focus on the stories written by people to express themselves (Robson, 2011). Narrative research tries to capture the lived experiences expressed in biography, autobiography, life history and oral history, with the hope of retelling the story in a narrative chronological manner (Creswell, 2014).

4.3.2.2 Phenomenological Research

Phenomenological research is a research enquiry focused on understanding the lived experiences of an individual (or individuals) concerning a phenomenon (Creswell, 2014). In other words, it emphasises the need to understand how humans view themselves and the world around them (Robson, 2011: 151). Interpretive phenomenology is the research methodology governing phenomenological research, which seeks to unveil and understand deep meanings embedded within life experience (Robson, 2011). Phenomenological research shows less interest towards physical events themselves, but concentrates on the experience derived from events (Fellows and Liu, 2008). Hence, what is directly perceived and felt is considered more reliable than explanation (Fellows and Liu, 2008: 70). Stemming from this, information or data is elicited from those that have experienced a phenomenon.

4.3.2.3 Grounded Theory

Grounded theory is probably the most common type of qualitative research method, and cuts across other strategies and designs (Punch, 2014). The purpose of grounded theory is to generate theory from data. 'Grounded' means theory is generated on the basis of data, and 'theory' implies - collected and analysed data is aimed at generating theory to explain the data (Punch, 2014). Grounded theory involves a systematic process of gathering and analysing a finite set of data to evolve a theory, after which the theory can be used to predict or explain the phenomena (Hunter and Kelly, 2008). However, more data is collected and examined till a saturation point is reached and a theory emerges (Fellows and Liu, 2008). Interviews are the most common method of data collection, though other methods such as observation and analysis of document are utilized (Robson, 2011).

4.3.2.4 Ethnography

Ethnography provides a description and interpretation of culture and social structure traced back to the study of anthropology (Robson, 2011). The observer stands at the heart of ethnography, by documenting meanings and people's behaviour within their natural settings over a prolonged period of time (Fellows and Liu, 2008; Creswell, 2014). According to Punch (2014) the point of ethnography is to study and understand the cultural and symbolic aspects of behaviour and the context of the behaviour. As such, the researcher or observer is immersed in the lives of the participants. Ethnography is focused on people, cases or small cases, and data collection involves observation and interviews (Creswell, 2014).

4.3.2.5 Case Studies

A case study explores a research topic or phenomenon within its context, or within a number of real-life contexts (Saunders, Lewis and Thornhill, 2012). Case studies involve in-depth enquiry into one case or a small set of cases, with the aim of gaining detailed insight of the underlying aspects of such cases (Thomas, 2013). Data are collected in case study researches via observation, interview, and documentary analysis (Robson, 2011).

4.3.3 Mixed Method Research Approach

Mixed method is a combination of both qualitative and quantitative approaches, and involves multiple strategies and some form of triangulation (Creswell, 2014). Mixed method has been greatly debated over the past two decades owing to the 'incompatibility thesis', which states that quantitative and qualitative research strategies cannot be combined, as they emerge from two distinct paradigms and study different phenomena (Gage, 1989; Mingers 1997; Yardley, 2001). The complexity in mixed method research results from the fact that the integrity of both paradigms' epistemological assumptions will need to be protected (Morse, 2003).

While stressing the difference between these two positions, Howes (1988) informed that there are possible similarities between them, which can be advantageous. Greene *et al*. (1989) cited in Rose, Spinks and Canhoto (2015) identified five possible benefits of combining quantitative and qualitative methods:

- ***Triangulation*** – to corroborate the findings of one method with those of the other to ensure stronger reliability of findings.
- ***Complementarity*** – is where findings from one type of research are used to clarify, elaborate upon or illustrate findings from the other method, or where two methods are used to dovetail different aspects of an investigation (Dainty, 2008).
- ***Developmen*t** – is where the output of one method is used to support the development of the other method.
- ***Initiation*** – is where questions or results of different methods are used to offer different perspectives or to uncover contradictions
- ***Expansion*** – range and scope of the research can be expanded on adopting different methods as appropriate for different research questions within the study.

According to Creswell (2014), these benefits should not be seen as essentials of mixed methods, but the combination of methods themselves should aim at producing better results than what would have been derived from using a mono-method. However, Bishop (2015) asserted that questions, concerning which method should come first and how findings should be analysed and integrated, will then arise. Towards this end, Creswell (2014) advanced three combinations of mixed methods research – convergent parallel, explanatory sequential and exploratory sequential mixed method.

- **Convergent Parallel Mixed Method**: converges or merges quantitative and qualitative results to resolve the research problem. This implies that both quantitative and qualitative data are collected separately at the same time and the results are compared to investigate any contradictions or common grounds.
- **Explanatory Sequential Mixed Method**: starts with a quantitative research, analyses the results and builds on these results with a qualitative research. It is considered explanatory

sequential based on the grounds that a quantitative research will precede a qualitative research.

- **Exploratory Sequential Mixed Method**: starts by exploring the view of the participant with a qualitative research, analyses the results and builds on the results with a quantitative research.

4.4 Justification for the Selected Research Approach

Pragmatism was selected to underpin the philosophical orientation of the research based on its flexibility to accommodate different methods from different paradigms whilst addressing the research objectives. Pragmatism, however, is the philosophical orientation underpinning a mixed method approach (Creswell, 2014). Pioneers of mixed methods advocate that emphasis should be on addressing the research questions, aim and objectives rather than getting involved in methodological issues of 'incompatibility thesis' (Onwegbuzie and Leech, 2005; Kelle, 2006; Tashakkori and Teddlie, 2010). Hence, it was appropriate to adopt a mixed methods approach, which sits well with the underlying paradigm in this study.

Besides this, there are increasing moves towards using mixed methods in built environment construction researches (Dainty, 2008). Dainty (2008) reveals that insights gained through the combination of methods are more persuasive and reliable in construction researches than a mono-method. In addition, the complementarity benefit of mixed methods is able to tackle the inherent problematic nature of construction researches, which require effective linking of judgement and analysis (Rosenhead, 1997 cited in Dainty, 2008). Hence, it was appropriate to adopt a mixed method approach in order to allow clarity, reliability and applicability of findings (Harty and Leiringer, 2007).

Similarly, explanatory sequential mixed method was adopted in this research to systematically tackle the research objectives. That is, quantitative data were collected and analysed before collecting and analysing the qualitative ones. The quantitative phase of the research fell into two stages; the data verification stage which involved the use of online questionnaire, and the LCA analytical phase which involved the use of industry standardised methodology. Results derived from the quantitative phases were used to inform the qualitative phase. The purpose of the qualitative phase was to validate and provide further insight on findings derived from the quantitative phase and to provide answers to the research questions.

4.5 Flow Chart of the Research Phases Conducted in this Study

The flow chart for the entire research process is presented in Figure 4.1. The flow chart provides a clear map of how the research is designed, and the necessary decisions that were made at each stage. The flow chart is divided into four phases – literature search; data collection; data analysis; and development of recommendations. These phases are outlined and discussed in subsequent sections.

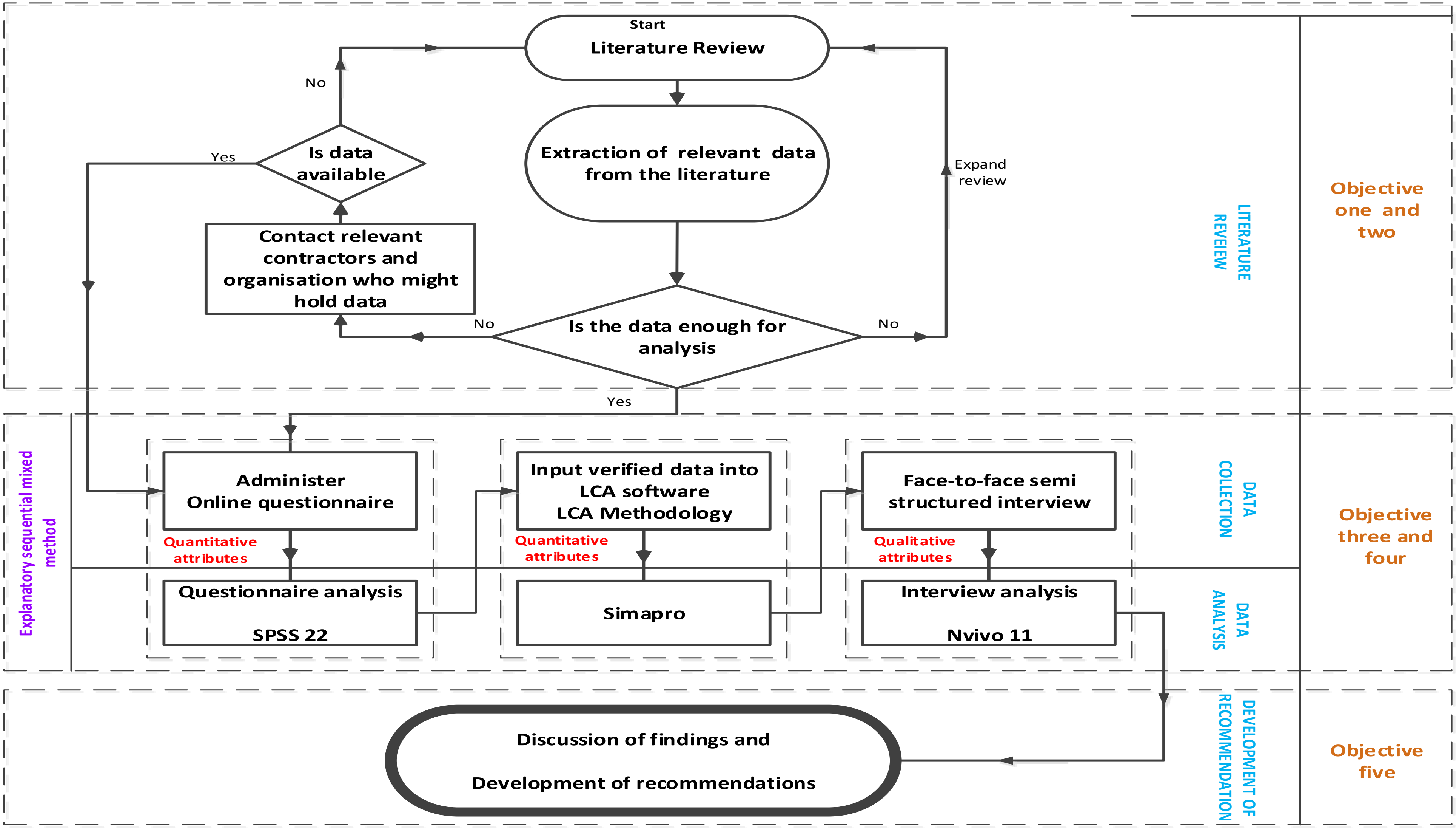

Figure 4. 1 Research flow chart

4.6 Quality of the Research

According to Robson (2011), fundamental issues about the research also need to be explained, rather than presenting the findings alone. In other words, a thorough and honest job needs to be demonstrated to ensure the quality of the research. To this end, Rose, Spinks and Canhoto (2015) recommend validity, reliability, and generalisability tests, for ensuring the quality of a research. These three tests were used to ensure the quality of this research.

4.6.1 Validity

Validity is based on the grounds that findings are true and certainly an outcome of the applied methods. Validity is the accuracy of the results which captures the real state of affairs (Robson, 2011). For this study, despite LCA researches being data intensive, validity was ensured through a thorough search of the literature for relevant data. Material quantities required for some bridge maintenance repair methods were initially gathered from peer review journals, government reports, manufacturer's guides, and reputable bridge contractors – which is normal in bridge LCA researches (Du and Karoumi, 2014). A preliminary verification of the data was conducted with bridge engineers and inspectors who piloted the data validation sheet and gave feedback. Feedback was used to design an online questionnaire for wider verification of the literature data.

Respondents were asked to either agree or disagree with the literature data. The study recognises the variability in bridge projects, and that material quantities will vary from project to project. Hence, respondents were asked to use their expert judgement to provide approximated quantities where they disagreed with the literature data. These steps were followed to ensure reliability of the data collected, which was used to inform the LCA analysis. Subsequently, the LCA of selected bridge maintenance methods was carried out using industry standardised methodology. Furthermore, widely accepted LCA software SimaPro was employed to conduct the life-cycle analysis, which promotes the validity of the results derived. Lastly, results derived from LCA findings were presented to experts who have experience in design, construction, and maintenance of bridges. The experts were able to relate with the findings and identify a middle ground between the findings and existing practices. These strategies ensured that an accurate interpretation had been made from the data analysis, and to a large extent this guarantees the validity of the research.

4.6.2 Reliability

Reliability is the consistency or stability with which something is measured (Robson, 2011; Rose, Spinks and Canhoto, 2015). It is the degree to which a research will produce the same findings if repeated by another researcher or the same researcher (Silverman, 2014). Reliability can be achieved if the research process, strategy, data collection and data analysis are transparent (Silverman, 2014). Reliability was ensured in this study by clearly revealing sources of information. For instance, details of peer reviewed journals from where data had been extracted are revealed in Table 4.3. Also, data collection instruments used in the research (that is, data validation sheet and interview schedules) are revealed in Appendix three and seven, respectively. In addition, a detailed description of targeted participants for survey and interviews is presented in section 4.8. SPSS 22 and Nvivo 11 were used to store and analyse verified data and interviewees' transcripts, respectively.

The LCA methodology applied for this study follows ISO 14040 guidance, which is an industry standardised methodology for LCA studies. Details of LCA methodology applied in this study are revealed in section 4.8. Normally, assumptions are used to cover missing data in LCA studies to allow fair comparison. As such, all assumptions made in the study are presented in section 6.6 of chapter six. These details have been revealed to ensure the reliability of the research.

4.6.3 Generalisability

Generalisability, sometimes called external validity, is the degree to which a study's findings can be applied externally or more broadly outside the scope of the main study (Cohen and Crabtree, 2006). The study ensured generalisability of findings having explored the environmental impact of commonly used corrective and preventive maintenance actions for popular forms of bridges (i.e.

concrete, steel and masonry). Also, the study employed LCA methodology which uses a standardised methodology for conducting environmental investigations and relevant input data were validated by industry experts.

Though this study does not aim to completely generalise findings, but to some extent experts' involvement is assumed to have influenced external validity. For instance, interviews continued till a saturation point was researched. Mason (2010) identified saturation point as when additional interviews will not yield new information. Hence, once this point was reached during the interviews, it was concluded that a majority of opinions had been adequately represented.

4.7 Literature Review

The literature review phase involved two major activities. These are: literature search and extraction of relevant data from the literature.

4.7.1 Literature Search

The literature review was used to understand and explore sustainability within infrastructural built environment (See chapter two). Firstly, historic background of sustainability and sustainable development concept was reviewed, which was founded on the Triple bottom line approach. The review exposed the slow adoption of sustainability concept within the bridge sector, especially with regard to the environmental aspect. The environmental aspect was, however, described as the most important entity supporting the existence of the social-economic aspect. The construction and maintenance of bridges require large amounts of material and resources from the environment and cannot be insulated from sustainability issues. It was understood from the literature that little or no attention is paid towards identifying the environmental consequences of life-cycle maintenance of bridges, let alone their being considered for decision making in new bridge design.

Furthermore, LCA approach was identified to be gaining ground in respect of identifying environmental implications. Though LCA had emerged from a product sector, it has gained wider application in other sectors including construction. The building industries amongst others have started to integrate LCA methodology within their operations, while the bridge industry is yet to integrate this in full. With this end in view, chapter three critically reviews LCA adoption within the bridge sector and its capacity to aid sustainable decision making.

4.7.2 Extraction of Relevant data from the Literature

Details of extracted data are presented in Table 4.3. Data have been extracted from highly ranked peer review journals including: ASCE (American Society of Civil Engineers); ICE (Proceedings of the Institution of Civil Engineers); and International journal of Life Cycle Assessment journals. A thorough search of these journals using keywords like ''bridge maintenance works'' revealed several publications on bridge repair/maintenance works, which had details of quantities of materials used on previous bridge projects. Apart from this, data were derived from manufacturers' guides of some reputable concrete and steel companies alongside published bridge reports. Characteristics of papers, reports, and manufacturers guides where data had been gathered are presented in Table 4.3. In addition to this, contractors and construction companies were contacted for data. An online search was used to retrieve contact details of major bridge construction companies and contractors who potentially may keep details of their past projects. These companies and contractors were contacted through email and phone calls to ask for data.

Table 4. 3 Sources of Extracted Data

Year	Authors	Focused on	Characteristics of content
1993	Arshurst	Masonry bridge	Repair and maintenance techniques data
1996	Page	Masonry bridge	Repair and maintenance techniques data
1996	Horvath and Hendrickson	Concrete and steel	Environmental impact of construction materials
2003	Steele *et al.*	Masonry	Bridge repair and maintenance techniques data
2003	Collins	Concrete bridge	Environmental impact of Construction
2004	Sustainable bridges	Concrete, steel, and masonry	Construction, maintenance, repair, and rehabilitation techniques
2005	Steele *et al.*	Masonry bridges	Maintenance data
2005	TAMP	Concrete, steel, and masonry bridge	Maintenance type
2006	Collins	Concrete, steel, and concrete-steel composite	Environmental impact of Construction materials
2006	Guettala and Abibsi	Concrete bridge	Types deterioration and repair techniques
2008	Hammond and Jones	Construction materials	Embodied energy for construction materials
2010	Pacheco *et al.*	Steel bridge	Energy, transportation, manufacturing data
2011	Zhang *et al.*	Steel bridge	Construction and maintenance data
2012	Guitozzi *et al.*	Road pavement maintenance	Maintenance and transportation data
2012	Du	Railway bridges	Maintenance data
2013	Hammervold *et al.*	Steel, wooden and concrete	Construction and maintenance materials
2014	Du and Karoumi	Railway bridges	Construction and materials
2015	Pang *et al.*	Structural bridge maintenance	Maintenance material
2016	Sarhosis *et al.*	Masonry bridge	Maintenance material

4.8 Data Collection

The data collection phase involved three major activities of;

1. Data verification (questionnaire),
2. LCA methodology, and
3. Semi-structured interviews

4.8.1 Data Verification

Extracted data were verified with the bridge design and maintenance experts. For this purpose, a data collection sheet was designed in questionnaire form, and submitted to the selected experts. This process allowed the experts to use their experience to verify the extracted data or suggest alternative estimates where they disagreed with the literature ones. The process was designed to ensure credibility of the data that would inform the LCA analysis. The section covers questionnaire design, pilot studies, sampling strategy and questionnaire administration.

Verification Sheet (Questionnaire) Design

As mentioned earlier, questionnaires are synonymous with quantitative research and are used for descriptive and analytical purpose, to determine facts, opinion, and views (Naoums, 2007; Fellows and Liu, 2008). Questionnaires occur in two main forms – open and closed forms (Fellows and Liu, 2008). While open forms allow respondents to answer questions with maximum flexibility, closed forms are rigid and contain a predetermined set of responses (Fellows and Liu, 2008). The verification sheet for this study was designed with open and closed forms. The closed aspect of the verification sheet comprised data that needed verification, while the open aspect gave room for experts to provide extra comments on selected methods and reveal their expectations on sustainability issues. Fellows and Liu (2008) revealed that answers to closed questions are given easily and quickly. Hence, it was best to make the data verification section closed questions, leaving other suggestions as open-ended questions. Questionnaires have been used in built environment researches (Dainty, 2008), and can be applied in this study. However, no current knowledge is available on the use of questionnaires in bridge LCA researches. Hence, this study stands as an exception against the norm of relying on literature data, government reports, manufacturer's guides, and various datasets alone for data verification.

Pilot Studies

The first stage of any data gathering should, if possible, be a dummy run – a pilot study (Robson, 2011). A pilot study is a test run of data collection instruments (Naoums, 2007). A pilot study helps to certify that the questionnaire will be understood when presented to a wider audience. It provides an opportunity to reshape the context of the questionnaire, in order to capture the phenomena of interest. Apart from all this, the methodological rigour of a survey is expressed in the use of pilot studies (Robson, 2011). For this research, a bridge inspection course held in UWE was a potential avenue to pilot the verification sheet. Over 20 bridge inspectors and engineers would gather on this occasion for a 5-day training, after which certificate of attendance was given. The course was officiated by an academic and a professional who are knowledgeable in the field of bridge engineering. The validation sheet was handed out in one of the classes and responses were received by post. Seventeen responses were received, which gave feedback on: wording; language; sentence structure in terms of clarity and style; material quantities; and number of questions asked. These areas were addressed and were used to strengthen, reshape, and reorganise a modified version of the questionnaire.

Selection of Experts – Sampling Strategy

Sampling is using a small portion of the entire population under study, because it will be too exhaustive to study the entire population (Bell, 1993). O' Leary (2010) identified two types of sampling strategy – random sampling and non-random sampling. Random sampling does not take specifics of the respondent into account; however, the respondent should be knowledgeable enough to provide answers to questions (Bell, 1993). Non-random sampling, on the other hand, takes note of specific details of respondents before their being asked to answer the required questions (Fellows and Liu 2008). Typical types of random and non-random sampling techniques (also known as probability and non-probability) are revealed below. These sampling techniques are explained in Robson (2011):

Probability /Random Sampling Technique:

- **Simple Sampling** – the required number of elements is drawn at random from the population such that there is equal chance of selecting each one. An example of simple sampling is traditionally found in lottery methods (Robson, 2011).
- **Stratified Sampling** – involves dividing the population into a number of groups or strata, where group members share a particular characteristic, after which a random sampling is carried out.
- **Cluster Sampling** – involves dividing the population into a number of units or clusters where each of the units contains individuals with a range of characteristics, though the clusters themselves are chosen on a random basis (Robson, 2011). Cluster sampling may apply due to geographic spread of target population (Rose, Spinks and Canhoto, 2015).
- **Systematic Sampling** – this involves taking every nth name from the population list. This type of sampling requires a full list of the population. For instance, after deciding on the sample size needed, the total number of names on the list is then divided by the sample size.
- **Multistage Sampling** – this is an extension of cluster sampling, where samples are selected in stages – that is, taking samples from samples.

Non-Probability /Non-Random Sampling Technique:

- **Quota Sampling** – is a strategy to obtain representatives of various elements of the population in the proportion in which they occur in the population, though there is a level of bias with regard to choosing the representative samples.

- **Snowballing Sampling** – is a strategy where the researcher identifies one or more individuals from the population of interest. Once the identified individuals have been interviewed, they are asked to identify other members of the same population who will also identify other individuals from the same population, and so on.
- **Judgement Sampling (or purposive sampling)** – this is where researchers select individuals based on their theoretical relevance to the aims of the research (Rose, Spinks and Canhoto, 2015). Basically, it allows the researcher to achieve a specific purpose of a project.
- **Convenience Sampling** – it involves choosing continuously the nearest and most convenient persons as respondents till the required sample size is reached. Hence, samples may or not be truly representative of the population.

It was best to adopt a purposive or judgemental sampling strategy, which provides a platform for reaching the relevant experts who are able to verify the literature data. Purposive sampling has been utilized in construction researches (Akadiri and Fadiya, 2013). Purposive sampling strategies are mainly used in construction research to select a sample that closely represents a larger group of experts to investigate certain interests (Teddlie and Yu, 2007). Target experts in this study were those experienced in bridge design, construction, maintenance, and management. Experts were further selected on the basis that they had;

- A minimum of National diploma as their highest educational qualification and
- A minimum of 5 years' experience in bridge design, construction, and maintenance

Administration of Verification Sheet

Typical ways of administering questionnaires are face-to-face, telephone interview, researcher delivery and collection, post or internal mail, email distribution and online (Rose, Spinks and Canhoto *et al.,* 2015). Choosing any of these mediums is dependent on: the sampling method and the degree of sensitivity or complexity involved in the research topic (Rose, Spinks and Canhoto, 2015). Interest has, however, risen in online survey administration (Punch, 2014). Online survey administration offers several benefits, such as: reducing time and cost implication of reaching the required participants (Rose, Spinks and Canhoto, 2015). Based on this, online administration was selected in this study, to reach the targeted audience easily. In addition, the layout, appearance, and usability of online questionnaires can be enhanced with online administration tools (Robson, 2011). Notable online administration tools include: Qualtrics, BOS (University of Bristol) and Survey monkey. For this study, Qualtrics was selected to administer the validation sheet. Criteria for selecting Qualtrics include:

- Long period of trial version with maximum benefits,
- Falls within the UWE Faculty Research Ethics Committee (FREC) ethical rules, in regard to data security and protection,
- Provides suitable formatting style for the questions involved,
- Design interface is user friendly and further support is provided by the host company, in case of technical difficulties,
- Stored data can be downloaded and exported into a workable format such as Microsoft excel spreadsheet.
- Accommodates a large number of responses.
- Respondent's location is trackable.
- No limitation to the number of questions that can be asked.

An invitation request was sent on LinkedIn to the targeted audience (those that had titles affiliated with bridges – example: bridge engineer, bridge manager, etc.) to establish a link of communication between them and the researcher. Once the request was accepted, emails, videos, and text were exchanged. Afterwards, an email containing a link to the questionnaire was sent to the targeted audience for ease of completion. Once respondents opened the link, they could access a Qualtrics page with the questionnaire. A one-month target was set for completion of the questionnaire survey.

4.8.2 LCA Methodology

LCA methodology as explained in chapter three involves four phases of;

a) Goal and scope definition,

b) Inventory analysis,

c) Impact assessment, and

d) Interpretation

The goal and scope definition phase falls under data collection stage, while the inventory analysis, impact assessment and interpretation phase falls under data analysis stage in this study. The goal and scope discussed in data collection stage covered: selected maintenance methods, justification for maintenance methods, and scope of the study.

a) Goal of the LCA Study

The goal of the LCA study in this research is to identify the possible environmental impact of some maintenance actions of concrete, steel and masonry bridge. The review conducted in chapter two reveals that only a couple of studies have investigated LCA of bridge maintenance methods. Most investigations have always been to compare the bridge materials, components, elements and structural form. However, bridges are regularly maintained to ensure serviceability and to extend their service life. Therefore, investigating the LCA maintenance of bridges could give useful insight towards the long-term environmental impact of bridges.

Selected Maintenance Methods

Several methods are used to ensure the serviceability state of bridges, while prolonging their life span, although some repair methods take place in response to accidents or emergencies (Parke and Hewson, 2008). Selected bridge maintenance methods for this study are corrective and improvement measures (of concrete, steel, and masonry bridges) depending on the time and purpose of application, and are presented in Table 4.4. Maintenance methods used on timber and composite bridges have been ignored, on the basis that they represent a smaller percentage of the UK bridge stock compared to concrete, steel, and masonry bridges (TAMP, 2005; Parke and Hewson, 2008). For this study, five maintenance actions have been selected for concrete, steel, and masonry bridges, which are envisaged to take place over the 120-year life span of a bridge. According to BS 5400 (bridge design code), the traditional design life of a UK bridge is 120 years, hence it was adopted for this study.

Table 4. 4 Selected Repair Methods

Structural Form	Maintenance/repair methods	Purpose
Concrete bridge	• Grouting	Corrective
	• Overlaying	Improvement
	• Deck replacement	Improvement
	• Bearing renewal	Improvement
	• Expansion joint renewal	Improvement
Steel bridge	• Structural metal work painting	Corrective/preventive
	• Deck waterproofing	Corrective
	• Pavement repair	Corrective
	• Bearing renewal	Improvement
	• Expansion joint renewal	Improvement
Masonry bridge	• Saddling	Improvement
	• Radial pinning	Corrective
	• Water-proofing	Corrective
	• Near surface reinforcement	Improvement
	• Sprayed concrete	Improvement

Justification for Selected Bridge Maintenance Methods

Selected methods were based on three criteria; effectiveness, cost, and intervals, as presented in Table 4.5. These criteria were previously applied in Ashurst (1999) to access the repair and strengthening of bridges and could be applied in this study. Common attributes of the selected methods include:

- Alleged detrimental effect on the overall safety and performance of the bridge if not done in time.
- Estimated cost of more than £10,000 – which can be reduced if alternative options are available.
- The least scheduled time for intervention is 10 years – which suggests their continuous use.

Table 4. 5 Selection Criteria for Maintenance Methods

Bridge Type	Maintenance Methods	Selection criteria			Source	Remarks
		Effectiveness	**Cost**	**Intervals**		
Concrete bridge	Grouting	- Used to fill crack holes and prevent collapse	- Slightly expensive - Estimated cost of £15,000	Every 30 years	(TAMP, 2005)	Less rigorous
	Overlaying	- Returns existing road surface to good condition	- More expensive - Estimated cost of £100,000	Every 30 years	(TAMP. 2005)	Very rigorous
	Deck replacement	- Restores totally damaged and deteriorated bridge	- Very expensive - Estimated cost of £622, 000	In 120 years	(TAMP. 2005)	Extremely rigorous
	Bearing renewal	- Ensures a serviceable limit state is maintained	- More expensive - Estimated cost of £60, 000	Every 30 years	(TAMP. 2005)	Less rigorous
	Expansion joint renewal	- Ensures a serviceable limit state is maintained	- Less expensive - Estimated cost of £15, 000	Every 20 years	(TAMP. 2005)	Less rigorous
Steel bridge	Structural metal painting	- Ensures physical defects like rusted parts are back to normal	- Less expensive - Estimated cost of £10,000	Every 12 years	(TAMP. 2005)	Less rigorous
	Deck waterproofing	- Provides adequate draining system for the bridge	- More expensive - Estimated cost of £30,000	Every 20 years	(TAMP. 2005)	Less rigorous
	Pavement repair	- Returns existing road surface to good condition	- More expensive - Estimated cost of £90,000	Every 30 years	(TAMP. 2005)	Slightly rigorous
	Bearing renewal	- Ensures a serviceable limit state is maintained	- More expensive - Estimated cost of £60, 000	Every 30 years	(TAMP. 2005)	Less rigorous
	Expansion joint renewal	- Ensures a serviceable limit state is maintained	- Less expensive - Estimated cost of £15, 000	Every 20 years	(TAMP. 2005)	Less rigorous
Masonry bridge	Saddling	- Able to solve multiple deterioration problems at once	- High cost amounting from material and labour intensity. - Estimated cost of £23400	Masonry bridges that have undergone this type of repair may not require such rehabilitation in 200 years	(Swoden, 1990; CIRIA, 2006; Parke and Hewson, 2008)	Rigorous work involved
	Radial pinning	- Able to strengthen the arch barrel	- less expensive - Estimated cost of £10, 000	Masonry bridges that have undergone this type of repair may not require such rehabilitation work in 120 years	(Swoden, 1990; CIRIA, 2006; Parke and Hewson, 2008)	Less rigorous
	Water-proofing	- Provides a drainage system for the bridge.	- Slightly expensive. - Estimated cost of £10,000	May not be required till another 100 years	(Page, 1996)	Less rigorous
	Near surface reinforcement	- Strengthens the arch barrel by providing resistance across underneath cracked areas	- Slightly expensive. - Estimated cost of £11,000	May not be required till another 100 years	(Page, 1996)	Less rigorous
	Sprayed concrete	- Able to solve arch ring deterioration problems - Affects the final appearance of the bridge	- Slightly expensive - Estimated cost of £10,800	May not be required till another 100 years	(Swoden, 1990; CIRIA, 2006; Parke and Hewson, 2008)	Less rigorous

Scope of the Study

The scope of the LCA study covers the system boundary for selected maintenance methods. These include the geographical and temporal boundaries. The scope also covers the functional units for the study.

A system approach was adopted in this study to allow the use of foreground and background systems. According to Clift *et al*. (1998), system approach is best analysed as a foreground and background system. Both processes are reliable, industry wise (Finnveden *et al*., 2009). Foreground and background system has been used in several studies including; Clift *et al*., 1998; Cowell, 1998; Tillman *et al*., 1994. The foreground systems as considered in this study were extracted data of previous maintenance actions – identified through an intensive literature search (as no specific case study was involved). The background data on the other hand were derived from the SimaPro dataset, which supplied data on energy, plants and electricity derived from a homogeneous market. The reliability of these datasets lies in the fact that they are standardised and were gathered across Europe, United States, and China. However, the Europe dataset was suitable for this study.

I. System Boundary

The system boundary reveals what would be accounted for during the LCA analysis and what will be excluded. The system boundary defined for each maintenance action is depicted in Figure 4.2. The main elements considered within the system boundary are; materials, transportation, energy, and resources. These are key elements for evaluating input and output processes for revealing environmental burdens (Heijungs and Guinée, 1994; Rebitzer *et al*., 2004; Finnveden *et al*., 2009). They have also been used in similar bridge LCA researches (Du *et al*., 2014; Pang *et al*., 2015), and hence can be applied in this study.

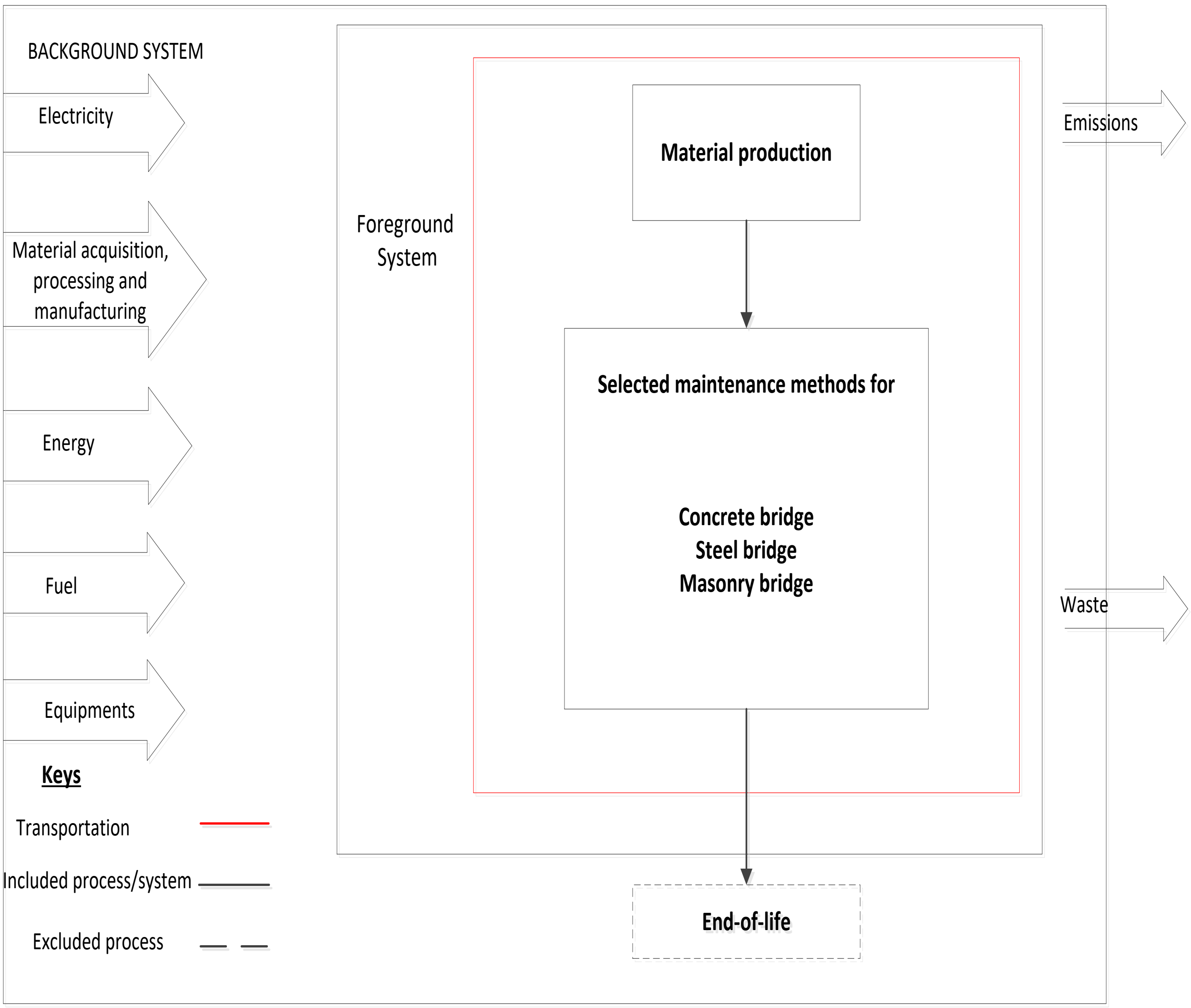

Figure 4. 2 System boundary for maintenance work

Temporal Boundaries (Time Based Boundaries)

Though the environmental impact of some selected concrete, steel and masonry bridges is being investigated over a 120-year design life, it is a reality that some bridges would not reach this threshold (Collings, 2003). This can be attributed to debilitating effects like ageing, traffic, and environmental conditions (Godart and Vassie, 2001). This study, however, is not aimed at completely assessing the entire life cycle of a bridge or any other debilitating matters, but advances towards identifying the long-term environmental consequences of the selected methods, and consequently analysis has been restricted to 120 years alone.

Geographical Boundaries

Technology employed in different regions will impact the data produced (Du and Karoumi, 2014). Hence, geographic region does influence collected data for LCA studies. To ensure the applicability of results to wider UK and Europe context data, collected data for this study were sourced from UK and Europe background.

Limitations in the System Boundaries

No bridge LCA study as yet has the capacity to account for all activities and associated processes (Du *et al*., 2014). While this will require considerable effort to achieve, McManus (2001) suggested that all processes accounted for within the system boundaries should be transparently presented to accurately judge the context of the result. On this account, the study presents what was accounted for and what would be omitted. For this study, environmental contributions of construction and end-of-life phase were exempted. Noise and traffic impact were excluded where possible.

II. Functional Unit

Functional unit provides the platform for comparison. For this study, the functional unit was defined as **"**one square meter bridge deck area over a 120-year life span**"**. According to Dequidt (2012), one square meter ($1m^2$) deck area allows a fair comparison between different bridge forms, irrespective of geometry, shape, size, length, width, and location. One square meter deck area has been used in previous LCA bridge studies including: Jin, Chryssanthopolous and Parke (2005); Dequidt (2012); Hammervold, Reenaas and Brattebø (2013), which confirms its suitability for this study.

4.8.3 Semi-structured Interview

Interviews were used in this study, which was in line with the explanatory sequential mixed method underpinning the research. Interviews were used to gather the qualitative opinion of experts on the LCA results. This section covers interview design, pilot interviews, sampling strategy and undertaking the interview.

Interview Design

The three types of interview include structured, semi-structured and unstructured interview (Naoums, 2007; Wilson, 2010; and Fellows and Liu, 2008). A structured interview involves the use of a structured set of questions towards an enquiry (Bryman and Bell, 2011). On the contrary, an unstructured interview involves starting a line of enquiry with a broad question, and the interviewer builds on the answers (Naoums, 2007). Semi-structured interview tries to fill the gap between unstructured and structured by employing both open and closed questions, but not in a specific way or schedule, thereby providing much scope for elaboration on certain points (Wilson, 2010). Even though the primary aim of the interview was to allow the respondent experts to comment on the LCA findings, it was also the holistic goal of the interview to verify grey issues discovered in the literature, particularly those relating to sustainability in bridge design, drivers of design solutions, and awareness of LCA. On this basis, a semi-structured interview was employed for this study, which allows a flexible approach to enquiry (Naoums, 2007). The interview was therefore designed to investigate four key issues. These include;

- Designers' views on sustainability components factored into new bridge design.
- Drivers of design solutions for structural or maintenance work.
- Experts' views on awareness and knowledge of LCA.
- Usefulness of the LCA results derived from chapter six during the design of new bridges.

Follow-up questions were employed in this study. According to Rose *et al*. (2015), follow-up questions can extract more information from the interviewee. As such, follow-up questions were used in this study to probe interesting issues, which significantly provided a wealth of information concerning the subject matter.

Pilot Interviews

Interview questions were piloted with fellow research colleagues, supervisors and consultants who gave feedback on structure and grammar. Feedback was used to improve the final version of the interview schedule. Interview schedule for the study is presented in Appendix three of the thesis.

Sampling Technique

Purposive sampling strategy employed in the quantitative phase of the study was equally adopted in the qualitative phase. Targeted Interviewees were those that indicated interest in the outcome of the quantitative findings and provided extra contact details. Invitation letters were sent to those who wished to be contacted. Snowballing strategy was engaged to gather more interviewees with similar background and experience. According to Fellows and Liu (2008), snowballing is employed when sources of data are scarce and collecting data from a smaller number of sources (respondents) is involved, by requesting them to identify further sources. Therefore, participants who responded to the invitation letter and took part in the interview were asked to refer other participants who might be interested in the research. Snowballing strategy has been used in similar expert research (Beauchemin and González-Ferrer, 2011), where respondents were scarce. Therefore, it was suitable to be applied in this research.

Undertaking the Interview

Interviews were conducted across the UK, including Bristol, Cardiff, Newport, Swindon, London, and Manchester. All interviews were held at the interviewees' office. The Interview itself entailed a physical presentation of the LCA results (in a graphical form) alongside other questions. The main interview questions were asked, alongside follow-up and probing questions to clarify issues. All interviews were recorded and marked to indicate date, time, and duration of the interview.

4.9 Data Analysis

The data analysis phase involved three major activities of;

(1) Questionnaire analysis

(2) LCA analysis and

(3) Interview analysis.

4.9.1 Questionnaire Analysis

Data collected at the validation stage were analysed with SSPS statistical package. SPSS 22 was used to run a frequency distribution analysis on the questionnaires, which gave a descriptive detail of respondents that took part in the survey. However, the peak of the analysis was to establish consensus about the experts' response. Consensus indicates agreement concerning a statement. The research explores three approaches to reaching consensus. They are; APMO, inferential statistics, mean value and standard deviation.

APMO

The Average Percent of Majority Opinions (APMO) is applicable to a nominal scale (that is, yes or no response), where percentages of agreed and disagreed responses, including percentages of no response are calculated to achieve a specific cut-off percentage (Cottam, Roe and Challacombe, 2004). Consensus is, therefore, reached on a statement or value when the percentage of "agreed" or "disagreed" values is higher than the APMO cut-off percentage (Kapoor, 1987).

Cut-off rate is determined by:

$$\mathbf{APMO} = \frac{\text{Majority Agreements} + \text{Majority Disagreements}}{\text{S of Opinions expressed}} \qquad \text{(Equ: 1)}$$

Inferential Statistics

Inferential statistics are used to establish relationships amongst variables and to determine consensus (Sekaran, 2003). However, this depends on the distribution of the studied data to permit the use of parametric test (Sekaran, 2003). If the data is nominally or ordinally scaled then non-parametric tests can be performed. Parametric and non-parametric tests have been used in expert-related studies for reaching consensus (Von der Gracht, 2012).

Mean Value and Standard Deviation

The mean is the best model of a dataset designed to produce least error (Field and Hole, 2003). Mean, however, is still prone to error but can be reduced by calculating the standard deviations to gauge the accuracy of the mean (Field and Hole, 2003). Standard deviation (SD) is used to assess the variation in a population and for a normal distribution (Grobbelaar, 2006).

Justification for APMO and Mean Value

APMO was applied in this study emerging from the nominal scale characteristics of the questionnaire. Participants were asked to either agree or disagree with the literature data, which sits well with the nominal scale for applying APMO. APMO had been used in expert-related researches (Saldanha and Gray 2002), confirming its suitability for this study. Once consensus is reached with APMO, no further investigation is required (Cottam, Roe and Challacombe, 2004). However, it is argued that where APMO does not provide clear consensus the mean value can be adopted (Cottam, Roe and Challacombe, 2004; Henning and Jordan, 2016).

In this study, participants were asked to supply alternative estimates for disputed data. The possibility of experts providing different material estimates is inevitable, as quantities may vary from project to project. This circumstance is beyond the scope of APMO, as the basis for nominal scale is compromised. However, the mean value of the suggested data can be taken as consensus since the mean is the best model of a data (Field and Hole, 2003). Means have been used in expert-related studies to measure consensus (English and Kernan 1976; Grobbelaar, 2006; Henning and Jordan, 2016). However, the mean value will only be considered accurate if the dataset was normally distributed, otherwise the median and mode of the distribution could be applied (Field and Hole, 2003). A normality test is therefore required to reveal the distribution of the suggested data.

Normality Test and Confidence Interval

A normality test was conducted in this study using Shapiro-Wilk significance value of 0.05 in SPSS 13. Shapiro-Wilk significance value is universally accepted for conducting a Normality test. The null hypothesis that the dataset was normally distributed is accepted or rejected if the mean of the distribution is greater or less than the Shapiro-Wilk significance value, respectively. As such, the normality test confirmed the reliability of the mean of suggested data in this study. Mean, however, is still prone to error, but this can be reduced by calculating the standard deviations (Field and Hole, 2003). Standard deviation (SD) is used to assess the variation in a population and for a normal distribution (Grobbelaar, 2006). SD allows the boundaries of the mean to be calculated, known as confidence intervals. A 95% confidence interval or 99% is statistically acceptable (Fellows and Liu, 2008). The SPSS was used to calculate the mean, SD, and confidence interval of suggested data.

4.9.2 LCA Analysis

LCA analysis phase involves three major activities of;

(a) Inventory analysis
(b) Impact assessment
(c) Software selection

(a) Inventory Analysis

A life cycle inventory analysis is the process of quantifying the inputs (energy and raw material requirements) and outputs (products, waste emissions to water, air, and land) for the entire life cycle of a product or process. It involves the collection of necessary data to meet the goals of the study. The reliability of the LCA result is determined by the quality of data collected (Trusty, 2004).

Much of the publicly available data is outdated and may not reflect the current technologies. According to Consoli *et al*. (1993) data quality can be divided into two main categories of primary and secondary data. While primary data are obtained from every possible facility or sources, secondary data are derived from published sources including journals, text books, conference papers and reports, government, and industry publications. However, ISO 14041 highlighted that whether it is primary or secondary, data should align with the goal of the study. Moreover, characteristics of the data in terms of time, geographical and technological coverage should also be stated. These issues are discussed under LCA methodology in section 4.8.

(b) Impact Assessment

Impact assessment phase helps to identify associated emissions from the inventory analysis phase and converts them into damage indicators. This involves selecting relevant impact categories for the study. Impact categories are results of emitted substances and resources used (otherwise known as environmental indicators). CO_2, NO_2, SO_2 and energy were considered for this study, as they underpin global environmental matters (UN, 2015). Besides, other bridge LCA studies have considered these indicators (Itoh and Kitagawa 2003; Keolein *et al*., 2005; Collings, 2006; Gervásio and da Silva, 2008). Therefore, selected emissions and resources are adequate on the account that they have been previously applied to justify sustainable decisions in related bridge LCA studies.

Suitable impact categories will be those which cover protection of resource depletion, human health, and ecosystem (Consoli *et al*., 1993). ISO 14042 also stated that selected impact categories for a study should be scientifically sound and internationally agreed. Selected impact categories for this study are acidification, eutrophication, climate change, ozone depletion, photochemical formation, fossil fuel depletion, metal depletion, and particulate matter. These impact categories are scientifically sound, widely agreed and commonly used (Bare, 2010). Many of these impact categories are imbedded in LCA software packages. Moreover, other impact assessment steps, such as classification, normalisation, and weighting can be calculated with suitable LCA software.

(b) Software Selection

There are many LCA software tools in the market. However, selection of LCA software for this study was based on:

- Should have regional data for Europe, especially for UK, on raw materials, process, power generation and transport.
- The process data should be up to date.
- The software package should comply with ISO guidelines and standards.
- The software should work on the Microsoft Windows® operating system.
- The software should integrate all the four phases of LCA and support data sensitivity checks.
- The software should have a graphical interface for interpreting results, and should be able to export these results into an excel spread sheet and Microsoft word documents.
- The price of the software should be reasonable.
- The software should target different types of users from learners to experts.

SimaPro fulfils most of the above criteria, and has the most number of sold licences (Earthshift, 2015). The software provider allows a discount for first time users and gives a 28 days free licence. Apart from this, SimaPro allows presentation of results in graphs, tables and flow charts which may be exported into other packages like Microsoft word and excel to support discussions and arguments. SimaPro follows the ISO standards and guidelines vital for external validity of findings. In addition, SimaPro 8.0.4 version is the most recent and contains many up-to-date datasets applicable to this study. The data libraries imbedded in SimaPro 8.0.4 version are divided into; materials, energy, transportation, processing, use, waste scenario and waste treatment. Key databases in SimaPro 8.0.4 version include Ecoinvent 3, ELCD, industry data, LCA foods, Swiss input and output database, and Agric footprint. Embedded methods within SimaPro 8.0.4 version are; Impact 2002+, CML 2007, EDIP, Traci, Eco-indicator 99, EPS 2000; 2013 and ReCipe. The ReCiPe methodology was preferred in this study on the basis that:

- It is recent, and includes state-of-the-art indicators at midpoint and endpoint levels (damage category) for most emitted substances.
- Underlying models embed a comprehensive cause-effect chain, which helps to identify the fate, transport, exposure, and final damage caused by emitted substances.
- Characterisation values are calculated at damage levels (of human health, ecosystem, and resource depletion)
- ReCiPe damaged categories are normalised on European scale (that is, damage caused by Europeans per year)
- Normalisation set is based on uncertainty perspective (that is, Egalitarian E, Hierarchist H, and Individualist I) used to simulate Monte Carlo uncertainty analysis

The ReCiPe methodology embeds the following impact categories; climate change, human toxicity, particulate matter, fossil depletion, metal depletion, ozone depletion, photochemical oxidation, ionising radiation, terrestrial acidification, agricultural land occupation, urban land occupation, terrestrial ecotoxicity, marine ecotoxicity, natural land transformation and freshwater eutrophication. However, not all these impact categories are relevant to bridges. Selected impact categories for this study are: climate change (CC), ozone depletion (OD), particulate matter (PMF), photochemical oxidation (POF), terrestrial acidification (TA), freshwater eutrophication (FE), metal depletion (MD) and fossil depletion (FD), which are emergent issues in agenda 2030 and need to be integrated within bridge design process for sustainable decision making.

4.9.3 Interview Analysis

Interviews were transcribed and formatted with a Microsoft Word document before being imported into Nvivo 11 software for further analysis. According to Rose *et al*., (2015), one of the benefits of transcribing audio recordings is to encourage the use of verbatim quotations which would be vital for reinforcing critical points in this thesis.

Data Analysis Process

The transcribed word document was read severally, edited, and organised into a suitable format before inputting into Nvivo 11 software for analysis. According to Bazeley (2013), data analysis involves several progressive and interactive stages, aimed at providing insight, and understanding of the data collected. Braun and Clarke (2013) presented stages for analysing a semi-structured interview, which was adopted for this study. They are;

Familiarisation

Familiarisation with data was achieved through a recursive engagement with the data and literature around the subject area and then ensuring no aspect of the data was omitted.

Transcription of Data

Transcription of data was key for the interview analysis. As such, thoroughness and rigour was ensured while transcribing the audio interview. This was another form of familiarisation with the data.

Pattern Identification

Pattern identification was achieved by reading and re-reading the transcribed data to identify patterns of meanings and areas that answered the research questions. Relevant words, phrases and segments were grouped together to achieve this purpose.

Coding

Coding is a process of assigning tags or labels against a piece of data, which relates to the research question under investigation (Braun and Clarke, 2013). According to Punch (2014), the coded data can be individual words, small or large chunk of words identified in the transcript. As such, relevant words that addressed the research questions were coded accordingly. There are two main approaches to coding, that is selective coding and complete coding. Selective coding is a deliberate selection of instances relating to the phenomena of interest. Selective coding requires pre-existing theoretical and analytical knowledge of the phenomena of interest (Braun and Clarke, 2013). Complete coding on the other hand does not look for particular instances within the dataset, but aims to identify anything and everything of interest or relevance to the research question (Saunders, Lewis and Thornhill, 2012). In line with this, the research opted for complete coding and captured any relevant information useful for answering the research question. As such, phrases and words identified to provide answers to research question one, two, four and five were coded accordingly. Emerging from the complete coding were relevant issues. Although these did not directly address the research questions, they appeared prominently during the interview discussions. This was an attribute of the thematic analysis adopted, as it strongly relied on collected data to produce new findings, even though no link may exist between the research question and response given.

Theme Development

Codes with a similar tag or label are gathered together as a theme (Robson, 2011). Developing themes involves a thorough review of similar codes with the hope of identifying similarities and overlap between them (Braun and Clarke, 2013). Identifying themes allows concepts and issues with similar focus to be gathered under a central organising concept. Therefore, a theme can capture vital information about the data in relation to the research question (Bazeley, 2013). On this account, the codes identified were sorted into potential themes. According to Braun and Clarke, (2013) themes appear on three main levels. These are:

- **Overarching Themes**: do not contain codes or data but capture an idea embedded in many themes,
- **Themes:** themselves may include sub-themes or not,
- **Sub-themes:** capture relevant and specific aspects of the central organising concepts that contribute towards a particular theme.

Data were coded based on the interview questions (emergent from research question one, two, four and objective four of the research). This potentially allowed four different areas to be identified for initial coding: Firstly, bridge designers' views on sustainability issues factored into new bridge design; secondly, drivers of design solutions for structural or maintenance work; thirdly, to reveal expert's opinion on the awareness and knowledge of LCA; and lastly, the usefulness of the results derived from chapter six. On this account, four overarching themes emerged, as revealed in Table 4.6. Other themes and sub-themes emerged from further coding in relation to the overarching themes of the analysis.

Table 4. 6 Overarching Themes

Overarching Themes	Interview Questions
Sustainability	In your experience how and to what extent is sustainability embedded in bridge design and maintenance?
Design Solutions	In your experience, what would normally influence design solutions?
LCA awareness	What do you know about LCA?
Usefulness of LCA results	What will be the usefulness of these LCA results/information of bridge maintenance methods during the bridge design process and its potential to improve their sustainability?

Thematic Analysis

Thematic analysis particularly suits this study, as it has the potential to reveal relevant themes from a pattern (Rose, Spinks and Canhoto, 2015). Thematic analysis provides the flexibility for data exploration. Boyatzis (1998) submitted that thematic analysis should be considered a tool rather than a method, considering its flexibility. Others opine that flexibility characteristics are a disadvantage (Braun and Clarke, 2006). However, the flexibility potential allows a wide range of analytical options to be considered. For instance, thematic analysis can be conducted from specific to general themes, while the researcher interprets the data with no theoretical underpinnings (Creswell, 2009). However, the thematic analysis can be conducted such that it is underpinned by the researcher's theoretical and analytical interest (Boyatzis, 1998). The format was adopted in this study in the sense that identified themes were not based on theory but had the potential to address the research questions. In general, thematic analysis is a more advantageous and reliable process, as it allows thematic adjustments, reduction and expansion useful for many researchers (Braun and Clarke, 2003).

4. 10 Development of Recommendations

The research aims at improving sustainability decision at the early bridge design stage. However, integration of LCA results of bridge maintenance methods during the early design stage of bridges will be a good start, considering the fact that bridge maintenance characteristics determine the longevity of the bridge. Recommendations were based on findings that surfaced while discussing the LCA results with industry experts. Emergent recommendations will help breach the gap between literature, current practice, and designers' perceptions, to allow smoother integration of environmental aspects of sustainability into bridge design with LCA.

4.11 Ethical Considerations

Ethical issues are taking on different dynamics in the field of research, such that there is a thin line between methodological rigour and ethical considerations (Breakwell, 2012). This means that the level of attention paid towards methodological design and approach is also being paid towards ethical issues. Fellows and Liu (2008, p.247) explain that "because research involves the furtherance of (human) knowledge; the requirement of ethical integrity is paramount". Therefore, important issues of anonymity, gaining access to highly sensitive data and right to disclose findings are being taken seriously. ESRC (2010, p.7) outlines six ethical principles that should be considered when undertaking any research. These include:

- *Research should be designed, reviewed, and undertaken to ensure integrity and quality.*
- *Research staff and subjects must be informed fully about the purpose, methods and possible uses of the research, what their participation in the research entails, and the risks, if any, involved.*
- *The confidentiality of information supplied by research subjects and the anonymity of respondents must be respected.*
- *Research participants must participate voluntarily, free from any coercion.*
- *Harm to research participants must be avoided.*
- *The independence of the research must be clear, and conflicts of interest or partiality must be explicit.* (source; ESRC, 2010, p.2)

These principles were followed strictly in this research, since it involved human participation. In addition, the University of the West of England has a structured system of checking researches requiring human participation. To this end, full approval needed to be sought from FREC before contacts were made with participants. FREC through an iterative process ensured that the above principles were satisfied before giving final approval.

4.12 Chapter Summary

The chapter gives an account of the research design and approach that was employed, and showcases the data collection and analysis process employed. An explanatory mixed-method approach was adopted, which combines both quantitative and qualitative attributes. LCA methodology and the links it shares with the current research were discussed. Ethical guidelines upheld during the research process were also discussed.

CHAPTER FIVE: RESULTS AND ANALYSIS OF QUESTIONNAIRE SURVEY

5. Introduction

The chapter presents the analysis and findings of the questionnaire survey and briefly captures the questionnaire design. It reveals vital information from the questionnaire analysis, such as: response rate, frequency, and descriptive distribution, and how consensus was reached on all agreed data. Results derived from the open-ended question are also presented.

5.1 Questionnaire (Validation sheet) Design

The questionnaire design was already explained in chapter four, and a copy of the questionnaire is located in appendix three. The questionnaire had three main sections. The first section captured participants' background information. Background information is used for descriptive analysis in a questionnaire survey (Fellows and Liu, 2012). Background information includes years of experience, role and so on. In the same vein, the background information captured in this study included the participant's role, qualification, professional membership, involvement in bridge maintenance, and years of experience. This information was used in the descriptive analysis and presented the need to apply some selection criteria.

Section 2 presented estimated material quantities for concrete, steel, and masonry bridge maintenance activities, which were gathered from the literature and converted to functional unit (i.e. $1m^2$ per deck area). Section 2 was designed to allow participants to agree, disagree and suggest alternative data. Section 3 gave room for participants to offer extra comments, mainly for participants who have highlighted any issue(s) with any of the methods presented. Section 3 also presented some open-ended questions aimed at exploring participant's expectation of sustainability in relation to bridges and how it can be improved. Insights from the open-ended questions were used to refine the interview questions.

5.2 Response Rate

A total of 400 emails were sent to the targeted audience and 68 responses were received to achieve a response rate of 17 per cent. Online surveys have the advantage of speed, cost reduction and greater interactivity, but response rate may be low (De Leeuw 2012). The low response can, however, be boosted by repeated reminders (Nulty 2008; Braun and Clarke 2013). As a result, targeted samples received reminders after 5 days of receiving the first email to boost the response rate. There is inconsistency with acceptable or appropriate response rate for a research (Christley, 2015). Acceptable response rate cannot be generalised, as it depends on the study and what is being investigated (Sheikh and Mattingly, 1981). Keeping this in view, the 17% response rate is adequate for this study, considering the fact that the survey was executed for verification purposes and was completed by knowledgeable experts in the field of bridge engineering.

5.3 Frequency and Descriptive Distribution

The frequency and descriptive distribution of respondents' background information is revealed in this section. Frequency distribution is a useful way to summarise and understand the characteristics of data (Punch 2014, p. 255). The frequency distribution presents the respondent's role, qualification, professional membership, involvement in bridge maintenance and years of experience.

5.3.1 Role in the Construction Industry

The targeted experts were bridge inspector, foreman, site engineer, construction manager, bridge manager and bridge engineer, who potentially have experience in bridge maintenance or construction activities. Table 5.1 presents that bridge engineers, mostly designers, had the highest frequency (n=37), followed by bridge managers and 'others' (i.e. expert's whose title were not captured in the question e.g. design consultant, design managers and technicians) with a frequency (n=10). Inspectors and site engineers had the least frequency (n=2) and (n=3) respectively. Inspectors and site engineers are generally concerned with the physical condition of the bridge, which does not necessarily require them to possess technical design details. However, the percentage of bridge managers and bridge engineers that completed the questionnaire was adequate, and they tend to hold more technical information. What was encouraging was that the designers completed most of the questionnaires, as the general output of the thesis mainly impacts them.

Table 5. 1 Frequency and Percentage Distribution of Experts' Role

Expert's role	**Frequency (n)**	**Percent (%)**
Site engineer	3	4.4
Bridge inspector	2	2.9
Bridge manager	10	14.7
Construction engineer	6	8.8
Bridge engineer (e.g. designer)	37	54.4
Others (e.g. design managers)	10	14.8
Total	68	100.0

5.3.2 Experts' Educational Qualification

Expert's educational qualification was used to demonstrate how qualified the respondents were in this study. Table 5.2 reveals that respondents were highly educated (qualified) individuals. Most respondents possessed a master's degree as their highest qualification (n=28), followed by bachelor's and doctorate degree (n=16 and n=11, respectively). Very few respondents possessed national diploma or higher national diploma as their highest qualification (n=2 and n=2, respectively). The result indicates that the respondents are highly qualified individuals and were competent enough to complete the survey.

Table 5. 2 Frequency and Percentage Distribution of Experts' Qualification

Expert's qualification	Frequency (n)	Percent (%)
National Diploma	2	2.9
Higher National Diploma	2	2.9
BSc	16	23.5
Master's degree	28	41.2
PhD or Higher	11	16.2
Professional qualifications	9	13.3
Total	68	100.0

5.3.3 Expert's Involvement with Bridge Maintenance

The targeted audience were recruited through LinkedIn network. It was important to recognise their validity in this research in terms of their involvement with bridge maintenance. Frequency analysis of respondents' involvement with bridge maintenance revealed that all respondents had been involved in bridge maintenance and were valid for this research. However, the credibility of their responses needed to be investigated.

5.3.4 Experts' Years of Experience

Respondents' years of experience are a credible criterion to determine validity of experts' responses. People with more years of experience in their undertakings are in a better position to provide reliable response (Guimarâes *et al*., 2015). The frequency and percentage distribution of respondents' years of experience is revealed in Table 5.3. Results revealed that 38.2% of respondents had between (5-10) years of experience and 30.9% of respondents had between (11-15) years of experience. 10% of respondents had over 20 years' experience. Only 16.2% of the respondents had less than 5 years' experience. The total percentage of respondents that had more than 5 years' experience is 83.3%. It is, therefore, concluded that a majority of the experts are well experienced professionals and their responses are credible.

Table 5. 3 Respondents' Years of Experience

Years of experience	**Frequency (n)**	**Percent (%)**
Less than 5years	11	16.2
5 -10 years	26	38.2
11 - 15 years	21	30.9
16 - 20 years	3	4.4
Over 20 years	7	10.3
Total	68	100.0

5.4 Selection Criteria

Selection criteria were applied in this research to ascertain the credibility of data provided by respondents. Selection criteria are used to ensure the credibility and validity of participants' responses (Akbari and Yazdanmehr, 2014). Selection criteria can reveal participants with potential to provide more credible responses, out of many responses. Braun and Clarke (2013) revealed a sampling strategy that allows the appropriate selection of sample from a sample size population. This can be used alongside purposive sampling strategy. Selection criteria applied for this study were that experts should have;

1. A minimum of National diploma as their highest educational qualification.
2. A minimum of 5 years' experience in bridge maintenance, design, and construction.

These criteria have been applied in construction related researches such as Hallowell and Gambatese (2010) and can be applied in this study. According to Hallowell and Gambatese (2010) these criteria - depending on the study - should be met at the minimum (by experts) for an expert related study. 57 experts met the selection criteria, out of 68 responses that were obtained from the survey. Hence, only the responses provided by these 57 experts were considered valid for this research.

5.5 Degree of Consensus and Agreement

Three approaches for reaching consensus were presented in section 4.9 of chapter four. APMO emerged suitable for this research owing to the nominal characteristics of the questionnaire (that is, agree or disagree). A normality test was conducted on suggested data to reveal their distribution and to allow revealing the mean value of the distributed data (which was taken as consensus).

5.5.1 Consensus on Concrete Bridge Repair Quantities

Consensus of 57 experts on the estimated quantities of selected concrete bridge maintenance activities is presented in Table 5.4. The APMO cut-off was derived from the sum of (438) majority agreements and (45) majority disagreements divided by the 570 opinions, which equates to an APMO rate of 87%. It therefore follows that consensus was reached on all literature quantities except for quantities of concrete and reinforcement of overlaying and deck replacement activities. Once consensus was reached on the basis of APMO cut-off rule, no further analysis was required (Cottam, Roe and Challacombe, 2004). As such, no further investigation was required for material quantities that met the cut-off criteria. However, where consensus was not reached, the data distribution was required to determine the mean.

Table 5. 4 Quantities of material for concrete bridge maintenance work

Maintenance activities	**Materials**	**Quantities of materials (tons/sq.m)**	**Agreed**		**Disagreed without suggestions**		**Disagreed with Suggestions**		**Opinion**	**Consensus**
			No.	**%**	**No.**	**%**	**No.**	**%**		
Grouting	Cementitious grout	0.14	53	92.98	2	3.51	2	3.51	57	Yes
Overlaying	Concrete	2.5	7	12.28	20	35.08	30	52.63	57	No
	Asphalt	0.27	53	92.98	3	5.26	1	1.75	57	Yes
	Bitumen	0.3	55	96.49	1	1.75	1	1.75	57	Yes
Bearing renewal	Reinforcement	0.25	54	94.73	1	1.75	2	3.51	57	Yes
Expansion joint renewal	Reinforcement	0.25	53	92.98	2	3.51	2	3.51	57	Yes
Deck replacement	Concrete	2.5	53	92.98	2	3.51	2	3.51	57	Yes
	Asphalt	0.27	54	94.73	2	3.51	1	1.75	57	Yes
	Reinforcement	0.3	3	5.26	24	42.11	30	52.63	57	No
	Bitumen	0.3	53	92.98	3	5.26	1	1.75	57	Yes
Total			**438**		**60**		**72**		**570**	

A total of 50 experts disagreed with the quantities estimated (for concrete overlay repair), and 30 of them provided alternative estimates. Similarly, 54 experts disagreed with the estimated quantities of reinforcement of deck replacement and 30 experts provided alternative estimates. The large disagreement is traceable to variability of consulted literature sources during data collection. Estimated data for bridge works are mostly approximations, which are susceptible to errors – a major limitation in bridge LCA study (Du and Karoumi, 2014). The next section will therefore evaluate the data supplied by experts for concrete overlay and deck replacement.

Suggested Values of Concrete for Overlaying

The first method without agreement was concrete overlaying. The histogram in Figure 5.1a presents the distribution of suggested values which indicated some outliers. However, Figure 5.1b also presents the distribution of suggested data but excluded the outliers. A normality test was then conducted on the distribution with and without outliers to reveal normality of the distribution. A Null hypothesis for the distribution was accepted if Shapiro-Wilk significance value of the normality test is greater than 0.05 and rejected when less than 0.05. Shapiro-Wilk significance was less than 0.05 for the distribution with outliers and greater when outliers were excluded. Normality test for distribution with outliers is presented in Table 5.5, while normality test for distribution without outliers is presented in Table 5.6. Results in Table 5.5 suggest that the null hypothesis should be rejected based on the fact that suggested data were not normally distributed with the outliers, but were without the outliers. The outliers were traced back to site engineers and construction engineers who most likely to agree with presented data. However, other respondents who were not outliers had more experience and their response could be relied upon. 0.22 was determined as the mean of the distribution as shown in Figure 5.1b and represents the best model for the normal distribution (Field and Hole, 2004).

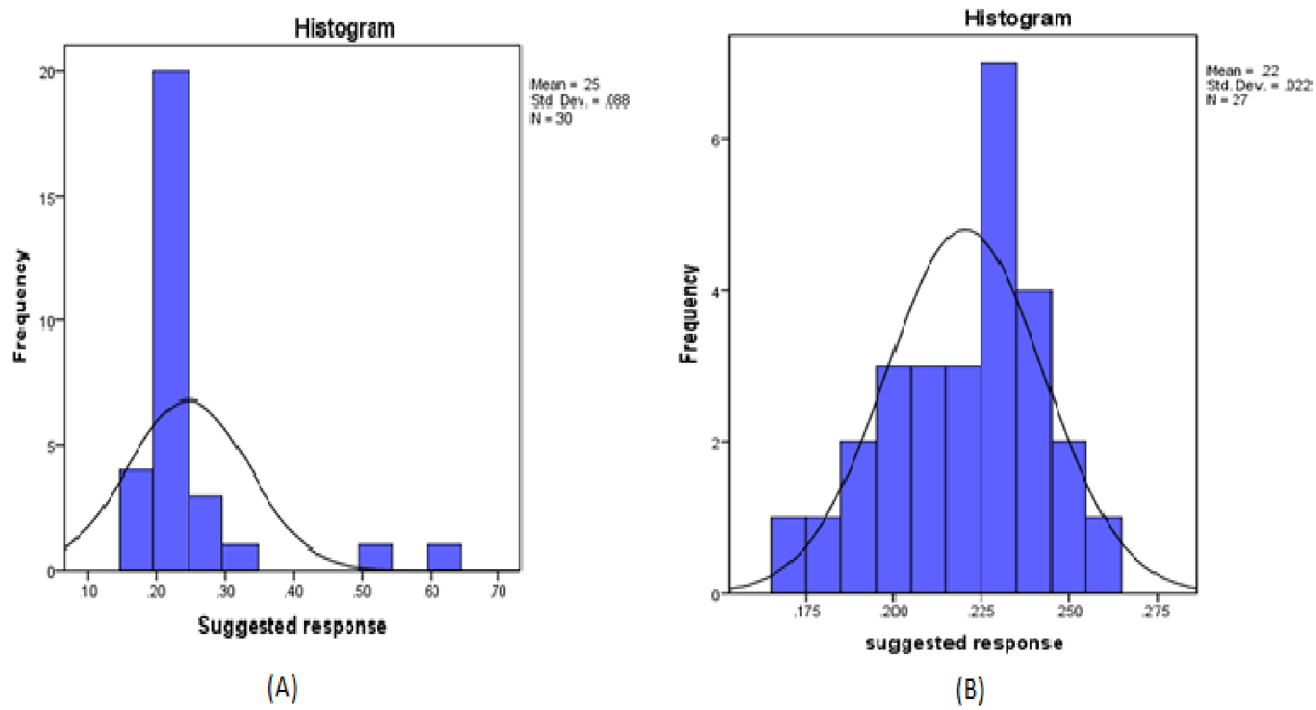

Figure 5. 1 Distribution [with outliers (A) and without outliers (B)]

Table 5. 5 Normality Test for Distribution with Outliers for suggested values of Concrete for Overlaying

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
suggested response	0.344	30	0.000	.556	30	0.000

Table 5. 6 Normality Test for Distribution without Outliers for suggested values of Concrete for Overlaying

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
suggested response	0.185	27	0.019	0.960	27	0.365

Based on the research strategy, a confidence interval was calculated for distribution without outliers to ascertain the adequacy of the mean. The 95% confidence intervals of the lower and upper boundaries are (0.21, 0.22) respectively, as revealed in Table 5.7. The confidence of the mean (0.22) is again ascertained, as it falls between the lower and upper boundaries.

Table 5. 7 Confidence Interval Calculations for suggested values of Concrete for Overlaying

Suggested response statistical evaluations			Statistic	Std. Error
	Mean		0.220	0.004
	95% Confidence Interval for Mean	Lower Bound	0.211	
		Upper Bound	0.229	
	Median		0.230	
	Variance		0.001	
	Std. Deviation		0.022	

Suggested Values of Reinforcement for Deck Replacement

The second method without agreement is reinforcement in deck replacement. The histogram in Figure 5.2 reveals the distributions of the suggested values and 0.12 is the mean of the distribution. Shapiro-Wilk significance value in Table 5.8 indicates that suggested data were normally distributed on the account that Shapiro-Wilk significance value was greater than 0.05. Hence, the null hypothesis was accepted and the mean (0.12) of the distribution was taken as consensus. The 95% confidence intervals of the lower and upper boundaries are (0.11, 0.12) respectively, as revealed in Table 5.9 which further authenticates the integrity of the mean.

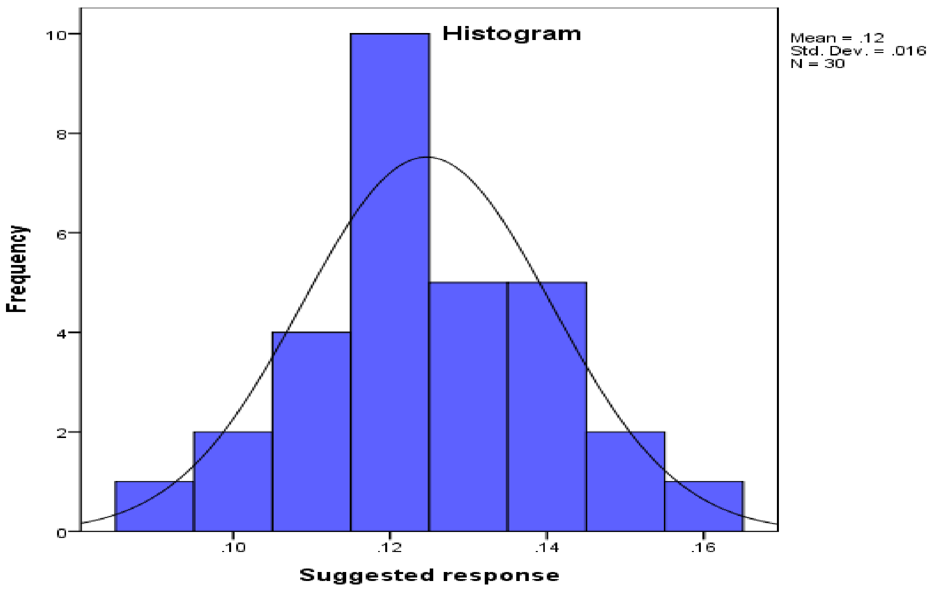

Figure 5. 2 Distribution of suggested values of reinforcement for deck replacement

Table 5. 8 Normality Test for suggested values of Reinforcement for Deck Replacement

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Suggested response	0.182	30	0.013	0.962	30	0.355

Table 5. 9 Confidence Interval Calculations for suggested values of Reinforcement for Deck Replacement

Suggested response statistical evaluations			Statistic	Std. Error
	Mean		0.124	0.002
	95% Confidence Interval for Mean	Lower Bound	0.118	
		Upper Bound	0.130	
	Median		0.120	
	Variance		0.000	
	Std. Deviation		0.015	

5.5.2 Consensus on Steel Bridge Quantities

Consensus of 57 experts on estimated quantities of selected steel bridge maintenance activities is presented in Table 5.10. Consensus was determined on the basis of APMO cut-off rate, which was derived from the sum of (331) majority agreements and (89) majority disagreements (without suggestions) divided by 511 opinions. The cut-off rate therefore equals 82%. Consensus was reached on all material estimates of pavement repair, deck re-waterproofing, bearing renewal, and expansion joint renewal. However, disagreements were found on the material estimates for structural painting. The large disagreement is traceable to various literature sources from which these data were obtained (as described in section 5.5.1). Moreover, quantities of paint are linked to cost savings which would vary from project to project and potentially affect the choice and volume of paints applied in previous literatures.

Table 5. 10 Quantities of Material for Steel Bridge Maintenance Work

Maintenance Activities	**Materials**	**Quantities of materials (tons/sq.m)**	**Agreed**		**Disagreed without suggestions**		**Disagreed with Suggestions**		**Opinion**	**Consensus**
			No.	**%**	**No.**	**%**	**No.**	**%**		
Structural painting	Epoxy paint	0.054	5	8.77	30	52.63	22	38.59	57	No
	Polyurethane paint	0.105	3	12.28	25	43.86	29	50.88	57	No
	Zinc coating	0.366	4	7.01	23	40.35	30	52.63	57	No
Pavement repair	Asphalt	0.27	54	94.73	2	3.51	1	1.75	57	Yes
	Bitumen	0.3	53	92.98	3	5.26	1	1.75	57	Yes
Deck waterproofing	Concrete	0.1	54	94.73	1	1.75	2	3.51	57	Yes
	Reinforcement	0.1	53	92.98	2	3.51	2	3.51	57	Yes
Bearing renewal	Reinforcement	0.25	53	92.36	2	3.63	0	0	55	Yes
Expansion joint renewal	Reinforcement	0.25	52	91.2	2	3.51	3	5.26	57	Yes
Total			**331**		**89**		**90**		**511**	

A total of 52 experts disagreed with the quantities estimated for epoxy paint and 22 gave alternative estimates. Similarly, 50 experts disagreed with estimated quantities of polyurethane and 29 suggested alternative estimates. 54 experts disagreed with estimated quantities of zinc coating and 30 gave alternative estimates. The three activities where consensus was not reached will next be discussed.

Suggested Values of Epoxy Paint

The histogram in Figure 5.3 presents the distribution of suggested values of epoxy paint. Normality test indicates that distribution was normally distributed on account of Shapiro-Wilk significance being greater than 0.05. Hence, the null hypothesis (presented in Table 5.11) was accepted and 0.0005 was identified as the mean of the distribution and taken as consensus. The 95% confidence intervals of the lower and upper boundaries are (0.001, 0.001) respectively, as revealed in Table 5.12, which further ascertain the integrity of the mean.

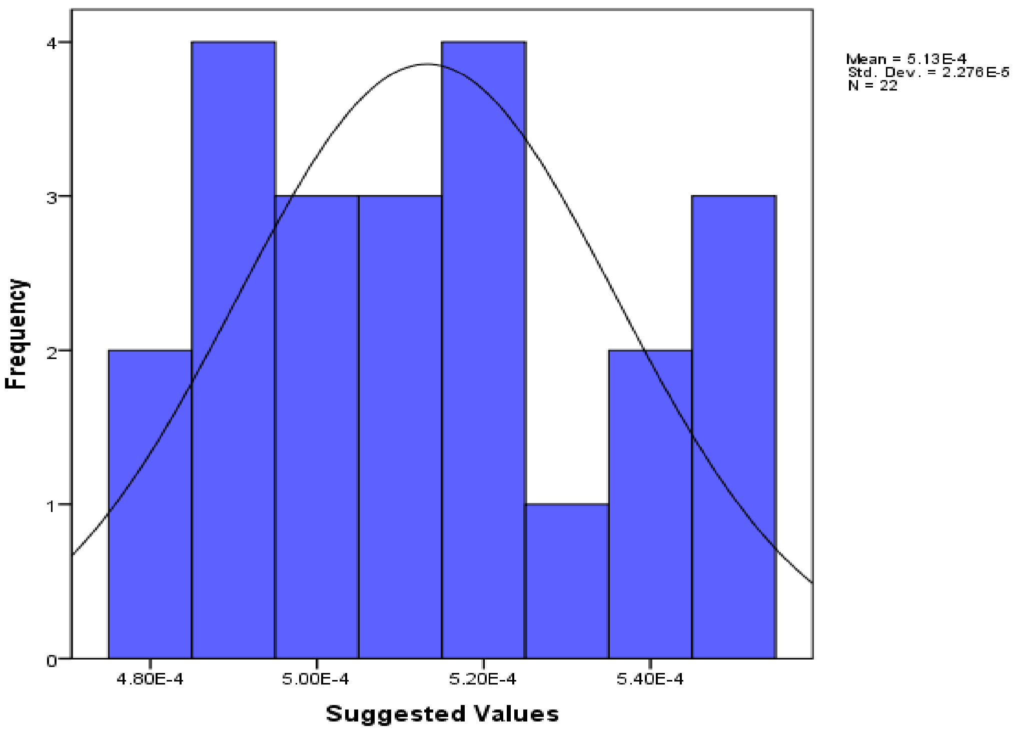

Figure 5. 3 Distribution of suggested values of epoxy paint

Table 5. 11 Normality Test for Suggested values of Epoxy paint

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	df	Sig.
Suggested Values	0.128	22	0.200*	0.929	22	0.116

Table 5. 12 Confidence Interval calculations for suggested values of Epoxy paint

			Statistic	Std. Error
Suggested Values	Mean		0.0005	0.00000
	95% Confidence Interval for Mean	Lower Bound	0.0005	
		Upper Bound	0.0005	
	Median		0.0005	
	Variance		0.000	
	Std. Deviation		0.0002	

Suggested Values of Polyurethane

The histogram in Figure 5.4 presents the distribution of suggested values of polyurethane. Normality test indicates that distribution was normal, on account of Shapiro-Wilk significance being greater than 0.05. Hence, the null hypothesis (presented in Table 5.13) was accepted and the 0.0001 was determined as mean of the distribution and taken as consensus. The 95% confidence intervals of the lower and upper boundaries are (0.0001, 0.0001) respectively, as revealed in Table 5.14, which further ascertain the integrity of the mean.

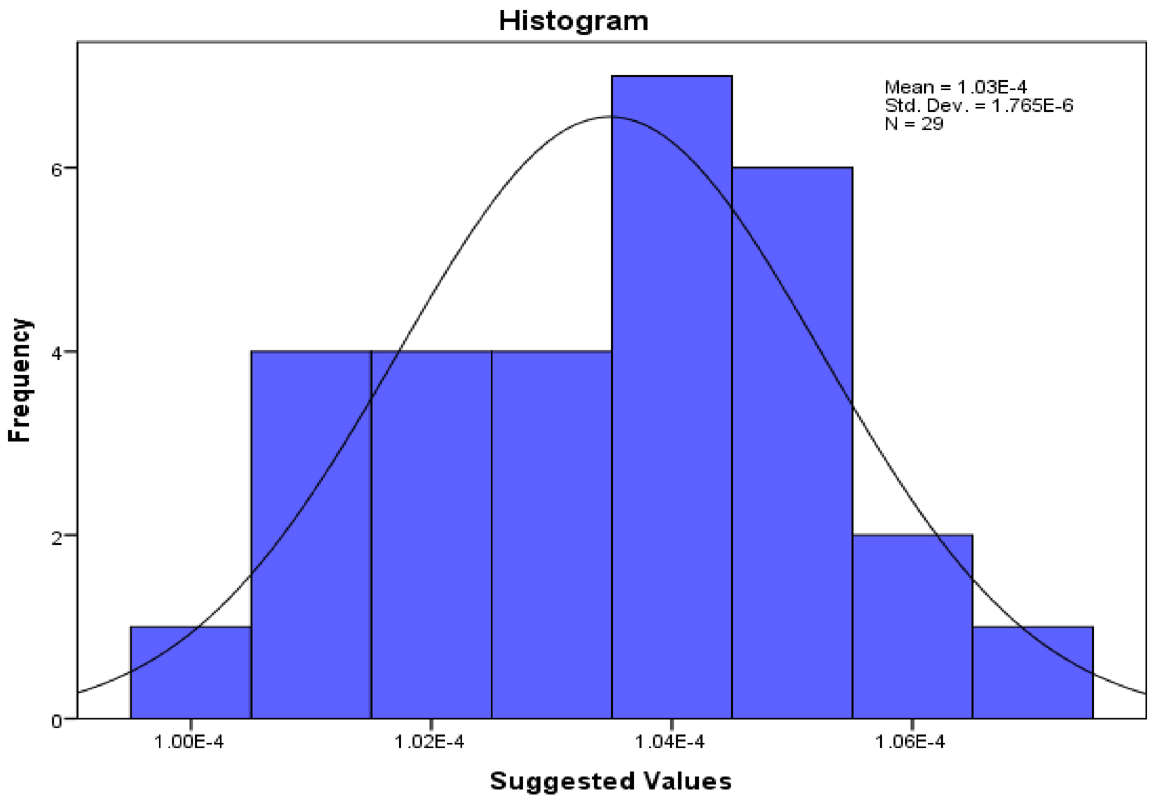

Figure 5. 4 Distribution of suggested values of polyurethane paint

Table 5. 13 Normality Test for suggested values of Polyurethane paint

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Suggested Values	0.167	29	0.038	0.957	29	0.279

Table 5. 14 Confidence Interval for suggested values of Polyurethane Paint

			Statistic	Std. Error
Suggested Values	Mean		0.0001	0.00000
	95% Confidence Interval for Mean	Lower Bound	0.0001	
		Upper Bound	0.0001	
	Median		0.0001	
	Variance		0.000	
	Std. Deviation		0.00000	

Suggested Values of Zinc Coating

The histogram in Figure 5.5 presents the distribution of suggested values of epoxy paint. Normality test indicates that distribution was normal on account of Shapiro-Wilk significance being greater than 0.05. Hence, the null hypothesis (presented in Table 5.15) was accepted and the 0.0004 was determined as the mean of the distribution and taken as consensus. The 95% confidence intervals of the lower and upper boundaries are (0.0004, 0.0004) respectively, as revealed in Table 5.16, which further ascertain the integrity of the mean.

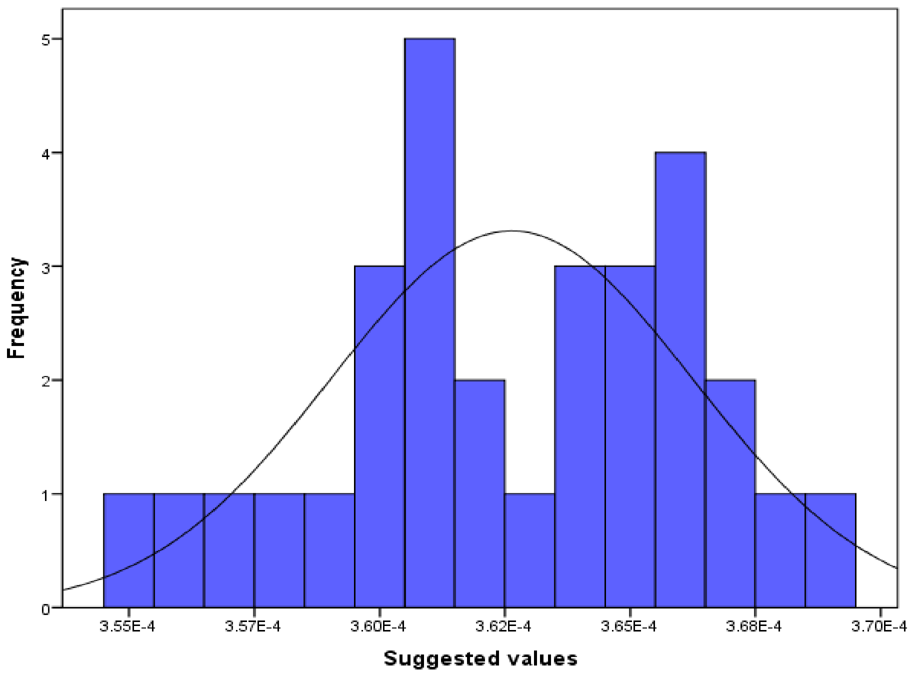

Figure 5. 5 Distribution of suggested values of zinc paint

Table 5. 15 Normality Test for suggested values of Zinc Paint

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Suggested values	0.114	30	0.200*	0.970	30	0.535

Table 5. 16 Confidence Interval for suggested values of Zinc Paint

			Statistic	Std. Error
Suggested values	Mean		0.0004	.0000
	95% Confidence Interval for Mean	Lower Bound	0.0004	
		Upper Bound	0.0004	
	Median		0.0004	
	Variance		0.000	
	Std. Deviation		0.0000	

5.5.3 Consensus on Masonry Bridge Estimated Material Quantities

Consensus of 35 experts on estimated quantities of saddling, radial pinning, waterproofing, near-surface reinforcement and sprayed concrete repair technique is presented in Table 5.17. APMO cut-off rate derived from the sum of (702) majority agreements and (23) majority disagreements (without suggestions) divided by 789 opinions equals 91% cut of rate. Therefore, all estimated quantities of selected masonry bridge were agreed upon and no further investigation was required.

Table 5. 17 Quantities of Material for Masonry Bridge Maintenance Work

Maintenance Activities	Materials	Quantities of materials (tons/sq.m)	Agreed		Disagreed without suggestions		Disagreed with Suggestions		Opinion	Consensus
			No.	%	No.	%	No.	%		
Saddling	Concrete	2.5	55	98.21	1	1.79	0	0	56	Yes
	Asphalt	0.27	55	96.49	1	1.75	1	1.57	57	Yes
	Reinforcement	0.25	53	93.81	2	3.51	2	3.51	57	Yes
	Bitumen	0.3	53	95.41	3	5.36	0	0	56	Yes
	Fill	2	55	96.49	2	3.51	0	0	57	Yes
Radial pinning	Cementitious grout	0.12	53	95.41	1	1.70	2	3.57	56	Yes
	Dowel	0.12	52	94.54	2	3.63	1	1.81	55	Yes
Waterproofing	Concrete	0.1	54	98.18	1	1.81	0	0	55	Yes
	Asphalt	0.1	54	96.43	1	1.70	1	1.70	56	Yes
	Mastic seal	0.1	55	96.49	2	3.51	0	0	57	Yes
Near-surface reinforcement	Cementitious grout	0.152	54	94.74	2	3.51	1	1.57	57	Yes
	Reinforcement	0.203	54	94.74	3	5.26	0	0	57	Yes
Sprayed concrete	Concrete	0.4	55	96.49	1	1.57	1	1.57	57	Yes
	Reinforcement	0.1	55	98.21	1	1.79	0	0	56	Yes
Total			**702**		**23**		**9**		**789**	

A summary for all agreed material estimates for concrete, steel and masonry are presented in Table 5.18. The verified data is therefore credible to be applied in the LCA analysis, conducted in chapter 6 of the thesis.

Table 5. 18 Agreed and Verified Material Quantities

Structural type	Maintenance Activities	Materials	Quantities of materials (tons/sq.m)	Quantities of materials (Kg)
Concrete bridge	Grouting	Cementitious grout	0.14	140
	Overlaying	Concrete	0.22	220
		Asphalt	0.27	270
		Bitumen	0.3	300
	Bearing renewal	Reinforcement	0.25	250
	Expansion joint renewal	Reinforcement	0.25	250
	Deck replacement	Concrete	02.5	2500
		Asphalt	0.27	270
		Reinforcement	0.12	120
		Bitumen	0.3	300
Steel bridge	Structural painting	Epoxy paint	0.0005	0.05
		Polyurethane paint	0.0001	0.10
		Zinc coating	0.0004	0.4
	Pavement repair	Asphalt	0.27	270
		Bitumen	0.3	300
	Deck re-waterproofing	Concrete	0.1	100
		Reinforcement	0.1	100
	Bearing renewal	Reinforcement	0.25	250
	Expansion joint renewal	Reinforcement	0.25	250
Masonry bridge	Saddling	Concrete	2.5	2500
		Asphalt	0.27	270
		Reinforcement	0.25	250
		Bitumen	0.3	300
		Fill	2	2000
	Radial pining	Cementitious grout	0.12	120
		Dowel reinforcement	0.12	120
	Waterproofing	Concrete	0.1	100
		Asphalt	0.1	100
		Mastic seal	0.1	100
	Near-surface reinforcement	Cementitious grout	0.152	152
		Reinforcement	0.203	203
	Sprayed concrete	Concrete	0.4	400
		Reinforcement mesh	0.1	100

5.7 Open-ended Questions

Two questions were presented in the open-ended question. Firstly, respondents were asked to give extra comments on the selected methods that were presented in the survey, but not many comments were received. Non-responses according to Robson (2011) are still a cause for concern in the field of research and were taken as a potential limitation of the survey. Secondly, respondents were asked to give comments on how to improve sustainability in bridge maintenance. A total of 18 experts provided comments on how sustainability could be integrated in bridge maintenance. A summary of participants' responses is presented in Table 5.19. 8 major themes emerged from 15 suggested ways of enhancing sustainability in bridge maintenance. 6 responses were associated with design, while 3 responses were associated with inspection. Quality material, proactive maintenance action and construction technique had 2 responses each. Respondents particularly highlighting design, suggests that improving sustainability for bridges should begin at the design stage. Therefore, it is valuable to research the sustainability of bridges from an environmental perspective in the hope of integrating the results at the design phase.

Table 5. 19 Ways to Improve Sustainability in Bridge Maintenance

Suggested ways to improve sustainability in bridge maintenance by participants	**Themes**							
	Design	**Detailing**	**Quality of material**	**Funding cost**	**Inspection**	**Method of analysis**	**Proactive maintenance action**	**Construction technique**
Better detailing and design to reduce maintenance	1	1						
Avoid the use of less quality material			1					
Carrying out proactive maintenance measures							1	
Generally better design to avoid maintenance operations	1							
Through maintenance free design and construction techniques	1							1
Using quality materials for maintenance rather than cheaper alternatives			1					
Regular routine and periodic maintenance							1	
More detailed design	1							
Initial concept to provide a sustainable solution	1							
Advanced methods of analysis for assessment						1		
Strategy in inspection regime					1			
Ensure bridge is built to a high standard at construction stage								1
Use lessons learnt in bridge maintenance to produce new bridge designs	1							
Bridge maintenance relies on funds and inspection and if either of these is expensive then the maintenance is unsustainable				1	1			
Increase the frequency of inspection					1			
Total	**6**	**1**	**2**	**1**	**3**	**1**	**2**	**2**

5.8 Chapter Summary

The chapter presents a comprehensive analysis of the questionnaire survey which was conducted to determine the reliability of the quantity of material used for some maintenance activities of concrete, steel and masonry bridge derived from the literature. 68 respondents completed the survey that provided a response rate of 17%. Where consensus was not reached on the proposed material quantities, APMO cut-off rate and mean were used (from plotting a normal distribution of the suggested values) to determine consensus. Material quantities from literature were mostly agreed upon by respondents. Response to the open-ended question suggested that the design phase would need more attention if sustainability improvements are to be made. Verified data was put into SimaPro software to conduct the LCA analysis. The next chapter presents the inventory analysis of selected maintenance actions.

CHAPTER SIX: INVENTORY ANALYSIS OF MAINTENANCE METHODS

6. Introduction

The chapter presents the inventory analysis of selected maintenance methods of concrete, steel, and masonry bridge. It presents the results of the impact assessment for selected maintenance methods, based on selected impact category indicators. Severity of impact on human health, ecosystem, and resources are used as indicators. Uncertainty analysis test was conducted to account for variability of data.

6.1 Inventory Data for Maintenance Methods

Obtaining specific data for bridge LCA analysis is a challenge (Du and karoumi, 2014). To obtain specific bridge maintenance data is even more challenging, and most studies used data from assumed maintenance activities (Keolein *et al*., 2005; Gerversio and da Silva, 2008; Hammervold, Reenaas and Brattebø, 2013). Others researchers sought maintenance data from inspection manuals (Itoh and Kitagawa, 2003) and some from practicing engineers and similar studies (Itoh and Kitagawa, 2003; Du and Karoumi 2014; Du *et al*, 2014). Some analysis simply assumed no maintenance (Bouhaya, Roy and Feraille-Fresnet, 2009). In the current study data for selected bridge maintenance method were collected from the literature. As the data was gathered from various sources it was subsequently verified by practising engineers.

No bridge LCA studies can consider all necessary processes yet, due to lack of data (Du *et al*., 2014). Hence, assumptions are made for missing information. Transportation distance to site and average fuel consumption were assumed to be 16km and 10l/100km respectively. While the assumed distance falls within the range of normal transportation of material to a UK site (Zhang, Amaduddin and Canning, 2011), the average fuel consumption had been utilized in previous bridge maintenance LCA studies (Pang *et al*., 2015). However, assumptions are affected by the number of times maintenance actions are likely to take place in 120 years. Origin of inventory data applied in this study is presented in Table 6.1

Table 6. 1 Origin of Inventory Data

Life cycle stage	Sub process	Data origin
Maintenance	Cementitious grout	Literature
	C30 and C40 Concrete	Literature
	Asphalt	Literature
	Bitumen	Literature
	Reinforcement	Literature
	Epoxy paint	Literature
	Polyurethane paint	Literature
	Zinc coating	Literature
	Reinforcement mesh	Literature
	Mastic seal	Literature
	Production of electricity, diesel, and gasoline	SimaPro
	Combustion of electricity, diesel, and gasoline	SimaPro
	Production of water	SimaPro
	Energy resources	SimaPro

6.2 Data Quality

A major concern with LCA applications is the quality of data used to inform the inventory analysis (Consoli *et al*., 1993; Finnveden *et al*., 2009). Two main approaches to data quality were revealed (Consoli *et al*. 1993), primary and secondary quality data. Primary data are obtained from accessible facilities or are site specific, while secondary data are obtained from published sources (e.g. journals, conference papers, books, manufacturers' guides, and government reports). ISO 14041 (2006) also recommends additional data quality checks (such as precision, completeness, representativeness, and consistency). These are, however, elements of the interpretation phase of an LCA study.

Secondary quality data was obtained for this study and verified by industry experts. Verified data from chapter 5 was used to inform the foreground system as indicated in Figure 4.2 in chapter 4. Primary data was obtained from SimaPro database, which has been gathered from relevant facilities applicable to this study. Applicable databases embedded in SimaPro include; Ecoinvent 3, ELCD, industry data, LCA foods, Swiss input and output database, and Agric footprint. These databases are confirmed to be reliable, having been employed in similar LCA studies which confirms their reliability (Mc Manus, 2001; Steele *et al*., 2003, Thiebault; 2010; Du, 2012; Hammervold, Reenaas and Brattebø, 2013). They have also been universally agreed upon by LCA experts and practitioners (Geodkoop *et al*., 2012). The primary quality data were used to inform the background system for the study.

6.3 Inventory Analysis

As mentioned before, inventory analysis is the process of quantifying the input and output effects of a product or process. Inventory analysis involves the collection of all relevant data, after the functional unit and the system boundary have been defined. In the current study, the maintenance phase covered only materials, transportation and energy used. Calculating inventory of materials, energy consumption and emission from transportation allows potential environmental impact associated with each maintenance action to be identified. Inventory data for selected maintenance methods presented in Table 5.18 for concrete, steel, and masonry bridges are presented in subsequent sections. After the weight of the assumed maintenance material is identified, the chapter will determine the frequency the maintenance activity is used in 120 years assumed life cycle of a bridge, relevant, means of transportation and distance to site.

6.3.1 Concrete Bridge

a) Grouting

Grouting repair is a simple corrective maintenance and does not require heavy machineries other than a drilling machine to drill holes along cracked areas. The grout material itself is a cementitious substance, and is mixed with water to form grout slurry. A paddle mixer operating at 220Vac running at 250rpm is assumed to be used for this operation. Inventory data for grouting is presented in Table 6.2

Table 6. 2 Inventory Data for Grouting Repair

Grouting	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
	Cementitious grout	30	140	560	Transit car	64

b) Overlaying of Asphalt

Overlaying asphalt is a corrective maintenance method. It involves machinery and materials that are energy intensive. The process requires bridge closure in severe circumstances. Overlaying of asphalt is not unique to concrete bridges, as it is generally applied to deteriorating road surfaces. Inventory materials for overlaying of asphalt are presented in Table 6.3.

Table 6. 3 Inventory data for Overlaying of Asphalt

Overlaying of asphalt	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
	Concrete	30	220	880	Mixer	64
	Asphalt		270	1080	Truck	64
	Bitumen		300	1200	Truck	64

c) Bearing Renewal

Bearing replacement is a frequent task in concrete bridge. Increased traffic reduces the life span of the bearing and will need to be replaced when that happens. Bearing replacement requires mobile cranes and scaffoldings for high level assess generally. The activity commonly involves removal of deteriorated bearing, securing loose bolt, and installation of new members. Inventory data for bearing renewal are presented in Table 6.4.

Table 6. 4 Inventory Data for Bearing Renewal

Bearing renewal	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
	Reinforcement (bearing)	30	250	1000	Truck	64

d) Expansion Joint Renewal

Expansion joint renewal follows the same activities as bearing renewal, but is more frequently done. Activities include, but are not limited to, removal of deteriorated joints, oiling and greasing of corroded members, and installation of new expansion joint. Expansion joint renewal impacts traffic condition if not properly planned, although traffic delays had been excluded from the study. Inventory data for expansion joints are presented in Table 6.5.

Table 6. 5 Inventory Data for Expansion Joint Renewal

	Material	**Frequency (years)**	**Weight (kg)**	**Weight in 120years (kg)**	**Transportation means**	**Distance to site (km)**
Expansion joint renewal	Reinforcement (expansion joint)	20	250	1500	Truck	64

e) Deck Replacement

Complete removal is best for highly deteriorated bridge deck, and the last resort. Deck replacement is a maintenance measure, but could be regarded as an end-of-life scenario, depending on the circumstance (Zhang, Amaduddin and Canning, 2011). It was however considered as a maintenance measure in the study, on the premise that the bridge deck is now significantly damaged. High cost is involved in deck replacement, due to materials and resources. The study accounts for (concrete pairs, abutments, drainage and kerbs) and the process is considered to take place once in 120 years, based on TAMP (2005); Parke and Hewson (2008). Inventory data for deck replacement are provided in Table 6.6.

Table 6. 6 Inventory Data for Deck Replacement

	Material	**Frequency (years)**	**Weight (kg)**	**Weight in 120years (kg)**	**Transportation means**	**Distance to site (km)**
Deck replacement	Concrete	120	2500	2500	Mixer	16
	Asphalt		270	270	Truck	16
	Reinforcement		120	120	Truck	16
	Bitumen		300	300	Truck	16

6.3.2 Steel Bridge

a) Structural Metal Painting

Steel bridges and steel members in bridges are generally maintained by taking off corroded areas before repainting. Cost and budget plans generally determine the quality of paint that would be applied. Bridge LCA studies like Gerversio and da Silva (2008), and Hammervold, Reenaas and Brattebø (2013) assumed painting schemes which were equally adopted in this study. Inventory data for structural metal painting are presented in Table 6.7.

Table 6. 7 Inventory Data for Structural Painting

	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
Structural metal painting	Epoxy paint	12	0.051	0.510	Truck	160
	Polyurethane paint		0.103	1.030	Truck	160
	Zinc coating		0.4	4	Truck	160

b) Pavement Repair

Pavement repair generally involves laying of a new asphalt layer on top of a layer or primer on the existing deck surface. New pavement can also involve an additional waterproofing membrane Inventory data considered for pavement repair are presented in Table 6.8.

Table 6. 8 Inventory Data for Pavement Repair

	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
Pavement repair	Asphalt	20	270	1620	Truck	96
	Bitumen		300	1800	Truck	96

c) Deck Waterproofing

Waterproofing system provides the pavement with a good drainage system and does not allow water to be retained on the pavement. Bridge maintenance engineers will normally recommend a waterproofing system for a new bridge deck. Inventory data for deck waterproofing are presented in Table 6.9.

Table 6. 9 Inventory Data for Deck Waterproofing

	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
Deck waterproofing	Concrete	30	100	400	Mixer	64
	Reinforcement		100	400	Truck	64

d) Bearing and Expansion Joint Renewal

Conditions for concrete bridge bearing and expansion joint renewal are similar to steel bridges, apart from variation in the amount of reinforcement used. Inventory data for both bearing and expansion joint renewal are presented in Table 6.10.

Table 6. 10 Inventory Data for Expansion Joint Renewal and Bearing Renewal

Repair	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
Expansion joint	Reinforcement	20	250	1500	Truck	96
Bearing renewal	Reinforcement	30	250	1000	Truck	64

6.3.3 Masonry Bridge

a) Saddling

Saddling can be applied to a variety of defects in masonry bridges (CIRIA, 2006). It is a material and labour-intensive rehabilitation technique. The main materials involved in saddling are concrete and steel reinforcement, as it involves casting a reinforced concrete arch on top of the existing masonry arch. As such, excavation and refilling activities are needed. Materials such as brick, mortar, sand, gravel, stones, and rubbles are excluded from the study as they are classified as inert materials and emit negligible environmental impact (HM Revenue & Custom, 2015). Saddling and other major rehabilitation activities for masonry bridge were reported to take place once in 190 years (Steele *et* *al*., 2002). As such, saddling was considered to take place once in 120 years for this study. Inventory data for saddling activities is presented in Table 6.11.

Table 6. 11 Inventory Data for Saddling

	Material	**Frequency (years)**	**Weight (kg)**	**Weight in 120years (kg)**	**Transportation means**	**Distance to site (Km)**
Saddling	Concrete	120	2500	2500	Mixer	16
	Asphalt		270	270	Truck	16
	Reinforcement		250	250	Truck	16
	Bitumen		300	300	Truck	16
	Fill		2000	2000	Truck	16

b) Radial Pinning

Radial pinning involves the insertion of dowel pins (through drilling operation) to strengthen the arch in masonry bridges. Radial pinning is considered to occur once in 120 years (Swoden, 1990). Inventory data considered for radial pinning operation are presented in Table 6.12.

Table 6. 12 Inventory data for Radial Pinning repair

	Material	**Frequency (years)**	**Weight (kg)**	**Weight in 120years (kg)**	**Transportation means**	**Distance to site (km)**
Radial pinning	Cementitious grout	120	120	120	Truck	16
	Dowel Reinforcement		120	120	Truck	16

c) Waterproofing

Waterproofing prevents water penetration and reduce water damage in masonry bridges. Swoden (1990) recommends that waterproofing should be replaced every 30 years. The study considers the installation of the waterproofing system and restoration of damaged asphaltic layer. Inventory data for waterproofing repair are presented in Table 6.13.

Table 6. 13 Inventory Data for Waterproofing

	Material	**Frequency (years)**	**Weight (kg)**	**Weight in 120years (kg)**	**Transportation means**	**Distance to site (km)**
Waterproofing	Concrete	30	100	600	Mixer	64
	Asphalt		100	600	Truck	64
	Mastic seal		100	600	Truck	64

d) Near Surface Reinforcement (NSR)

NSR is applied to the intrados of the arch as an easy to use strengthening technique if the arch barrel is not strong enough to carry the loads. A transverse, longitudinal or shear reinforcement can be applied. The NSR technique is relatively new and there is little real information on its real life expectancy. However, it was assumed to reach 120 years in this study as other maintenance techniques considered for masonry. Inventory data for NSR are presented in Table 6.14.

Table 6. 14 Inventory Data for NSR

	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
NSR	Cementitious grout	120	152	152	Truck	16
	Reinforcement		203	203	Truck	16

e) Sprayed Concrete

Sprayed concrete is used on the intrados of masonry bridges as an alternative easy to install strengthening technique to near surface reinforcements. Sprayed concrete can be combined with reinforcing mesh. The process involves mixing concrete with water (and fibre if used) and spraying the mixture on the intrados through a nozzle. Strengthening masonry bridge with sprayed concrete is expected to reach or exceed normal design life of 120 years (Swoden, 1990). Inventory data for sprayed concrete are presented in Table 6.15.

Table 6. 15 Inventory Data for Sprayed Concrete

	Material	Frequency (years)	Weight (kg)	Weight in 120years (kg)	Transportation means	Distance to site (km)
Sprayed concrete	Concrete	120	400	400	Mixer	16
	Reinforcing mesh		100	100	Truck	16

6.5 Impact Assessment

Impact assessment was discussed earlier in section 3.2.3 of chapter 3. The impact assessment will identify the environmental impact of materials and processes (based on inventory data) for the selected maintenance methods, that can be useful for decision making during design. Impact assessment involves mandatory stages (of classification and characterisation) and optional stages (of normalisation, weighting, and grouping). Though both mandatory and optional phases were considered for the study, it excluded the weighting and grouping stages.

6.5.1 Environmental Results

Categorising environmental indicators into impact categories is referred to as classification. The section presents environmental results of selected maintenance methods based on four environmental indicators (CO_2, NO_2, SO_2 and Energy).

A. Concrete bridge

The environmental impact of maintenance methods for concrete bridges is shown in Figure 6.1 (results were derived from analysing literature data verified by experts, see Table 5.18). Expansion joint replacement indicates the highest CO_2 emission 40kg, followed by bearing renewal (27kg), overlaying of asphalt (19kg), deck replacement (12kg), and grouting (2kg). Although deck replacement is more material intensive than expansion-joint replacement its CO_2 emission is low due to difference in the frequency of maintenance activities. The result differs from Zhang, Amaduddin and Canning's (2011) evaluation of CO_2 emission in a typical bridge deck replacement, which gave 3 times higher CO_2 emission. Zhang, Amaduddin and Canning (2011) accounted for the demolition, construction, and maintenance phase, which further increased the system boundary (allowing more processes to be evaluated). The current study considers deck replacement as a maintenance technique, with narrower system boundary (excluding demolition and construction). Results similarly indicate that expansion-joint replacement has high SO_2 and NO_2 emissions as shown in Figure 6.2., whilst overlaying of asphalt as indicated in Figure 6.3 requires very high energy (62GJ) based on non-renewable fossil. The result is attributed to the asphaltic material required per scheduled maintenance, which is highly energy intensive (Giustozzi, Crispino and Flintsch, 2012).

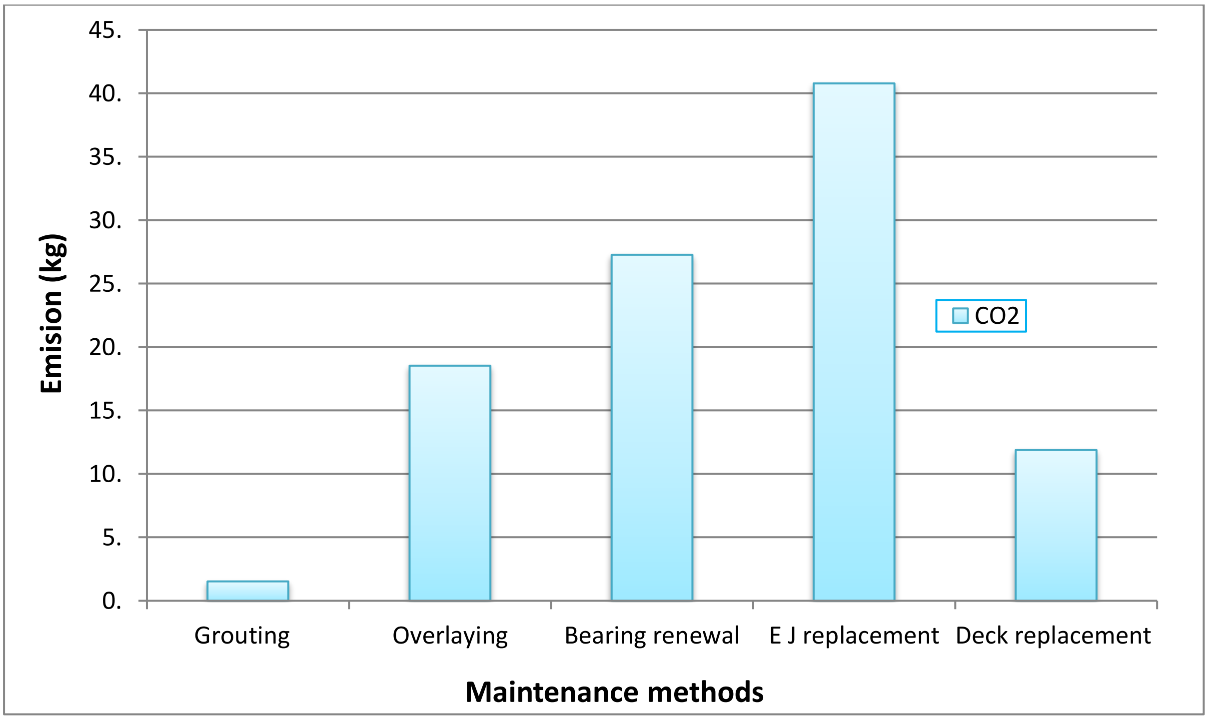

Figure 6. 1 CO_2 emissions from selected maintenance/repair methods of concrete bridge

Figure 6. 2 SO_2 and NO_2 emissions from selected maintenance/repair methods of concrete bridge

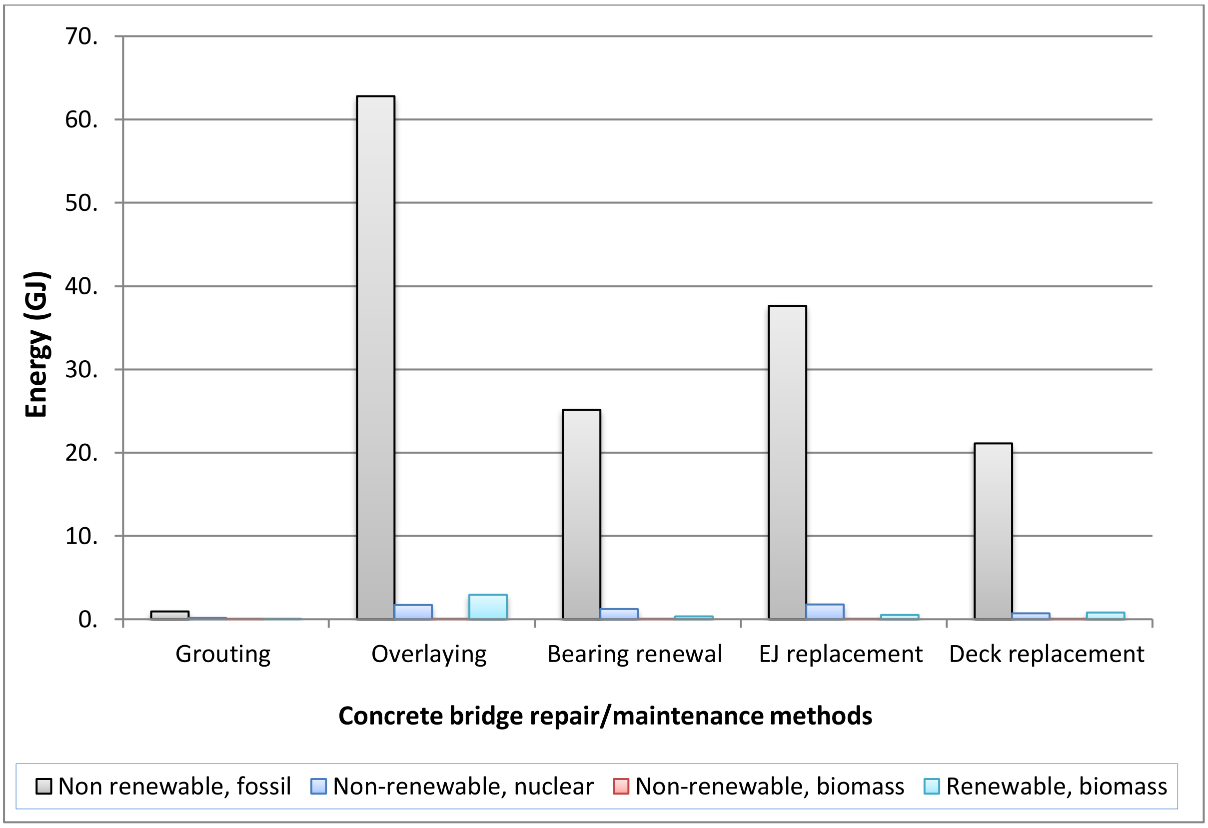

Figure 6. 3 Energy used by selected repair/maintenance methods of concrete bridge

B. Steel Bridge

Environmental results of selected maintenance methods of steel bridge indicated that expansion joint replacement had the highest CO_2 emission (37kg), followed by bearing replacement (25kg), pavement repair (22kg), deck waterproofing (12kg) and structural painting (5kg), as shown in Figure 6.4 (results were derived from analysing literature data verified by experts, see Table 5.18). Structural painting created the least CO_2 emission differs from the results of Horvath and Hendrickson (1998) on comparing steel and steel-reinforced concrete bridges, wherein structural painting had significant CO_2 emission from the maintenance phase. Differences in results emerge from the intervals at which painting was scheduled and the quantity required. Zhang (2010) explains that paint is a high carbon intensity material, but only a small quantity is applied, which in effect prevents deterioration and reduces maintenance. For this study, structural painting was scheduled to take place every 12 years (i.e. 12 times in 120 years), with very small quantities, compared to 8 years by Horvath and Hendrickson (1998). Expansion joint replacement had the highest SO_2 and NO_2 emissions as shown in Figure 6.5, whereas pavement repair consumed the highest energy, using up to 57GJ of non-renewable fossil fuel as revealed in Figure 6.6.

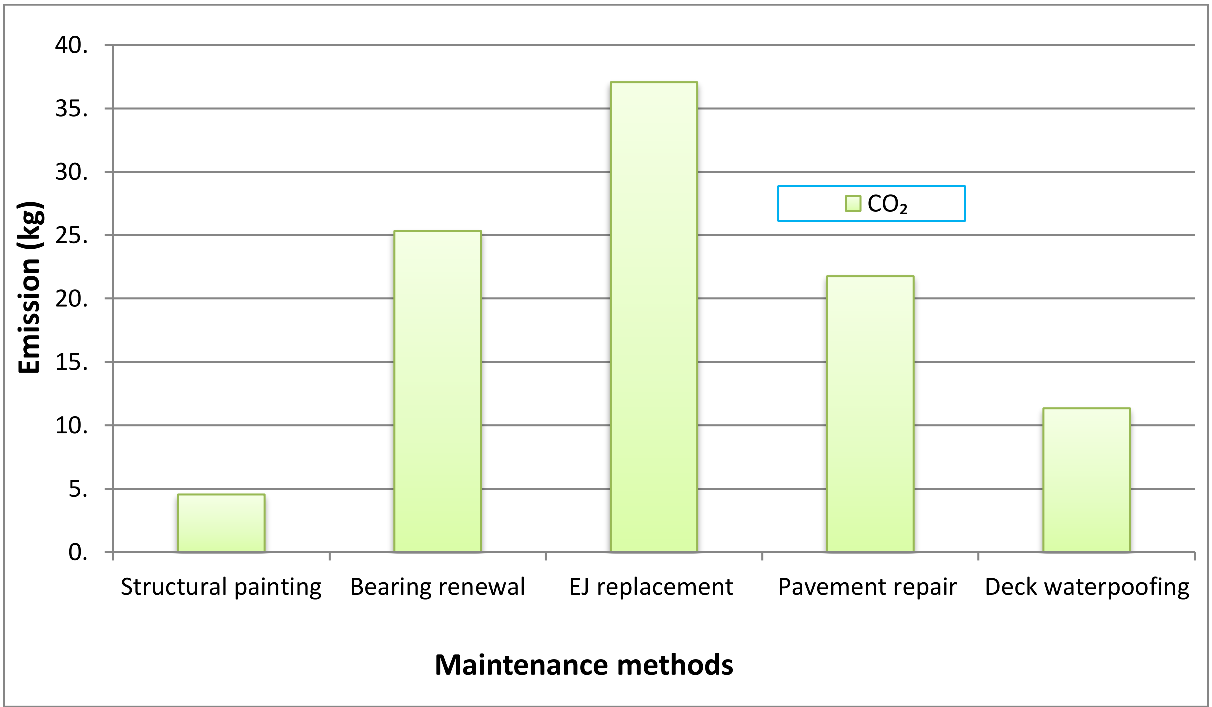

Figure 6. 4 CO_2 emissions from selected maintenance/repair methods of steel bridge

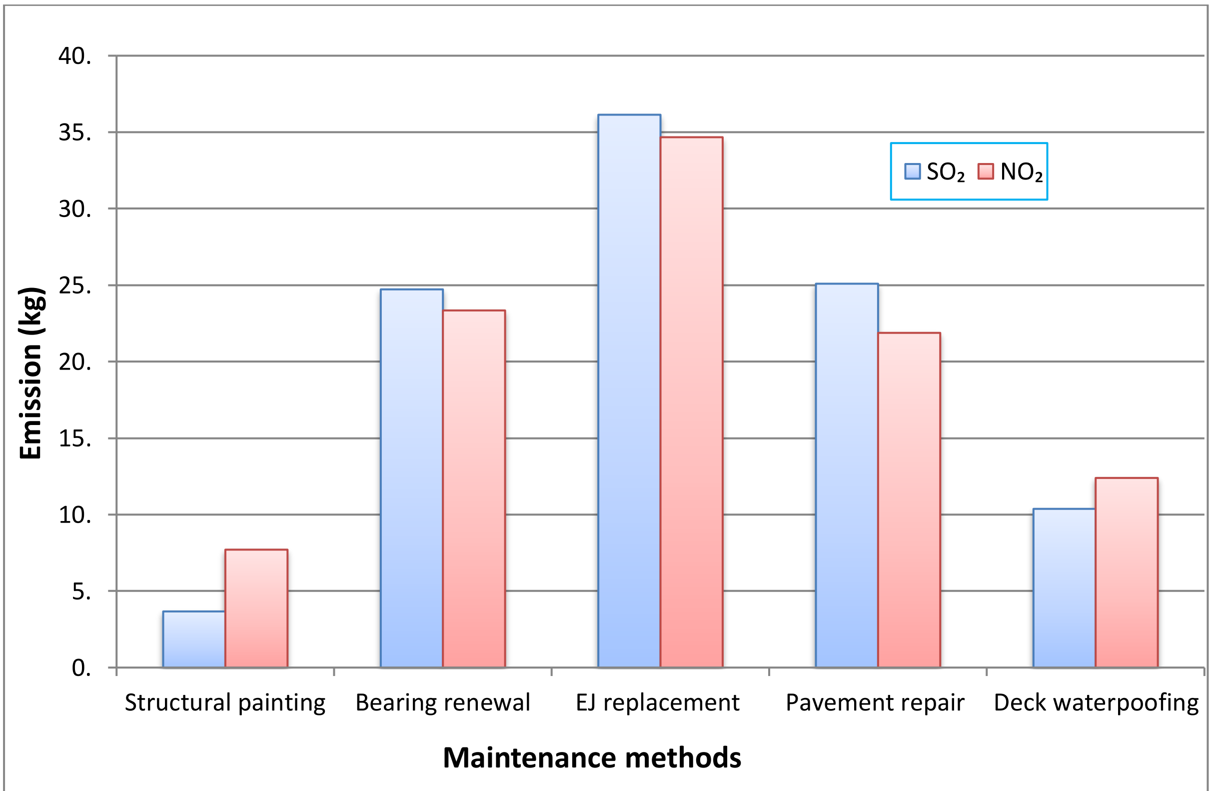

Figure 6. 5 SO_2 and NO_2 emissions from selected maintenance/repair methods of steel bridge

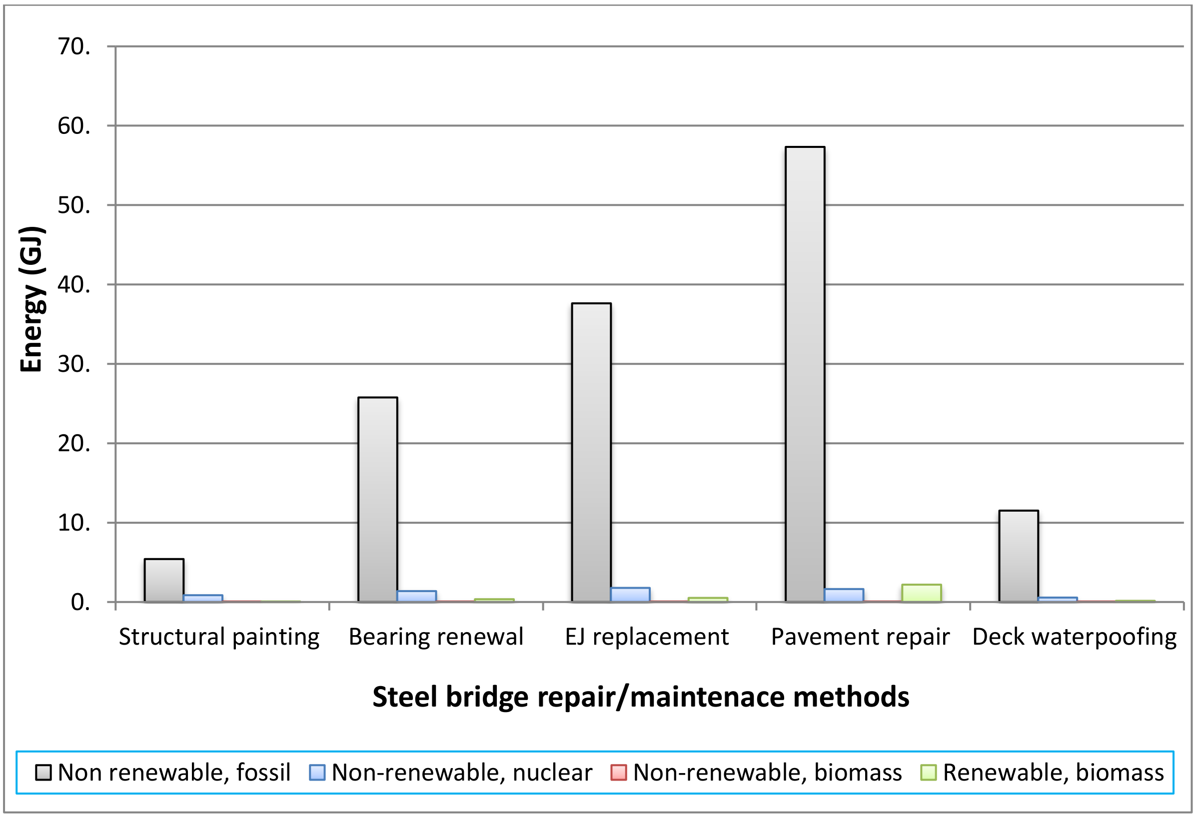

Figure 6. 6 Energy used by selected repair/maintenance methods of steel bridge

C. Masonry Bridge

Environmental results of selected maintenance methods of masonry bridge indicated that saddling has the highest CO_2 emission (58kg) as per Figure 6.7 (results were derived from analysing literature data verified by experts, see Table 5.18). Other methods had significantly low CO_2 emissions. Saddling also had high SO_2 and NO_2 emissions and used more energy (see Figure 6.8 and 6.9) compared to other selected repair methods. The result agrees with Steele *et al*. (2003), comparing anchoring and concrete saddle, where saddling had higher impact than anchoring. However, traffic delay which has the potential to increase the overall relative impact from detouring (Pang *et al*., 2015) was included in the study – Traffic delay was excluded in this study, but accounted for asphalt material.

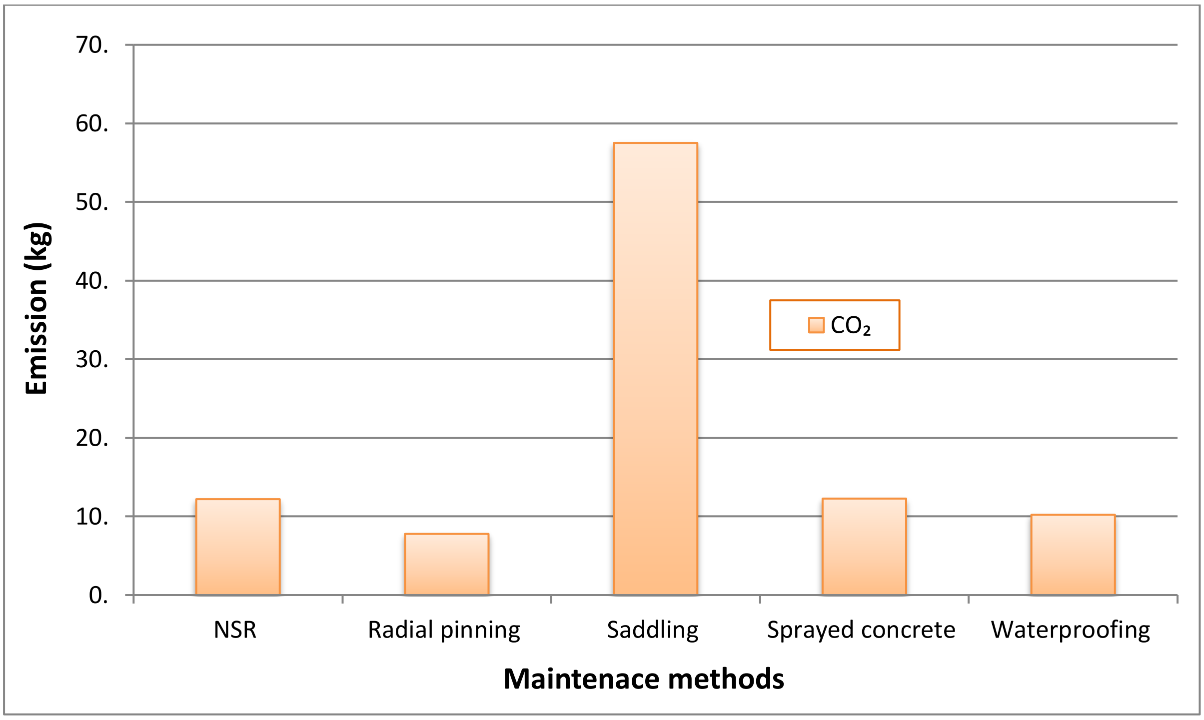

Figure 6. 7 CO_2 emissions from selected maintenance/repair methods of masonry bridge

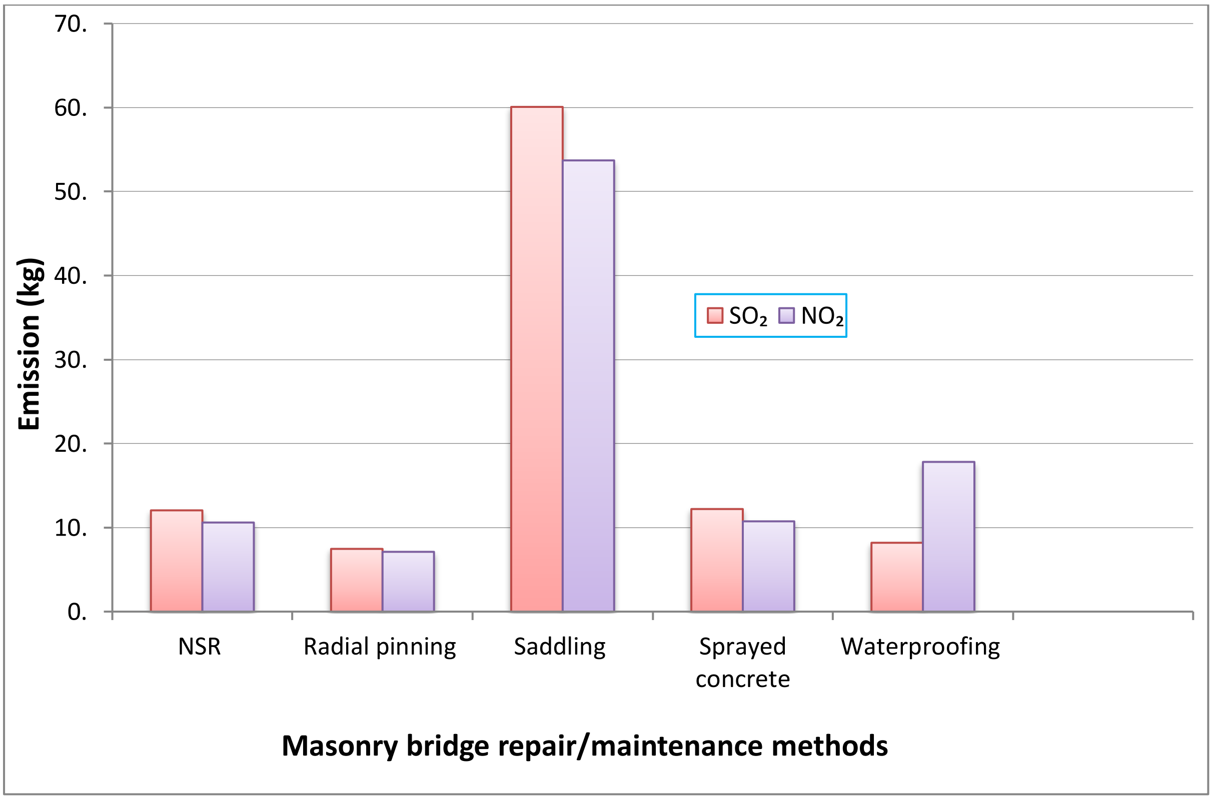

Figure 6. 8 SO_2 and NO_2 emissions from selected maintenance/repair methods of masonry bridge

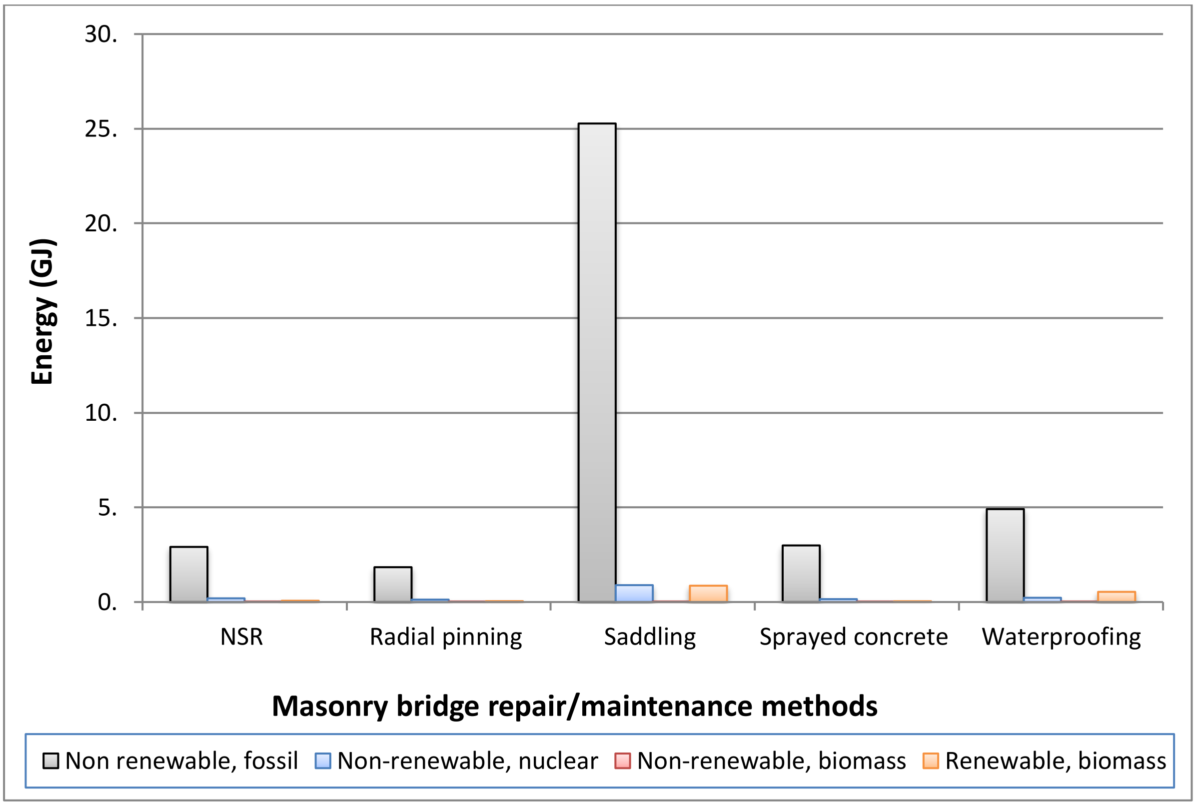

Figure 6. 9 Energy used by selected repair/maintenance methods of masonry bridge

D. Environmental Results of Combined Concrete, Steel, and Masonry

Environmental indicators for combined maintenance method for concrete, steel and masonry bridges are presented in Figure 6.10 and 6.11. Result reveals steel bridge as the highest contributors of CO_2 emission (100kg), SO_2 and NO_2, although the result were only slightly higher than concrete bridge by 10kg. Result agrees with Collings (2006), that CO_2 emissions for concrete and steel are broadly similar over their working life and that most of the CO_2 emissions during maintenance originates from resurfacing works. Masonry bridge show the lowest CO_2 emission (25kg). In terms of energy consumption, concrete bridge require the most energy (142 GJ) and masonry bridge the least energy (39 GJ) as shown in Figure 6.12.

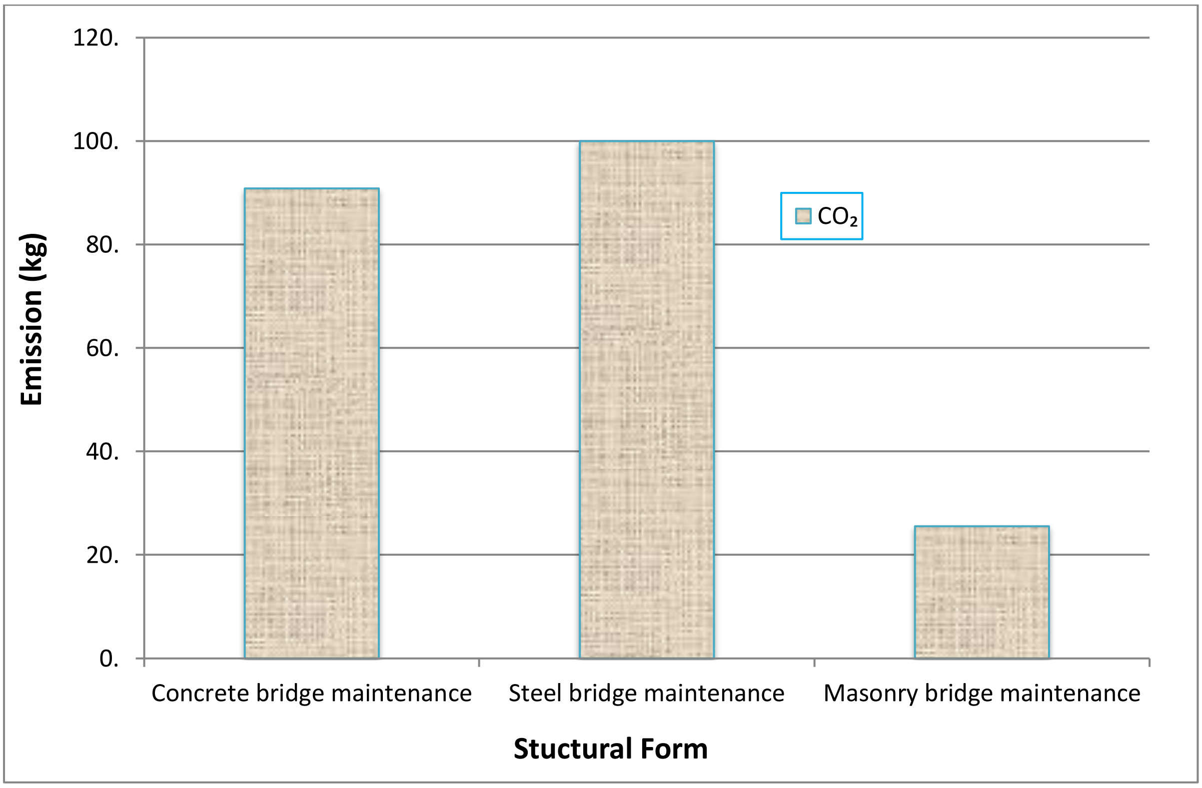

Figure 6. 10 CO_2 emissions from combined results of concrete, steel and masonry bridge maintenance

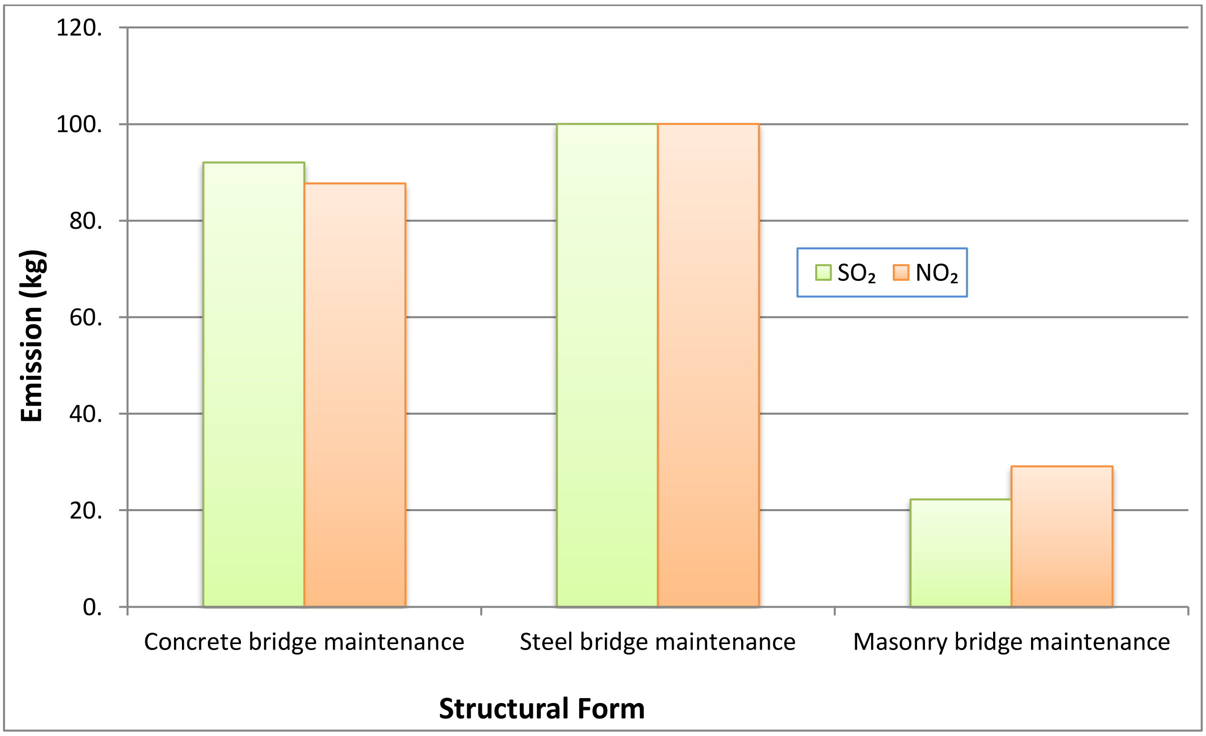

Figure 6. 11 SO_2 and NO_2 emissions from combined results of concrete, steel and masonry bridge maintenance

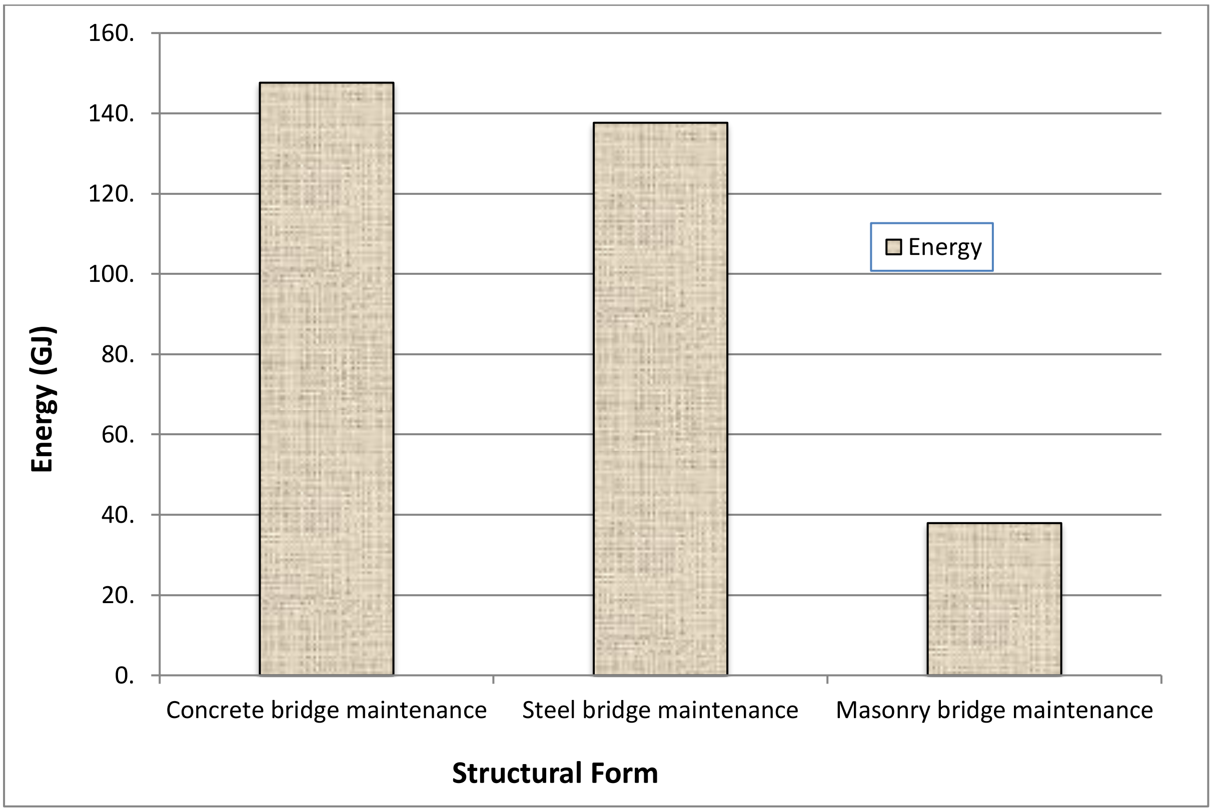

Figure 6. 12 Energy used from combined results of concrete, steel and masonry bridge maintenance

6.5.2 Characterisation Results for Selected Maintenance Methods

Characterisation for selected impact categories were conducted in SimaPro. Impact categories selected for the study are CC, OD, POF, PMF, FE, TA, MD, and FD. Characterisation results for selected maintenance methods are presented below.

A. Concrete Bridge

Expansion-joint replacement had high relative impact on CC, POF, PMF, TA, FE and MD (with 40%, 45%, 48%, 40%, 56% and 60%, respectively) as shown in Figure 6.13 and also shows expansion joint replacement has the greatest contributor to CO_2, SO_2, and NO_2, emission. Bearing renewal was the second largest contributor, followed by overlaying, deck replacement and grouting. Overlaying, had particularly high impact on OD and FD (with 47% and 45%, respectively).

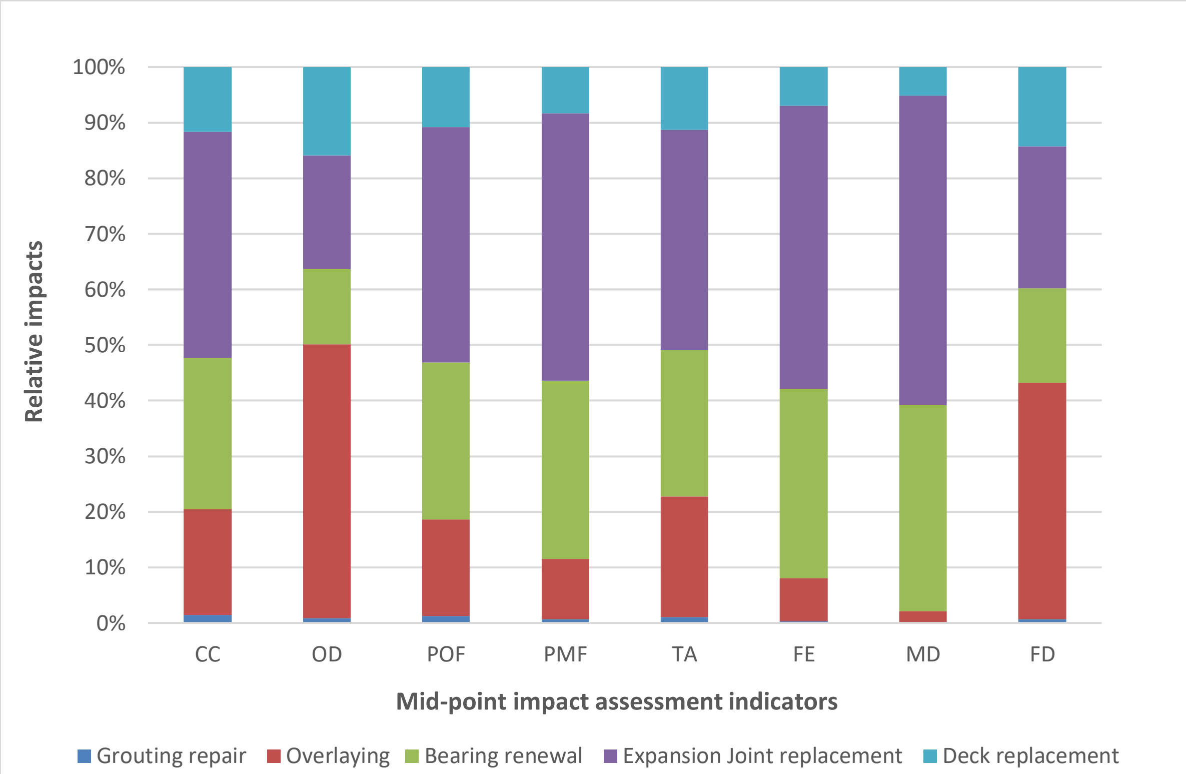

Figure 6. 13 Characterisation results for *selected concrete bridge repair/maintenance*

B. Steel Bridge

Expansion joint similarly had high relative impact on CC, POF, PMF, TA, FE and MD (with 42%, 48%, 52%, 44%, 56% and 62%, respectively) as shown in Figure 6.14. However, pavement repair had high impact on OD and FD (with 49% and 47%, respectively).

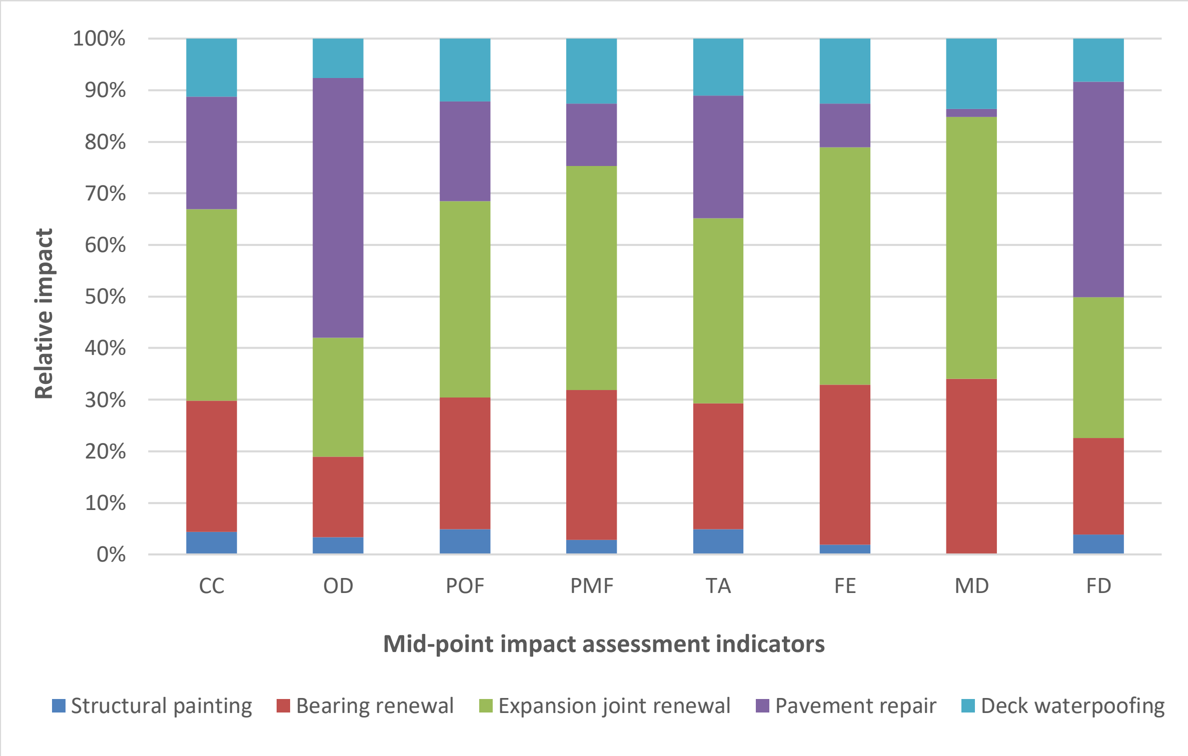

Figure 6. 14 Characterisation results for *selected steel bridge repair/maintenance*

C. Masonry Bridge

Saddling had the highest impact on all selected impact categories of CC, OD, POF, PMF, TA, FE, MD and FD (with 58%, 67%, 54%, 53%, 57%, 54, 50% and 58%, respectively), as shown in Figure 6.15. Other methods had low impacts on selected impact categories.

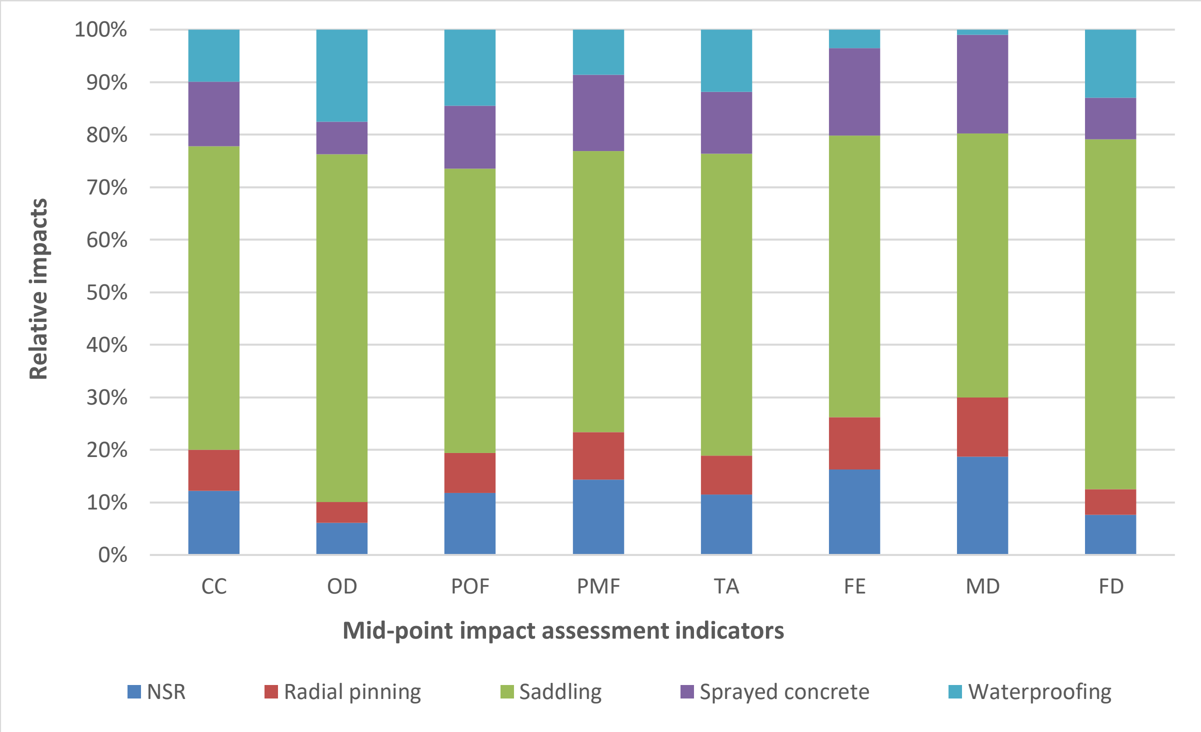

Figure 6. 15 Characterisation results for *selected masonry bridge repair/maintenance*

D. Characterisation Results of Combined Concrete, Steel, and Masonry

Combined results for concrete, steel and masonry bridge maintenance methods are presented in Figure 6.16. Result highlight steel bridge to have the highest impact on CC, POF, PMF, TA, FE and MD, followed by concrete. However, masonry bridge show the least impact on all the selected indicators.

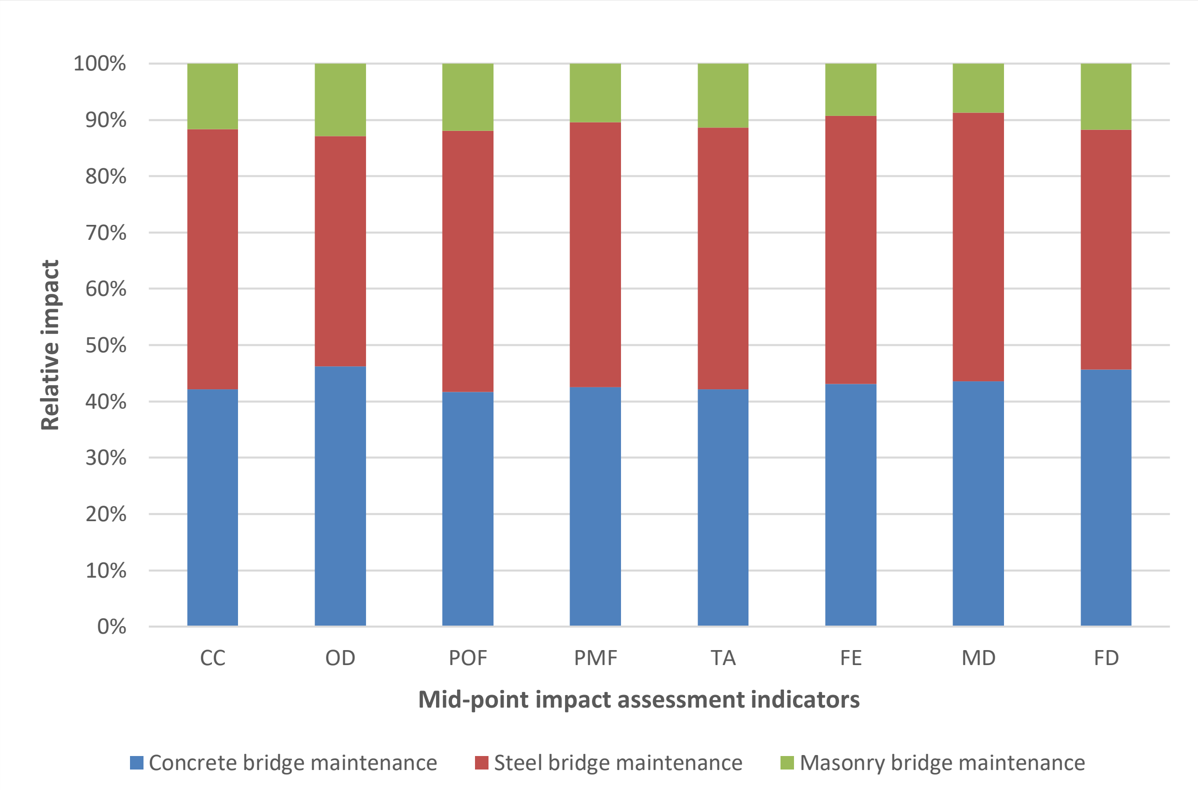

Figure 6. 16 Characterisation results of combined *maintenance methods of concrete, steel and masonry bridge*

6.5.3 Normalisation Result

Normalisation reveals the severity of the impact category on specific issues of human health, ecosystem, and resources from a reference point (Bare, 2010). The section presents the severity impact of maintenance methods on human health, ecosystem, and resources based on European scale. Human health is based on disability-adjusted life years (DALYs) and expresses the number of life years lost and the number of years lived disabled. Damage to resources is measured in surplus energy, and indicates the surplus energy required for future extraction of minerals and fossil fuels. Damage to ecosystem quality is expressed as the loss of species over a certain area, during a certain time, using the unit potentially disappeared fraction of species (PDF m^2 year). Note that normalised points are dimensionless, and are used for scoring purposes to enable comparison.

A. Concrete Bridge

Normalised result of concrete bridge maintenance methods is presented in Figure 6.17. All maintenance methods (expansion joint replacement, bearing replacement, overlaying and deck replacement) had the highest impact on resources (resource depletion), average impact on human health and little impact on ecosystem.

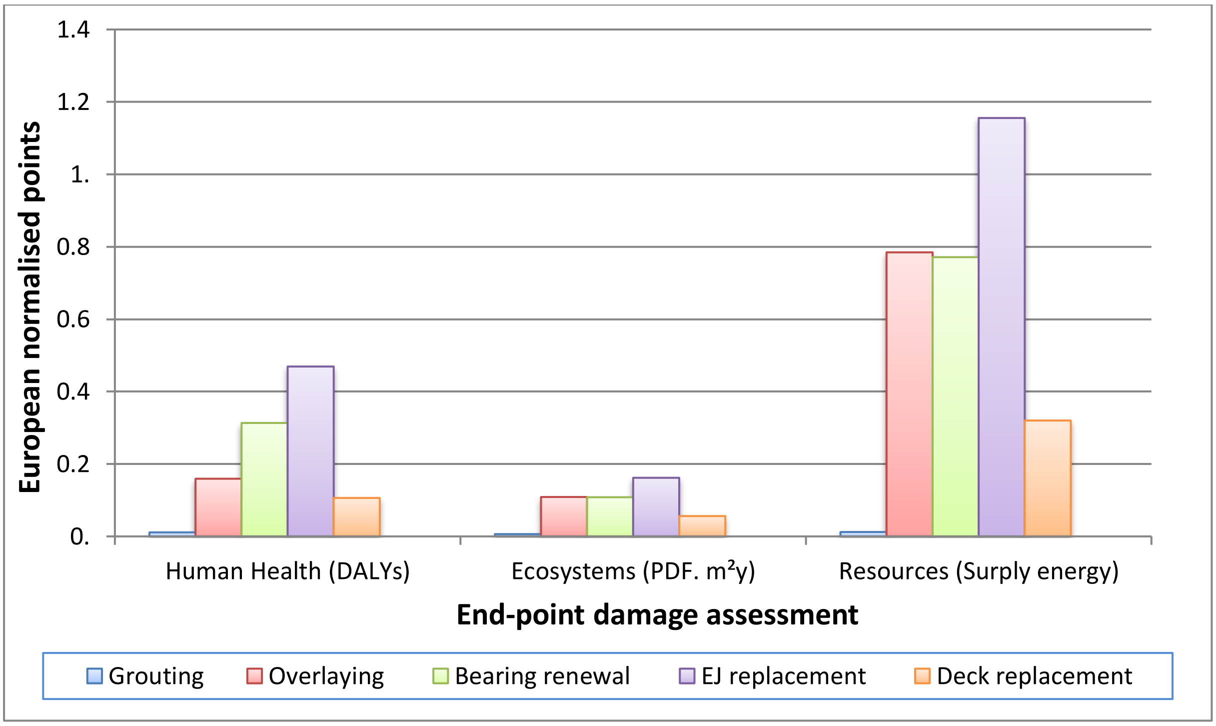

Figure 6. 17 Normalised results of concrete bridge maintenance methods on European scale

B. Steel Bridge

Normalised result of steel bridge maintenance methods is presented in Figure 6.18. All maintenance methods (expansion joint replacement, bearing replacement, pavement repair, deck re-waterproofing and painting) had the highest impact on resources (resource depletion), average impact on human health and little impact on ecosystem.

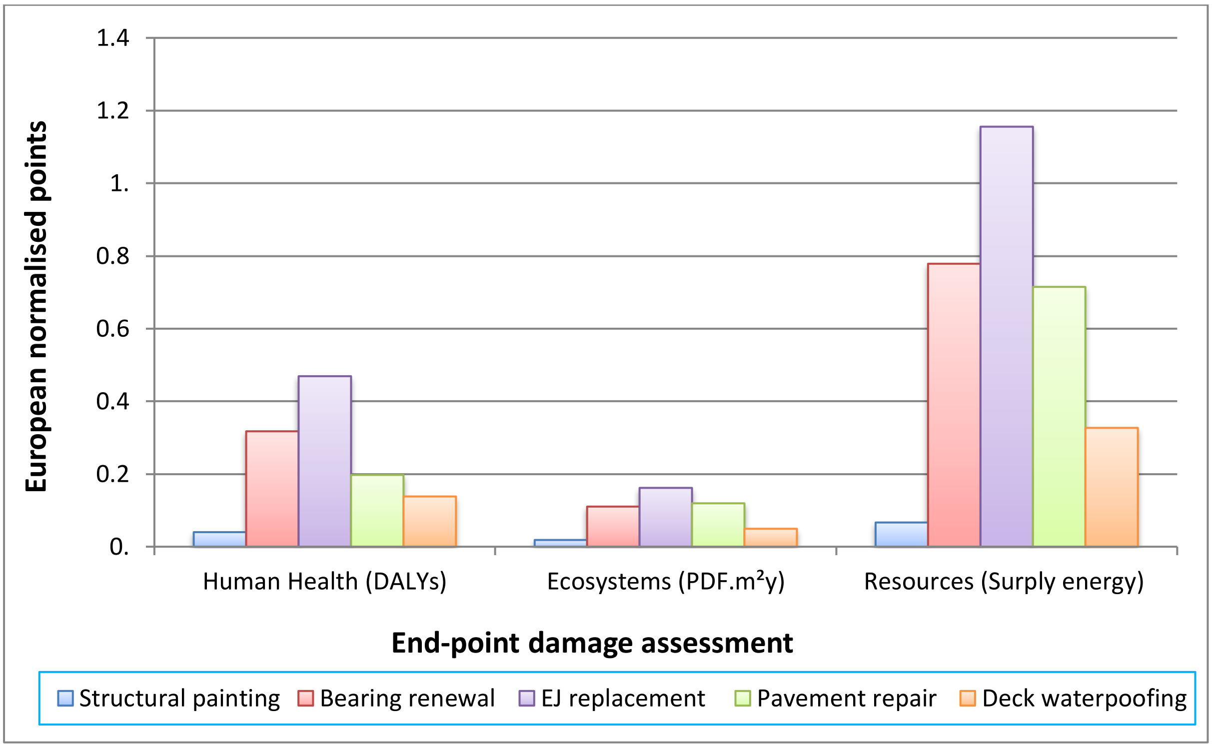

Figure 6. 18 Normalised results of steel bridge maintenance methods on European scale

C. Masonry Bridge

Normalised result of masonry bridge maintenance methods is presented in Figure 6.19. The result indicated that saddling had significant impact on resource depletion and average impact on human health and little impact on ecosystem. Other maintenance methods had very little impact on the European normalised scale.

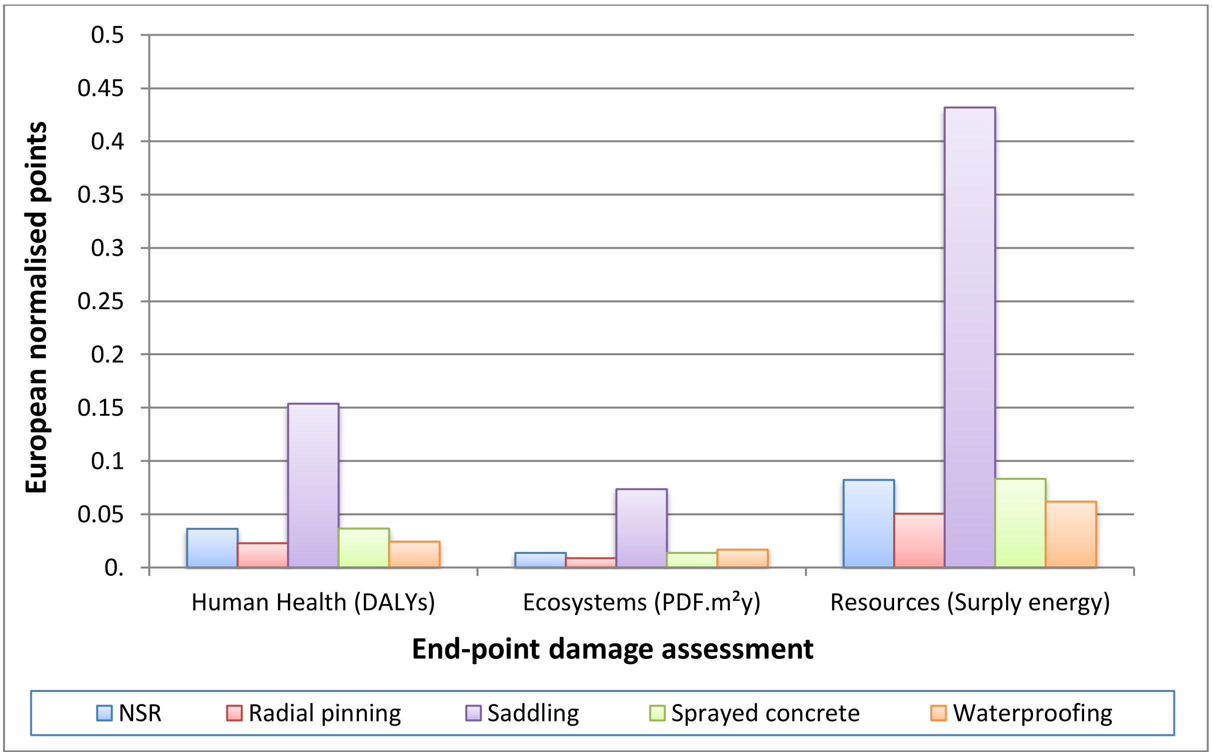

Figure 6. 19 Normalised results of masonry bridge maintenance methods on European scale

D. Normalisation Result of Combined Concrete, Steel, and Masonry Bridge

Normalised result of combined concrete, steel and masonry maintenance methods is presented in Figure 6.20. Result indicate that maintenance of concrete and steel bridge had significantly higher impact on human health, ecosystem and resources than masonry bridge. Impact of concrete and steel bridge maintenance activities are relatively similar in all aspects.

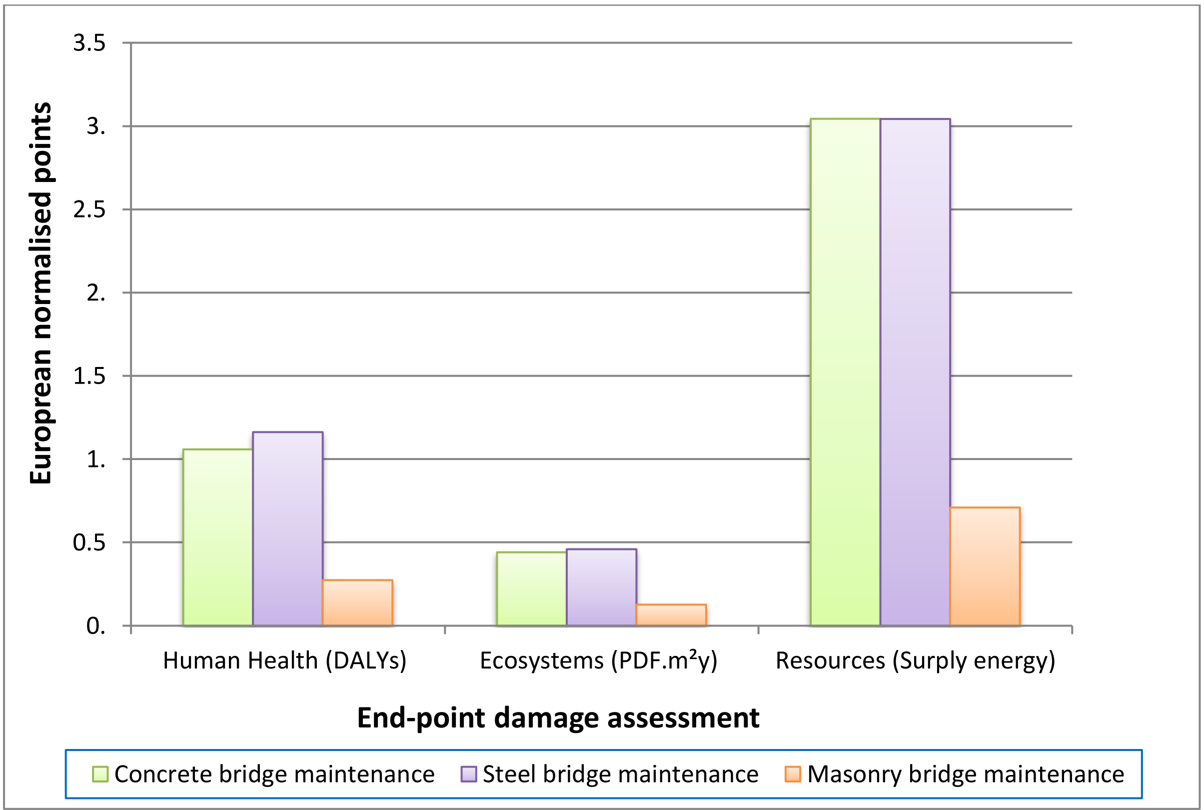

Figure 6. 20 Normalised results of concrete, steel, and masonry bridge maintenance methods on European scale

6.6 Uncertainties and Sensitivity Analysis

Input data for this LCA study were obtained from the literature, industry experts and SimaPro database. Assumptions were, however, made for input data that could not be easily identified. For example, the average transportation distance of materials from factories to site was assumed to be 16km for all maintenance activities and average fuel consumption for each vehicle was assumed to be 10 l/100 km. The assumed data will ensure fair comparison between selected maintenance methods. However, values would vary with frequency of maintenance, leading to uncertainties. Although maintenance was assumed to take place at scheduled times, it would vary from bridge to bridge and due to incidental impacts (e.g. accidents, environmental conditions, etc.). Similarly, uncertainty is also related to the use of SimaPro data, based on a European database instead of Local data. As such, Monte Carlo simulation was performed to account for the variability of input parameters. Monte Carlo simulation can estimate the variability of environmental scores associated with the transportation distance, maintenance times, fuel consumption and other input parameters. The SimaPro software allowed a Monte Carlo simulation at a statistical confidence interval of 95% to be determined. A lognormal distribution was assumed in Figure 6.16 for input data to allow the Monte Carlo simulation to identify the parameter with significant variation in respect of the result obtained (i.e. the characterisation result for the compared maintenance methods for concrete, steel, and masonry bridge). One thousand iterations were conducted based on previous studies (Parsons, 2016). Overall simulation outputs are presented in Figures 6.21, 6.22 and 6.23, comparing maintenance activities for concrete and masonry, masonry and steel, and concrete and steel at characterisation level. No new result emerged from the simulation as the result presented in Figure 6.16 was similar to Figures 6.21, 6.22 and 6.23. It therefore implies that the result obtained in Figure 6.16 has negligible uncertainty regarding transportation, frequency and fuel consumption and can be relied upon.

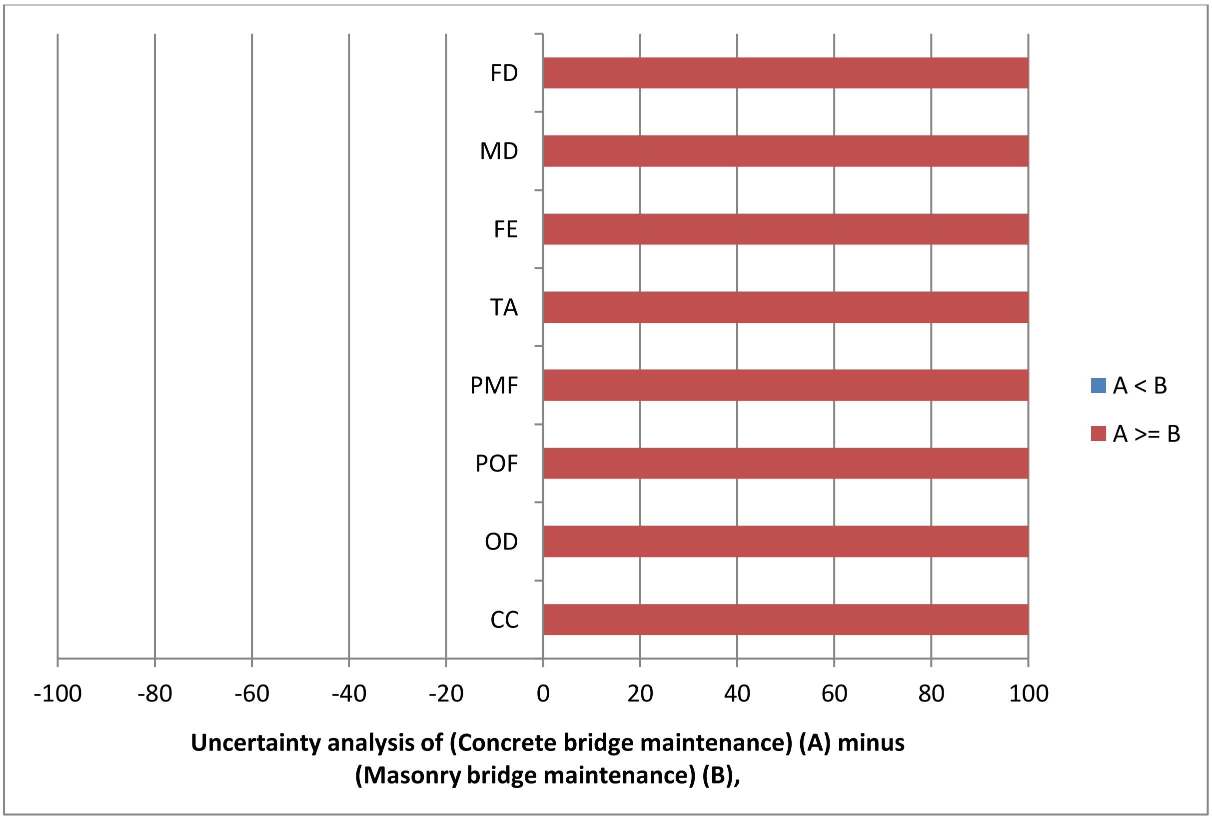

Figure 6. 21 Uncertainty analysis for compared concrete and masonry bridge maintenance

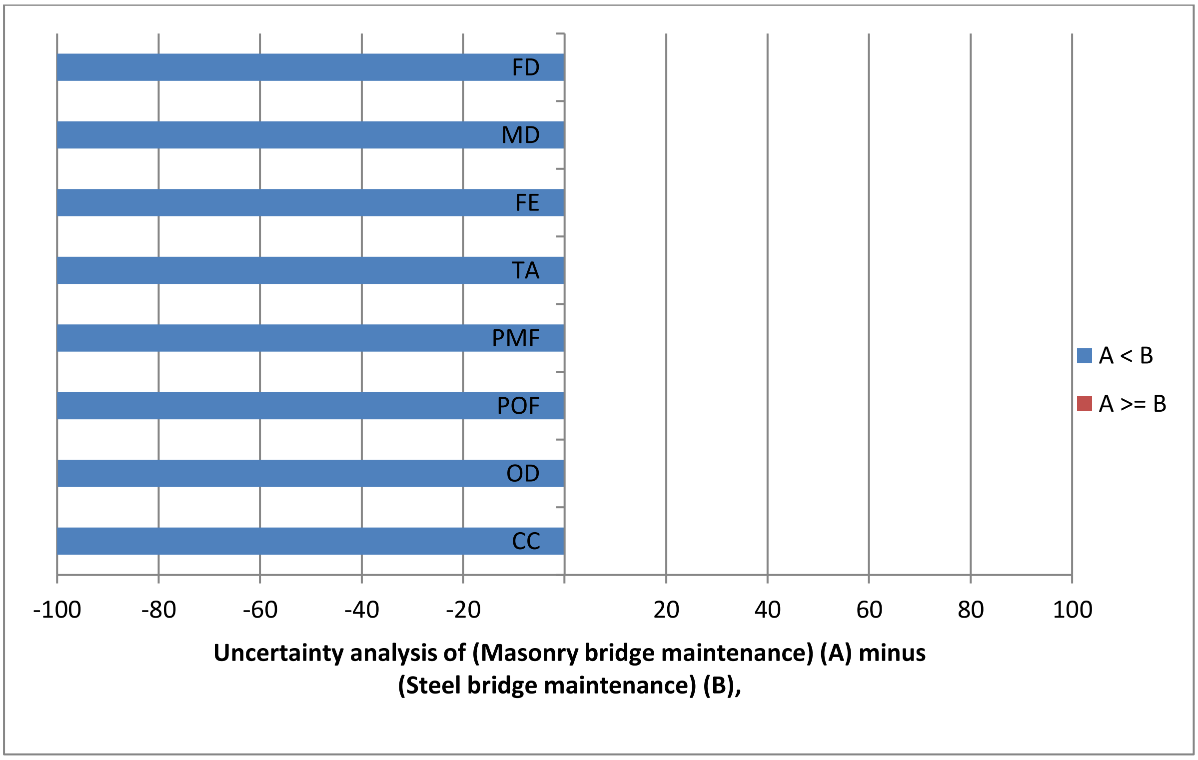

Figure 6. 22 Uncertainty analysis for compared steel and masonry bridge maintenance

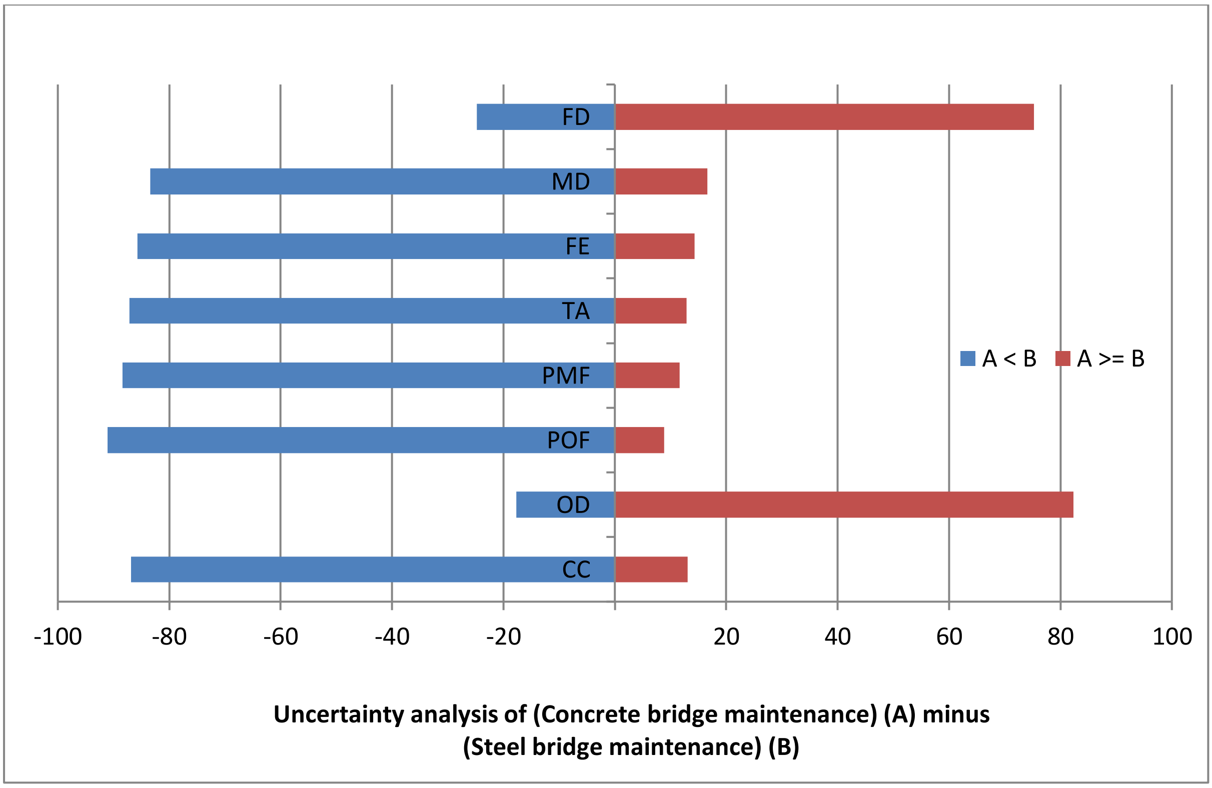

Figure 6. 23 Uncertainty analysis for compared concrete and steel bridge maintenance

6.7 Chapter Summary

The chapter presents LCA analysis for a range of commonly used maintenance methods for concrete, steel, and masonry bridges. The assessment was based on selected environmental indicators (classification), impact category indicators (characterisation) and normalisation (based on European scale). Steel and concrete bridge maintenance methods had systematically significant greater impact than masonry bridge maintenance. Impact of steel and concrete bridge works were relatively similar. The result is empirical, based on collected data from literature and consultation. Sensitivity analysis was conducted to identify the impact of uncertainties and indicated good reliability of the results. As detailed in the next chapter, the LCA results were presented to bridge experts to reveal the potential usefulness of the result and possibilities to assist sustainable bridge design.

CHAPTER SEVEN: INTERVIEW ANALYSIS AND FINDINGS

7. Introduction

The chapter presents findings from the interviews conducted and emergent themes. A detailed description of the coding process, data reduction and data display elements of the interview analysis is presented. The chapter particularly provides answers to research questions one, two, four, five and objective four of the research.

7.1 Interviewees' Profiles

In all, 21 experts were interviewed in this research, not including pilot study. Each interview lasted approximately one hour for each participant. The interviewees included nine bridge designers, eight bridge engineers, one design manager, one renewal engineer and one asset engineer. Interviewees cut across major bridge owners, clients, contractors, and consultants within the UK bridge industry. Background of participants that took part in the study is presented in Table 7.1. All interviewees had a minimum of 15 years' experience, with a university degree, which qualifies them to be suitable for this study.

Table 7. 1 Participants' Profiles

Participants	Role	Male	Category	Experience (years)	Highest Qualification
A	Bridge designer	Male	Consultant	15 – 20	BSc, MSc
B	Design manager	Male	Consultant	>20	BSc, MSc, PhD
C	Bridge designer	Male	Consultant	15 – 20	BSc
D	Renewal engineer	Male	Client	>20	BSc
E	Bridge engineer	Male	Contractor	15 – 20	BSc
F	Bridge designer	Male	Consultant	15 – 20	BSc, MSc
G	Bridge designer	Female	Client	15 – 20	BSc
H	Bridge designer	Male	Consultant	>20	BSc
I	Bridge designer	Male	Client	15 – 20	BSc
J	Asset engineer	Female	Client	15 – 20	BSc, MSc
K	Bridge engineer	Male	Client	>20	BSc
L	Bridge designer	Male	Client	15 – 20	BSc
M	Bridge engineer	Male	Consultant	15 – 20	BSc
N	Bridge engineer	Male	Contractor	15 – 20	BSc
O	Bridge engineer	Male	Contractor	15 – 20	BSc
P	Bridge designer	Male	Consultant	15 – 20	BSc
Q	Bridge designer	Male	Consultant	15 – 20	BSc
R	Bridge engineer	Male	Consultant	15 – 20	BSc
S	Bridge engineer	Male	Contactor	15 – 20	BSc
T	Bridge engineer	Male	Contractor	>20	BSc, MSc

7.2 Data Analysis

The analysis began by importing the transcribed script into the Nvivo 11 CAQDAS package. Miles and Huberman (1994) proposed three strategies for qualitative analysis, which were adopted for this study (i.e. data reduction, data display and conclusion or verification). Conclusions are discussed and presented in chapter eight and nine respectively.

7.2.1 Data Reduction

A careful data reduction process was conducted in this study. Interview generally comes with some irrelevant stories which are synonymous with qualitative studies (Miles and Huberman, 1994). As such, analysis began with data reduction, where relevant data is extracted, sorted, and organised as a large segment into relevant code (Miles and Huberman, 1994). Coding as discussed in chapter four is used in Nvivo CAQDAS package to store important extracts from the transcript. Based on the research question, data were coded at free nodes under respective overarching themes. These nodes were revised as more data were coded and a clearer picture of the dataset began to unfold. Examples of data assigned to codes are displayed in Table 7.2.

Table 7. 2 Data extract with relevant codes

Data extract	Coded for
In terms of the asset management life cycle erm you've got cradle-to-grave approach erm not something that we do look at especially where the replacement structures are in lines where existing structures are in that cycle	LCA awareness
So there is a life cycle assessment done but not formally with your decision making about what route you going done. I haven't come across a life cycle assessment where is taking into account how much CO_2 is gonna be used for the construction or during the planned maintenance of this. If that make sense, so it doesn't really come into it.	Consideration for LCA

As discussed in chapter four, an open coding was adopted for this study. The open coding allowed all relevant information including that which did not directly address the research questions to be coded. This allowed useful information to be coded, even though it did not directly address the research question but was otherwise valuable information useful for future studies. The coding process allowed the researcher to search for data similarities, differences, and patterns, which in itself is an attribute of thematic analysis employed for the study. Seven major themes and three sub themes emerged from the overall coding process. The explore function in Nvivo 13 was used to generate a visual encrypted node which housed the codes that formed the developed theme. Developed codes gave insight towards answering the research question. An initial map for the seven themes is revealed in Figure 7.1.

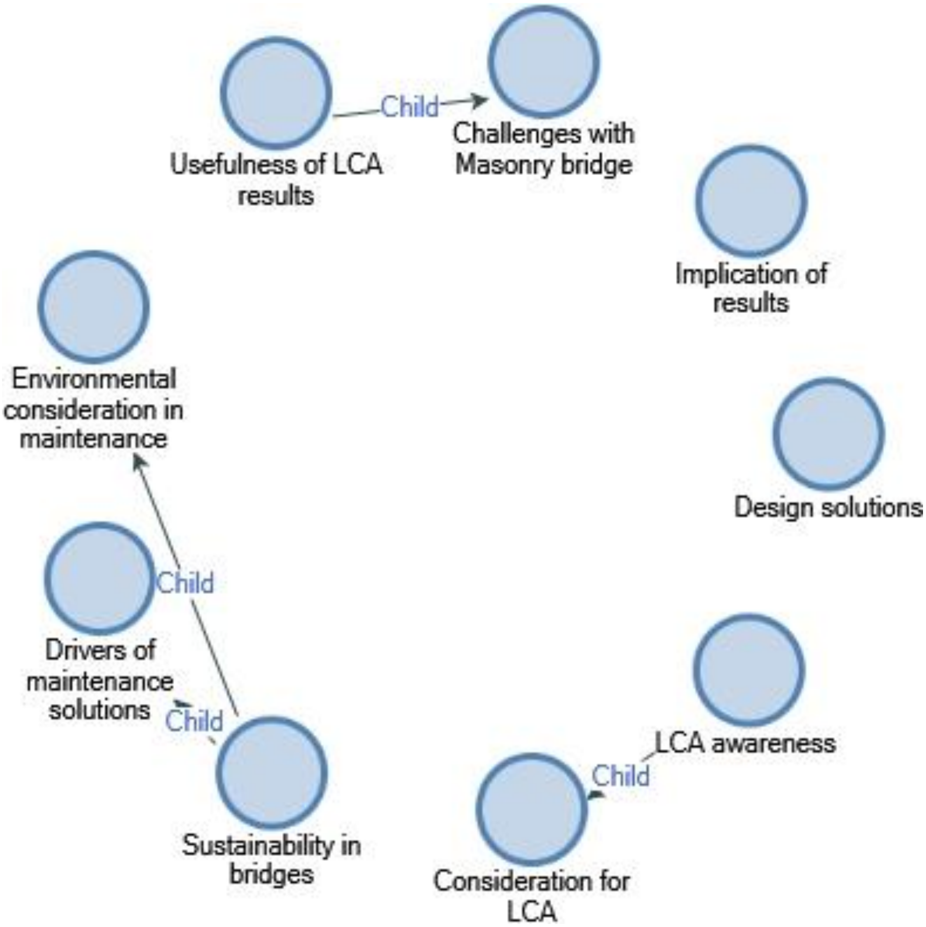

Figure 7. 1 Initial thematic map showing the major themes from the interview questions

7.2.2 Data Display

Data display is an organised and compressed representation of information, which allows effective conclusions to be drawn (Miles and Huberman, 1994). The displayed information reinforces evidence to be presented as per participants' responses to the interview question. As such, data display contributes to the validity of the data analysis process (Miles and Huberman, 1994). Pattern of data display adopted in this study is consistent with the thematic conceptual matrices discussed in Miles and Huberman (1994), in the sense that matrices reflected emergent findings across the data which were derived using the matrix coding query function in Nvivo 13. The thematic conceptual matrix was used to present relevant findings on account of the major themes. Findings are presented and discussed in subsequent sections.

Sustainability

Sustainability is an overarching theme that emerged in relation to research question one, and comprises three major themes. These are; sustainability in bridges, environmental considerations, and environmental indicators. These themes are discussed below.

a) Sustainability in Bridges

Bridge design experts consider and implement sustainability in bridge design differently. Interviewee (I) stated that '*sustainability is one of those tick box exercises to say yes we are environmentally friendly all those kind of stuff, but it depends on how you define sustainability, you want a structure which has long life which is 120 years with little amendments*.' On the contrary, Interviewee (B) points to the need to understand why the bridge is needed before commencing the design at all – '*otherwise you would be wasting materials and cost if you don't necessarily need the bridge*.' Therefore, sustainability in bridge design is considered on the basis that there is a need for the bridge. Furthermore, Interviewee (N) informs that sustainability in bridge design is considered from the aspect of access to future maintenance. Interviewee (E) argues –

'…So you design a bridge in such a way that you can get to the bearing to take out the existing bearing and replace with new one whether you think they are going to need replacement or not, you always make provisions, so they can be done.' – (Interviewee E)

Again, sustainability is considered from the aspect of quality materials. Interviewee N reveals – '… *the drive is to apply certified quality material which will provide functionality and durability for the design life which itself it's a prerequisite so you don't have to build the thing again in 20 years' time.'*- (Interviewee N)

Therefore, quality material is a sustainability component factored into bridge design for achieving a structure with longer life span with little amendments. Besides this, interviewee (P) expresses that sustainability from a contractor's perspective is considered with a cost saving approach. That is, if something is cheap then it is sustainable. Sustainability in bridge design can, however, be a casualty if cost is the motivating factor. Interviewee (D) expresses that –

'… *You could have several structural engineers designing bridge works to minimise carbon foot print but then the people who undertake the work who source the material could undermine it by bringing materials from overseas with all the transportation cost because it works out cheap for them*'. – (Interviewee D)

From the arguments presented, it can be inferred that sustainability is factored into bridge design in five key areas – need for the bridge; access to future maintenance; use of quality materials; consideration for long life with few amendments; and cost saving options.

b) Environmental Considerations

Environmental consideration theme had emerged, based on interviewees' responses on environmental awareness during bridge maintenance work, with sustainability in mind. Interviewees revealed that environmental considerations during bridge maintenance are about protecting the wildlife such as bats and badgers, and the surrounding areas. Similarly, Interviewee (E) explains that the environmental agency is quite keen on bridge maintenance work over a river and has provided rules and guidelines to ensure the aquatic ecosystem is protected. Interviewee (D) reveals that –

'… *It has always been about avoiding any harmful material from getting into the watercourses, avoiding salt being kicked up into watercourse, avoid disturbing the flora and fauna in or around the watercourse and that's always been the main environmental drive.'* (Interviewee D)

Apart from protecting flora, fauna, and watercourses, little or no attention is paid towards other environmental effects of bridge maintenance – especially for designers – as long as the structure is maintainable. Furthermore, interviewee (L) explains that environmental effect of bridge maintenance is taken less seriously, as sometimes only a small portion of the bridge needs to be replaced with like for like parts, which may not necessarily require environmental assessment. Interviewee (E) highlights –

'… *In terms of maintenance we don't think a lot about environmental effect of maintenance but we do try and think and make things that can be maintained.'*

Extracts from interviewees D, E, L reveal that environmental considerations for bridge maintenance involve protection of flora, fauna, surrounding environment and watercourses. It therefore implies that environmental concerns for bridge maintenance activities are at an incipient stage and need to be improved if the current sustainability target is to be met. This again reinforces the need for the research, as areas that require improvement are being revealed.

c) Environmental Indicators

Environmental impact indicators such as CO_2, NO_2, SO_2 and so on are now part of urgent sustainability matters in Agenda 2030 (United Nations, 2015). Therefore, it was important to consider these indicators for bridge maintenance activities – which holistically will aid UK's target to reduce CO_2 and other harmful emissions across major construction sectors (especially the transport sector) by 2020. On this premise, environmental impact of bridge maintenance emerged as a theme, to reveal issues pertaining to CO_2 and other emissions associated with bridge maintenance activities. Interviewee (D) plainly expressed that -

'… I think in my experience it is quite far from it, the primary driver for environmental in my experience has been protecting the environment especially the watercourses. In my experience when have put together repair jobs have never really taken that as a primary consideration. It's been about primary environment, secondary materials and the idea of carbon I wouldn't necessarily consider'. – (Interviewee D)

Similarly, interviewee (K) argues that environmental impact in terms of CO_2 and other emissions tends to be considered for new and large projects alone, and not necessarily for minor works. Rather, a traditional route of replacing like for like parts – standard element replacement – is taken, which does not necessarily require such assessment. Hence, it is rare to consider environmental impact of bridge maintenance for existing bridges in this regard. Interviewee (M) reveals –

'… It is more of standard element replacements, which generally has been developed over a number of years and tend to be the best economic solution. Although not that the issue of environmental impact with regard to emissions is not considered but it is down the list and not a driver'. – (Interviewee M)

From the arguments presented, it can be inferred that CO_2 and other environmental indicators are minimally considered for bridge maintenance activities. However, the LCA envisaged to improve the sustainability of bridge design is heavily based on these environmental indicators. Hence, it will be key to clarify why these environmental indicators are rarely considered or omitted for existing bridges.

Structural Design

Structural design overarching theme emerged from research question two and embeds three major themes. These are; structural and maintenance decisions, drivers for maintenance solutions, and new approaches.

a) Structural and Maintenance Decisions

Emerging from the interview question two are issues relating to drivers for structural and maintenance solutions. Interviewees revealed that clients are key decision makers, and are largely driven by construction cost and long-term maintenance cost. According to interviewee (H) –

'… *Clients make decisions on structural solutions and decide the overall choice between concrete, steel and masonry structures and decisions are generally based on cost implication on the organisation'*. – (Interviewee H)

On this account, interviewees who are bridge designers revealed that they have approached most of their designs with the aim of minimising long-term cost implications for the clients. Interviewee (H) enlightens –

'… *Any client we work for likes to have a bridge that requires as little maintenance as possible so they don't have to keep going back and forth to repair them. In which case we design the structural parts and select materials that have low maintenance'*. – (Interviewee H)

It can therefore be inferred that decision makers of structural designs are clients within the bridge industry, and they are mainly driven by initial construction and long-term maintenance cost. Consequently, bridge designers also have started to approach their designs with the hope of minimising long-term cost implications.

b) Drivers for Maintenance Solutions

Drivers for maintenance emerged when interviewees began to discuss factors that currently influence their maintenance choices. These factors were revealed with the matrix coding query (presented in appendix 8B2). Interviewees highlighted finance, speed of completion, funding choices, structural efficiency – in terms of functionality, buildability (being safe to build), maintainability, minimal disruption for running trains, construction method and constructability – as drivers of maintenance decisions. In terms of finance, speed of completion and minimal disruption, interviewee (J) stated –

'… *the stuff is more financially driven rather than environmentally driven and we are also constrained by speed of completion because we've got 50hrs to replace a structure in order to avoid less disruption to the train lines'*. – (Interviewee J)

Furthermore, with regard to funding choices, Interviewee (L) reveals –

'*… When we have a programme of work to do, how we go about that and the choice we make is influenced by – does that affect our funding or not, if it does affect our funding, we do it as we've always done it. If it starts to affect or reduce our funding or gives us the need to increase our funding then we change the way we work, it is as simple as that really.'* – (Interviewee L)

Based on this, it is imperative that other pressing factors are considered for making bridge maintenance decisions, even though not all are considered with sustainability at heart. This conclusion reinforces why environmental impacts of bridge maintenance actions in terms of environmental indicators (such as CO_2 and other emissions) are minimally or not considered for bridge maintenance work.

c) New Approaches

A theme emerged in the area of approaches taken to minimise future maintenance cost. The matrix coding query revealed interviewees' views on current approaches, materials and methodologies used or envisaged to reduce future maintenance cost (shown in appendix 8B3). One of the approaches includes designing part of structures that require minimal routine maintenance. In other words, activities such as bearing replacement will be minimised. Interviewee (F) expresses that –

'*… We know that bearings have a typical life of forty years and if you are trying to make it last a hundred and twenty years you need three sets of bearings so we can go about designing with less bearings or low bearing.*' - (Interviewee F)

However, having fewer bearings comes with some disadvantages, such as an additional structural performing member will be required instead. Based on this, there is a shift towards integral bridges which eliminate the need for bearings or extra performing members. As a matter of fact, interviewees enlightened that UK Highway England and West Scotland spearhead the use of integral bridges for certain length of the bridge, in order to minimise the maintenance effect of joints and bearings of concrete and steel bridges. Interviewee H further reveals –

'…. *We can make integral bridges instead of one that needs bearings and clients like that because they don't have to manage or replace them in the future'*. – (Interviewee H)

Furthermore, weldering steel has currently been introduced, over the traditional painting system, in which case the 25 years interval generally assumed for painting is eliminated. Interviewee M explains –

'… We are moving *towards something that is maintainable as possible for instance weldering steel is the one that is used a lot now, going forward just that you wouldn't need to go and repaint it'* – (Interviewee M)

Moving forward, the industry is beginning to consider fibre reinforced polymers (FRP) modular bridge deck for footbridges – as revealed by interviewees L and M – which is considered great from a maintainability point of view. This area is relatively new and has not been explored in detail; as interviewee (M) explained, there is no current data on it from the longevity perspective. Moreover, it is only being envisaged for footbridges now, and not for under bridges due to its flexible nature.

LCA Awareness

LCA awareness overarching theme emerged from research question four and embeds one major theme (that is, LCA amongst designers). The theme revealed the state of LCA awareness in bridge design.

a) LCA Amongst Designers

The matrix coding results presented in appendix five revealed that Interviewees generally showed little or no awareness of LCA. However, they claimed it was embedded in the context of whole life cost (WLC). WLC is, however, outside the scope of the research. Designer Interviewees claimed that major clients engage with WLC issues for decision making, before getting involved. Interviewee (K) reveals –

'… *If we decide to replace it, part of our renewals team, we pass the bridge onto effectively program manage all of the replacement works, but part of their scope and tender submission or things like that would have life cycle cost within it, life cycle maintenance and all that kind of stuff within it and helps us decide what the best option is.*' – (Interviewee K)

Interviewee (D) further expresses that –

'… *There is a life cycle assessment done but not formally with decision making about what route you are taking. I haven't come across a life cycle assessment where it is taken into account how much* CO_2 *is gonna be used for construction or during a planned maintenance. If that makes sense, so it doesn't really come into it'*. – (Interviewee D).

However, a design manager among the interviewees revealed that proving a structure's environmental performance in terms of CO_2 and other environmental indicators – offered through LCA – is currently not an actual design requirement. Furthermore, interviewee (L) expresses that LCA may soon be an essential part of the decision-making process, as funding bodies are beginning to reward projects that demonstrate substantial environmental life cycle performance in terms of emissions. Interviewee (J) points out –

'… *Sustainability is a big issue at the moment and is a key factor when designing new structures in terms of environmental impact assessment. If you can prove that your option is low or less impactful, then it would certainly be favourable by funding authorities. May be cost a little bit more but being a greener structure, that would help because cost these days doesn't mean we should be skimping out and creating problems latter on'* – (Interviewee J)

Therefore, it is evident that LCA is currently low, in terms of usage and awareness amongst bridge designers and amongst bridge experts generally. Yet, there is a feeling that LCA may soon be part of the decision-making process, as funding bodies are craving to fund greener projects. In addition, tenders with LCA results stand a better chance of selection – which would seem to consider life cycle environmental impacts of emissions.

LCA Results

Part of the research strategy was to present the results derived from chapter six to bridge design experts to obtain their views on the relevance of those results during bridge design. Therefore, the LCA results' overarching theme emerged from research question five and embeds three major themes. These are; usefulness of the results, challenges with masonry bridge, and implication of results.

a) Usefulness of the Results

The emergence of masonry bridge as being less environmentally impactful was a key usefulness of the result according to the matrix coding result in appendix eight. Chapter six revealed environmental impact of masonry arch bridge – life-cycle maintenance – as significantly low compared to concrete and steel bridge life-cycle maintenance. While interviewees expressed their surprise over the result, some were happy about their initial feelings about masonry structure, now backed by facts. Interviewee (D) revealed –

'… *I'm actually not surprised at all, this result makes perfect sense when you consider the nature of maintenance of masonry structures. It is generally repointing and replacing bricks and stones is not that big. With the concrete and steel am also really not surprised. Steel has an energy intensive, producing steel is energy intensive, is energy intensive to get the ore out of the ground, is energy intensive to sort and is actually intensive to turn the steel into beams and bars and as well producing concrete that's also energy intensive as well*.' – (Interviewee D)

Furthermore, interviewees revealed the emergence of expansion joint as a major contributor of environmental impact as another usefulness of the results. Expansion joints are, however, currently knocked out with the introduction of integral bridges as mentioned previously. Hence, the result derived further justifies the need to eliminate expansion joint, although interviewee (M) argues that the success of integral bridges is limited to highway structures and not railway structures, where plate and ballast are used in place of expansion joint. Hence, the knowledge from the results is useful to decision makers of highway bridges.

Interviewees also identified the usefulness of the results as enlightening to decision makers, persuading them not to pay attention to cost, methodologies, and functionality alone, but to equally consider long-term material consumption, which is an integral part of environmental impact in terms of energy usage. Interviewee (D) expresses that –

'… *The focus is so much on choosing the right design, the right methodology, but there is also the actual production material that should be taken into account'* – (Interviewee D)

Finally, interviewees revealed that the result could be used to justify between concrete, steel, and masonry structures, especially for small span footbridges. Interviewee (P) highlighted –

'… *There are a lot of small concrete footbridges, where you could quite easily have built a masonry bridge instead. I think that's quite an interesting thing to note*.' – (Interviewee P)

Hence, this section highlights a significant contribution of the research to the body of knowledge, which should be readily explored by key decision makers in highway and railway bridges.

b) Complementing the Results

Interviewees argued the need to provide extra information to complement the result of LCA (matrices query result presented in appendix eight). Interviewees claimed that the extra information will strengthen the LCA result when making a proposal for a new bridge. Extra information required by Interviewees includes;

1. Associated maintenance cost for the same span of concrete, steel, and masonry bridge

2. Associated construction cost and environmental impact for the same span of concrete, steel, and masonry at construction phase

Interviewee (P) explains –

'… *In going forward, it would be interesting to know what the construction cost added in not necessarily the value is the same proportion, you know, but will masonry still be the best by a long way or does the construction cost still make masonry bridge still the best but not quite as much or does the construction cost actually make masonry arch a lot worse in terms of whole life cost*. *So over that difference between, concrete and steel I can show that actually steel can be better in long term and or whatever the case may be and that's exactly the life cycle values I can put in front of a client*'. – (Interviewee P)

Apart from this, interviewees R, T and U revealed that LCA midpoint indicators (that is; CC, OD, POF, and so on) are too complex to fit into a design process. However, the endpoint indicators (human health, ecosystem, and resources) can easily be integrated. Interviewee (R) enlightens –

'… *Indicators like carbon because that's what most engineers are conversant with and say this end-point categories the human health, ecosystem and especially the resources might be worth having in the design process so we can have it in the scoring system like we score other things. But having these other indicators the mid-pint indicators might be too much*'. – (Interviewee R)

c) Challenges with Masonry Bridge

Although masonry bridge was the least environmentally impactful structure (from a maintenance perspective), it does not override the prospective challenges that limit their usage. Result of the matrix coding query for challenges with masonry bridge is presented in appendix eight. Firstly, interviewees cited span limitation as a core constraint of masonry arch bridge. Interviewee (S) enlightens –

'… *It's interesting that the masonry one has come out significantly less than the steel and concrete. But not many clients would particularly want a masonry bridge, but more information you can back it up in terms of these numbers it is probably a stronger case to present when people are pushing for sustainable solutions you probably limited to your span*'. – (Interviewee S)

Secondly, interviewees envisage that the initial construction cost and environmental impact of masonry bridge would be very high, being very labour intensive. Interviewee (E) asserts –

'… *I think the initial construction cost and environmental impact on that would be quite condemning, it's also very manual intensive construction and I suspect, that makes the cost, if nothing else disproportionate*'. – (Interviewee E)

Thirdly, from a railway perspective, interviewees revealed construction speed as a key constraint towards the use of masonry. Interviewee (M) reveals –

'… *Masonry have lasted for years but impossible to maintain if you need to replace it on the network 'cause you can't rebuild the arch because it would take too long so that's why you end up replacing with steel or concrete deck which aren't as good.'* – (Interviewee M)

Besides this, Interviewee (J) highlights that only 50 hrs is allowed to replace a structure on the railway network, which will not be realistic, if a masonry bridge is considered. To buttress this, interviewee (K) explains –

'… *We've got to make sure we could put a structure in that can be put in quickly and is structurally sound straight away and that's where even if the environmental effect of a masonry arch are much less. For us we potentially negate it because of the financial demands for shutting the line, it would cost us a lot of money so that's why we have to do the balance of what we can deliver*'. – (Interviewee K)

In spite of these constraints, interviewees revealed the advantages and benefits of masonry arch bridge solutions over concrete and steel bridge solutions. Interviewees revealed that masonry bridges last for a very long time with minimal maintenance. Interviewee (P) asserts –

'… *my perception is that masonry arch bridge only gets repaired when they have failed whereas the concrete bridges you are expected to have to do something with them in the course of 120 years*' – (Interviewee P)

In addition, interviewees revealed that masonry bridge materials can be locally sourced and transported. Interviewee (L) asserts –

'… *from my opinion they are environmentally sustainable, 'cos you got a lot of masonry arch structures out there and have been out there for 300 years and with very little maintenance on them and they come from naturally sourced materials so quite easily local material and minimal transport. So, you could see that masonry structures are quite good*'. – (Interviewee L)

Therefore, it is argued that despite the constraints presented in the use of masonry arch bridge, there are appreciable long-term benefits. However, the constraints may be overcome with additional information.

A sophisticated map that captured all the developed themes and sub-themes and showed links with an overarching theme is revealed in Figure 7.2.

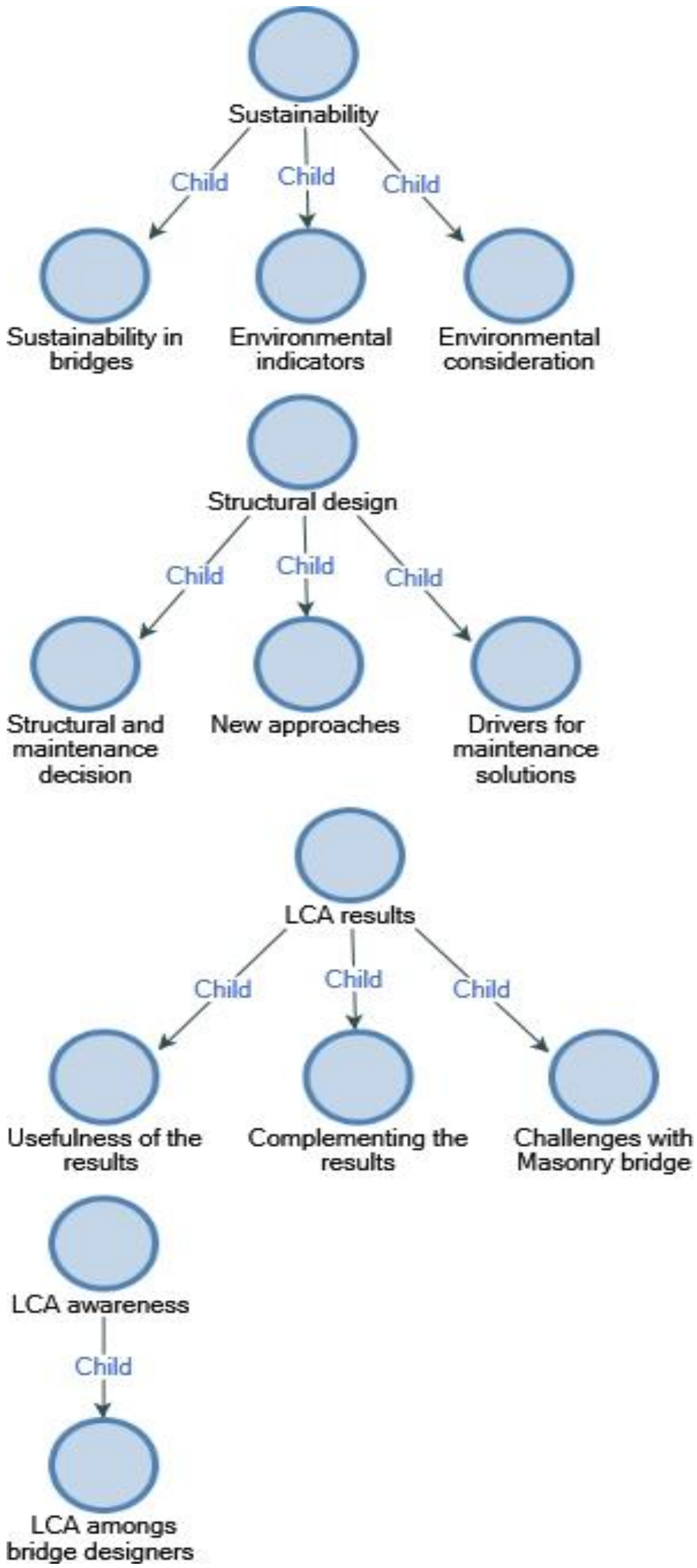

Figure 7. 2 Developed thematic map showing overarching theme, major themes and sub-themes extracted from the interview questions

7.3 Chapter Summary

The chapter presents the analysis of data collected in the interviews and relevant findings. Emerging from the interview analysis were four overarching themes and ten major themes. Need for the bridge, access to future maintenance, quality materials, and long life with little maintenance and cost savings were revealed as a generic way of thinking about sustainability in bridge design. However, environmental emissions such as CO_2, NO_2, SO_2 and so on are not usually part of sustainability thinking. Rather, protection of flora, fauna, surrounding environment and watercourses take precedence.

Furthermore, finance, speed of completion, funding choices, structural efficiency (in terms of functionality, buildability, maintainability), minimal traffic disruption, and construction methods were revealed as factors that gain precedence for decision making, though not all are considered with sustainability at heart. Considering the complexity already embedded in these factors, bridge designers will naturally struggle to recognise such aspects as environmental issues during design.

Significantly, the chapter reveals the low popularity of LCA among bridge designers. Hence, using LCA for bridge design decision making is still a very low priority. However, LCA stands a chance of gaining wider recognition among designers, as funding bodies are beginning to reward projects that incorporate elements relating to life cycle emissions at the tender stage, although it is not an actual design requirement. In addition, the chapter presented that emphasis should not be placed on design methodology alone, but also on material production, which is the genesis of environmental pollution. Finally, it was revealed that, despite masonry bridge being that most environmentally sustainable in terms of life-cycle maintenance, issues relating to span, initial construction cost, and speed of completion appeared as a major barrier. In spite of these barriers, masonry bridge was recommended to be the best for small span footbridges.

In conclusion, major findings and contribution to knowledge have been revealed. Hence, the next chapter will discuss these findings in light of the existing literature, where after recommendations for improvement will be developed.

CHAPTER EIGHT: DISCUSSION OF FINDINGS AND DEVELOPMENT OF RECOMMENDATIONS FOR THE INTEGRATION OF LCA IN BRIDGE DESIGN

8. Introduction

The chapter discusses the research findings and presents key recommendations for incorporating LCA of bridge maintenance methods into bridge design. Similarities and divergence between research findings and existing knowledge are discussed. The chapter is divided into three main sections: discussion of findings (8.1); deductions from discussion (8.2); and development of recommendations (8.3).

8.1 Discussion of Findings

Findings were mainly derived from LCA and interview analysis conducted in chapter six and seven of the study. Findings are discussed under the main research questions and compared with extant literature.

8.1.1 Research Question One *(What sustainability criteria are factored into new bridge design?)*

Literature revealed a lack of clarity on sustainability requirements for infrastructure projects (Willets *et al*., 2010; Gilmour *et al*., 2011; Wessels, 2014). The bridge industry for one is seriously lagging behind (Du and Karoumi, 2014). Interviews with experts unveiled five areas (depicted in Figure 8.1) where sustainability is appraised in bridge design. Unfortunately, sustainability issues rarely go beyond these areas. Elements of the triple bottom line approach (environmental, economic, and social) need to be fully incorporated. For instance cost, programme, aesthetics, constructability, health and safety, maintainability, environmental issues and so on need to be considered (Collings, 2006). At this time, areas revealed in the interviews only cover economic and social aspects in some way, but not environment. Though the areas identified agree with Zhang (2010), yet, there is need to consider more environmental matters, as other sustainability elements depend on it to thrive (Selmes, 2005; Ainger and Fenner, 2014). Attention is increasingly being drawn to environmental matters stemming from the risk and uncertainty of resource depletion, CO_2 emissions and other GHG matters (UN, 2015), yet, they are not being considered as essential design criteria in bridge maintenance work. Interviews revealed that protection of flora, fauna, surrounding environment and watercourses are the only sustainability consideration accorded to bridge maintenance works, although these checks are a statutory EIA requirement, and align with Yeang's (2010) recommendation for achieving a green built environment. Environmental emissions (such as CO_2, NO_2, SO_2 and so on) from the actual maintenance work are still being neglected. The LCA analysis conducted revealed how impactful some commonly applied maintenance actions were, which may have been certified ok on the basis of statutory requirement. It is advisable to consider the life-cycle impact of proposed maintenance actions, as detailed life-cycle analysis can reveal the most sustainable maintenance option. For instance, Giustozzi, Crispino and Flintsch (2012) compared three types of pavement options, and the most cost-effective option also had the most environmental impact. The question then for clients, bridge owners, policy makers and designers is this, is it about cost or a safer future? The bridge industry, therefore, needs to move away from the traditional cost driven approach and embrace a more environmentally friendly approach, especially at the design stage where every choice will affect the long-term sustainability performance of the bridge.

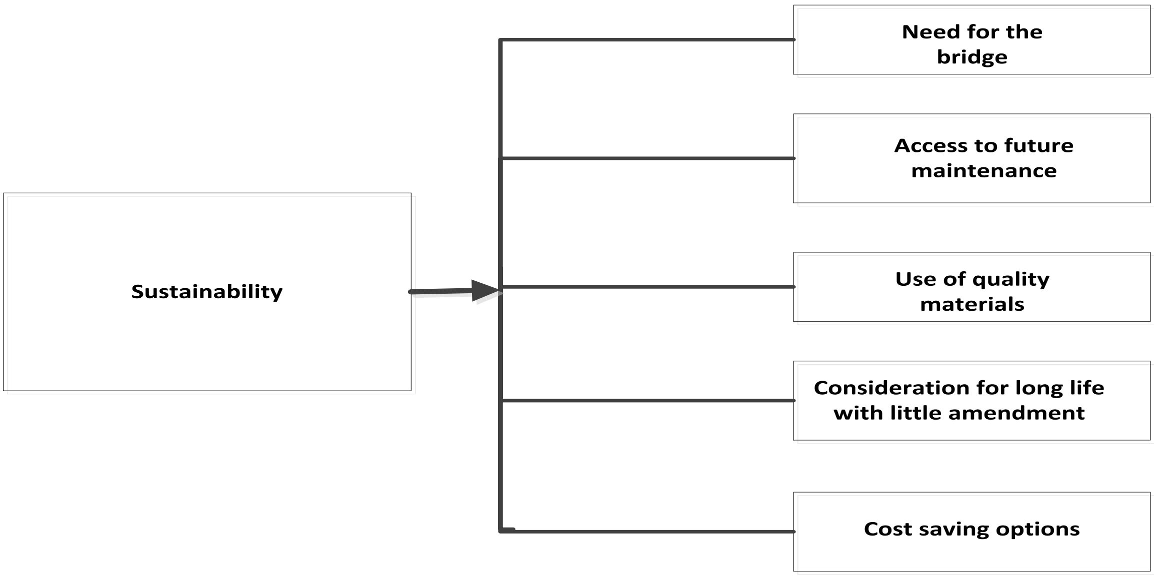

Figure 8. 1 Sustainability issues considered in bridge design

8.1.2 Research Question Two *(What are the drivers of structural or maintenance solutions?)*

Structural choices for bridges (e.g. concrete, steel, masonry and so on) are mostly determined by economic and social needs as revealed in section 8.1.1. Moreover, interviews also revealed that clients are the major determinants of structural choices, and their choices are based on construction and long-term maintenance cost. It follows that designers need to suggest and justify sustainable options to clients. Suggestions can be accepted or rejected depending on the depth of justification (Wessels, 2014). Assessments such as CEEQUAL have been developed to facilitate such justification and reward projects that demonstrate detailed sustainability considerations (CEEQUAL, 2017). Apart from the areas revealed in Figure 8.1, nine other drivers are revealed in Figure 8.2 (derived from the interview), which determine the choice of bridge maintenance actions. These drivers take precedence before any environmental matter is considered. Environmental concerns are increasingly becoming a global concern and need to be considered in structural and maintenance solutions. Designers may, therefore, need to advise clients on issues of resource depletion, energy use, and CO_2 emissions at early design stage or maintenance phase in line with their choice, with reasonable justifications. Otherwise, bridge designers will struggle to consider detailed environmental issues in their design. Materials and methodologies that lead towards minimal maintenance are also considered in design and maintenance choices. The use of alternative methods and materials to address environmental issues in bridges aligns with Zhang (2010). However, client choices and the designers' justifications play a major role in making these decisions.

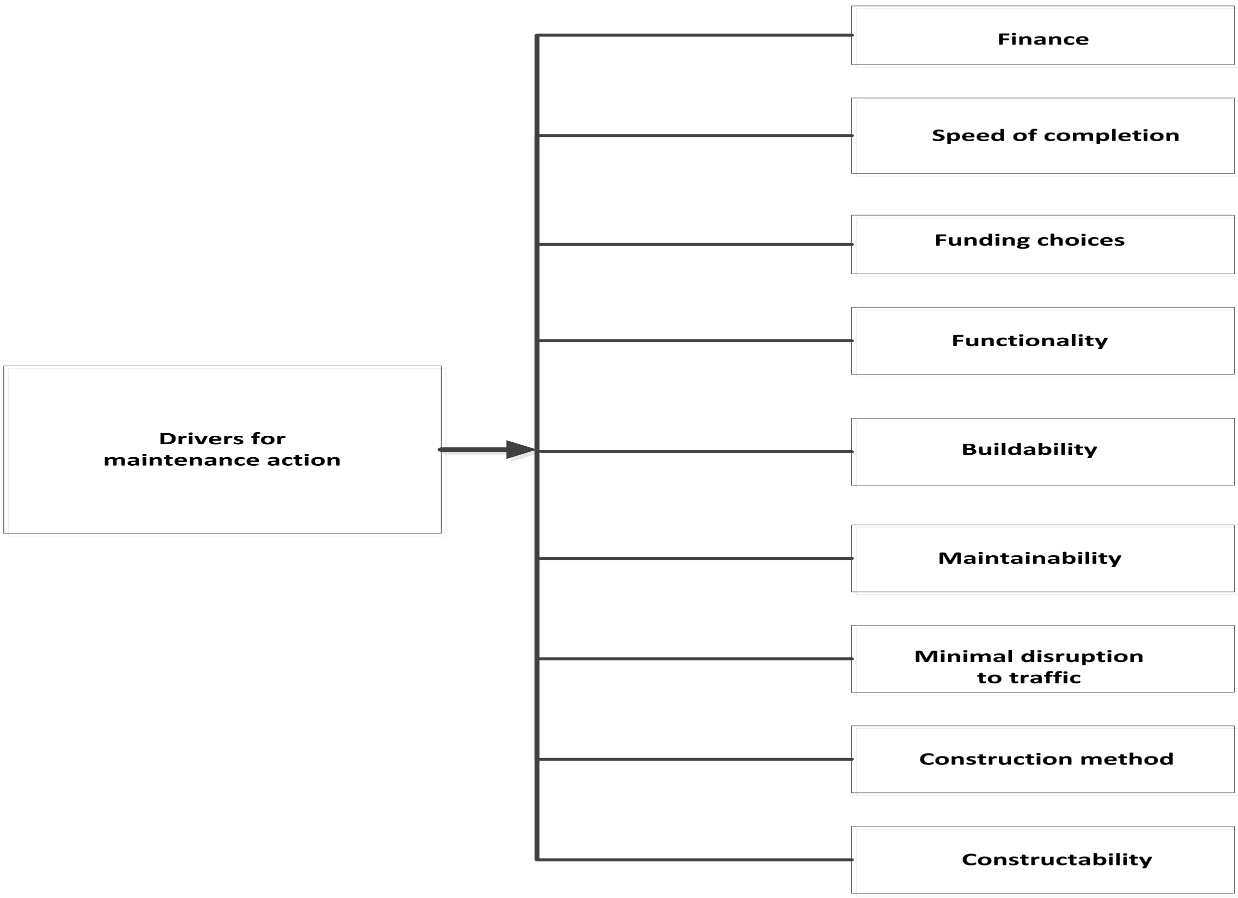

Figure 8. 2 Drivers for maintenance action in bridge design

8.1.3 Research Question Three *(What are the likely environmental impact results of bridge maintenance actions over a 120-year life span?)*

Expansion joints are the least environmentally friendly activity. This was demonstrated through the LCA analysis and confirmed by the interviews. Expansion joint had the highest CO_2, NO_2, and SO_2 emission and consumed the most energy. More importantly, it had a high impact on CC, POF, PMF, TA, FE and MD midpoint indicators, and high impact on resource consumption damage categories. Collings (2006) earlier proposed the minimal use of expansion joint due to its life-cycle cost implications. This study further confirms their impact on environment. Bridge designers are beginning to design it out for integral bridges, as evidenced by the interviews.

Saddling activity was also less environmentally friendly. Saddling had the highest CO_2, NO_2, and SO_2 emission, and consumed the most energy amongst the selected methods for masonry bridge. It also had high impact on CC, POF, PMF, TA, FE and MD midpoint indicators and high impact on resource consumption damage category. Results agreed with Steele *et al*. (2003), who compared anchoring and concrete saddle. It emerged that concrete had more environmental impact than anchoring technique. The major source of environmental pollution occurred at detouring stage, which was excluded in this study. This study, however, accounts for asphalt material – an essential paving material – which was excluded in Steele *et al.'s* (2003) analysis.

Structural painting was found to be more environmentally friendly. The result contradicts Horvath and Hendrickson (1998), who found for steel and reinforced concrete bridges that structural painting had significant CO_2 emissions. The difference in results emerges from the intervals at which painting was scheduled and the quantity of paint considered in this study. This agrees with Collings's (2006) empirical rules that "*The ongoing environmental burden of a bridge will be approximately proportional to the amount of maintenance required. A bridge requiring regular repainting or replacement of joints and bearings is likely to have increased energy use and CO_2 emissions in comparison with one without these elements*". For the current study, structural painting was scheduled every 12 years (12 times in 120 years), with very little material used compared to 8 years suggested by Horvath and Hendrickson (1998). Hence the reason for divergence in results. However, regular painting increases environmental impact (Collings, 2006), and designers have started to design with weldering steel, which is more cost effective and a more environmentally friendly alternative.

Masonry bridge emerged as the least environmentally impactful structure on account of the selected methods. Previous reports on masonry bridges called for more work on life-cycle appraisal of masonry bridge maintenance methods to justify its sustainability attributes (CIRIA, 2006). This research accomplishes that task in greater detail with LCA methodology consistent with related studies (Steele *et al*., 2003; Steele and Cole, 2005). The finding reinforces previous findings that masonry bridges are environmentally friendly to construct and dispose of (Steele *et al*., 2003). This is good news, as they are a large part of our existing bridge stock (Melbourne, Tomor and Wang, 2007), and already many exceed their design life. This improved knowledge of their environmental performance during maintenance might be helpful in extending their longevity even further. However, new masonry bridges are not favoured as structural choices are made between concrete, steel, and composite structures (Collings, 2006). Literature identified cost of centring and preparation of masonry blocks and scarcity of required skills as major limitations with constructing new masonry (Long *et al., 2008*). The interviews further revealed span limitation, construction time and initial construction environmental impact as factors that reduce the attractiveness of masonry bridges.

8.1.4 Research Question Four *(What is the degree of LCA awareness amongst bridge designers?)*

LCA awareness is limited amongst bridge engineers, let alone its usage. This was revealed from the interviews, as little interest was shown towards the LCA methodology. Experts claimed that the midpoint indicators (discussed in section 3.2.3) were too complex to be incorporated into the design process. However, there could be room to incorporate the endpoint indicators. LCA was considered for only new build, if at all, but never for existing bridge maintenance work. According to Pang *et al*. (2015), LCA for bridge maintenance action is limited. However, failure to consider LCA for bridge maintenance action could impinge upon UK's effort to reduce CO_2 emissions by 2050. This stems from the fact that maintenance actions improve the serviceability and longevity of bridges, and require substantial material consumption (over a life-span), with the relative impact on the environment. LCA provides guidance on these impacts and potentially improves decision making, as demonstrated in this study. The reality, however, is that design process is already a complex one

(Riches, 2003), and incorporation of LCA methodology could compound the complexity, even though the environmental indicators offered through LCA are becoming important sustainability matters (UN, 2015). But the interviews revealed that there may be scope to include the damage indicators (resource depletion, ecosystem, and human health) of LCA in bridge design, although the desire to factor environmental considerations into bridge design is ongoing (Du *et al*., 2014). LCA may struggle to meet this purpose, as it is mainly suited to a definite system which requires components, process, and materials data to be precise (Millet *et al*., 2007). Unfortunately, precise data for bridges are scarce, and estimates and assumptions will need to be made (Du and Karoumi, 2014; Hammervold, Reenaas and Brattebø, 2013).

8.1.5 Research Question Five *(What is the usefulness of LCA results of bridge maintenance actions within a bridge design process?*

The usefulness of the LCA result derived in chapter six was revealing masonry bridges as the most sustainable structural form in terms of life-cycle maintenance. The result may seem expected, considering their minimal maintenance (CIRIA, 2006). However, empirical evidence provided in this study puts the sustainability argument for masonry bridge in a stronger position. In support of this, literature reports that 40% of Surrey County bridge stocks undertook major refurbishment at an average age of 190 years into the service life. However, only masonry bridges exceeded current design life without significant repairs (Steele *et al*., 2002). Masonry bridges are therefore worth reconsidering, despite the shortcomings identified with constructing new ones.

Another usefulness of the LCA results was revealing expansion joint as the most environmentally impactful activity. Both Collings (2006) and Zhang (2010) suggested reduction in the use of Joints and bearings in order to cut down CO_2 emissions. As such, material used and frequency of replacement will be limited, which was the basis for high impact in the LCA analysis. Finally, the LCA results inform decision makers to consider long-term maintenance of the bridge in terms of material consumption, environmental impact and energy used alongside the drivers identified in Figure 8.1. Both Zhang

(2010) and Ng *et al*. (2015) suggest the need to focus on environmental significance of bridge construction and maintenance materials to holistically support environmental sustainability targets.

8.2 Deductions from Discussions

Key deductions emerged from discussing the research findings. The deductions are envisaged to pivot the development of recommendations for integrating LCA of bridge maintenance actions into bridge design. A first deduction emerged from findings attributed to question one. This revealed that sustainability is still a tick box exercise within the bridge industry, and that vital environmental concerns such as CO_2, NO_2, and other GHG emissions are neglected for bridge maintenance work. Rather, protection of flora, fauna, environment, and watercourses are a more significant concern. However, environmental issues of CO_2, NO_2, and other GHG emissions are becoming more pressing environmental concerns and should be factored into bridge maintenance operations. LCA could be applied to achieve this purpose, as demonstrated in this study. As such, CO_2, NO_2, and other GHG emissions associated with maintenance work can be revealed and the result can guide sustainable maintenance and design choices. A second deduction emerged from findings attributed to question two, which suggest that bridge designers can promote more environmental details such as resource depletion, energy, CO_2 and so on to clients, as the least they could do to influence sustainable decisions. However, this will require appropriate justification within the design brief. LCA becomes a useful tool in this regard, as demonstrated in this study.

The third and fourth deductions originate from findings attributed to question four. The findings revealed that LCA awareness is limited amongst bridge engineers, much less its usage. Again, LCA awareness will be unproductive if environmental matters are not significantly considered as design criteria. Interviews revealed that environmental matters are not necessarily a design criterion compared to cost, programme, aesthetics, constructability, health and safety, and maintainability. LCA awareness can gain more traction amongst bridge designers, should relevant environmental matters be formally considered as a design criterion. Furthermore, a fourth deduction emerges from the fact that there is scope to integrate only the damage indicators (with other design criteria) in bridge design. The incorporation of the damage indicators alone will perhaps help to address the complexity of embedding the entire LCA process in bridge design. The question now is how flexible can the LCA be before it's no longer an LCA. While tackling the complexity of LCA in bridge design, the process itself should not be undermined, in that the damage indicators themselves are outputs from the whole LCA process.

8.3 Development of Recommendations

Four recommendations emerged from the deductions presented in section 8.2. These recommendations should pave the way for general integration of LCA into bridge design and help the bridge industry contribute towards the overall built environment environmental sustainability development goal. Providing recommendations towards the improvement of environmental sustainability practices within the built environment sector is not unusual (CIRIA, 2006). However, recommendations facilitated by stakeholders' input are yet to come into existence for bridges. Although Zhang (2010) presented some recommendation to help bridge designers improve practice and contribute towards CO_2 reduction, these recommendations did not consider expert input. Though the integration of LCA results of maintenance method was the central point of this study, an underlying interest was also to promote the integration of LCA methodology into bridge design for wider applicability. As such, extrapolation from the interview findings revealed areas that need to be worked on for such integration to occur. This distinguishes the study from other related studies. Recommendations are presented in Figure 8.3. The first three recommendations emerged from first, second and third deductions. These recommendations are key to achieve effective consideration of LCA in bridge design. In fact, future recommendations in this field depend on them to thrive. The final recommendation is based on the fourth deduction, though care should be taken not to detract from the whole environmental viewpoint.

1. Detailed environmental matters such as CO2, NO2 and other GHG emissions should be considered as design criteria

2. Encourage designers to highlight emerging environmental matters within the design brief

3. LCA awareness should be increased amongst bridge designers

4. LCA damage indicators may be factored into bridge design process

Figure 8. 3 Recommendations for integrating LCA result into bridge design

8.4 Chapter Summary

This chapter discusses the research findings and their similarities with related literature. A detailed discussion on how potential recommendations were developed was also presented. Principally, four key recommendations have been derived from the study to help steer the course for integrating LCA results into the bridge design process. The next chapter is the concluding chapter, which sums up the achievements of the thesis.

CHAPTER NINE: CONCLUSIONS AND RECOMMENDATIONS

9. Introduction

The chapter presents the overall conclusions and recommendations of the study, and unveils how the original research objectives have been achieved. It details the unique contribution of the research to theory, methodology and practice, and justifies the practical implications of the research. It concludes with recommendations to policy makers, researchers, designers and bridge owners, and highlights areas for future research.

9.1 Achievement of the Research Objectives

Five objectives were pursued to deliver the research aim. Mixed-method approach was adopted to execute each research objective, as they addressed different phenomena. This section presents a succinct discussion on how each objective was achieved.

1. Objective One

Objective one sought to understand and explore the environmental aspects of sustainability in infrastructure. There are three pillars of sustainability revealed in the literature (economic, environmental, and social elements). Objective one particularly explored the extent to which the environmental aspect has been considered for bridges, especially at the design stage. Objective one was achieved through an extensive literature review, which revealed that environmental issues were only cursorily considered for bridges. Objective one was achieved in chapter two of the thesis. Arguments presented in chapter two sit well within academic and industry contexts and reinforce the need for the research.

2. Objective Two

Objective two sought to understand the trend and usefulness of LCA results in bridge industry. The construction industry is now concerned with the environmental impact of their activities in light of the commitment to help reduce CO_2 emissions by 2020. Major environmental assessment tools were reviewed in chapter two, where LCA had emerged to pivot sustainable results for buildings and other sectors. Objective two was achieved through a detailed literature review presented in

chapter three, which revealed the breadth and depth of LCA and its application to bridges. It was revealed that LCA had mostly been used for comparison (materials, components, elements, structural forms) of bridges, but was rarely used to compare their maintenance methods. Also, the usefulness of the LCA result was only based on the empirical evidence (that is, output of the LCA analysis), which from the literature is prone to uncertainties. No usefulness of LCA results has been championed (or verified) by stakeholder investigations, as demonstrated in this study.

3. Objective Three

Objective three aimed to demonstrate the practical application of LCA on maintenance actions of three structural forms of concrete, steel, and masonry to reveal their environmental impact. Objective three was achieved by selecting common but vital maintenance methods of concrete, steel, and masonry bridge. The selected methods themselves are guaranteed to take place in the service life of a bridge. Inventory data for selected maintenance actions were derived from the literature. Bridge experts were afterwards asked to verify the gathered data to confirm their reliability. Data verification was achieved, using an online questionnaire survey. The targeted audience were bridge experts, and were asked to agree, disagree, or suggest in view of the literature data, using their engineering judgment and experience. Chapter five presents a detailed analysis of the questionnaire, which embeds the statistical and analytical means employed to reach consensus on agreed, disagreed, and suggested data. The LCA was afterwards conducted using the verified data and SimaPro software. Therefore, the practical application of the LCA produced credible and reliable results. A detailed LCA of selected maintenance actions is presented in chapter six of the thesis.

4. Objective Four

Objective four sought to explore stakeholders' perspective on the usefulness of the LCA results derived in chapter six. As mentioned earlier, the usefulness of LCA results is mainly based on the empirical results of the LCA analysis. Objective four was achieved by conducting an in-depth semi-structured interview with bridge design experts in order to gain industry insight and assess the practical relevance of the derived results. Experts directly commented on the derived results and gave valuable insights on the LCA methodology itself. From a practical perspective, the experts agreed with the LCA results and certified the importance of such analytical results, especially for masonry bridge which emerged as the least impactful. Engagement with industry experts is reported in chapter seven of the thesis.

5. Objective Five

Objective five sought to provide useful recommendations for integrating LCA result of bridge maintenance methods into design of new bridges. Until now, no structured recommendation underpinned by stakeholder engagement is available for integrating LCA result into the bridge design process. Objective five was achieved by careful extraction of key findings derived from discussing the research questions. Four major deductions emerged from discussing the research questions, on which the recommendations were based. The recommendations are principally the results of the interviews. The developed recommendations are vital for integrating LCA result into the bridge design process. Discussions that led towards the development of the recommendations and the recommendations themselves are presented in chapter eight of the thesis.

9.2 Research Limitations

The literature revealed limited consideration for environmental impact in bridge design. Bridges, however, will require maintenance throughout their service life. An enquiry into this research reveals that there is a degree of environmental impact associated with these maintenance methods, which in turn affects their overall sustainability performance.

The study in this regard applied LCA on some maintenance methods of concrete, steel, and masonry bridge to reveal their potential environmental impact. Since the aim of the overall research was to improve sustainable design decisions, it would be complementary to also investigate the construction and end-of-life phases of these bridges with LCA.

LCA studies are mainly constrained by data availability, apart from the other shortcomings identified in the literature. Generally, LCA data for bridges are scarce, let alone their maintenance data which are normally assumed (Gervársio and da Silva, 2008; Hammervold, Reenaas and Brattebø, 2013). Major assumptions made in the study are for transportation distance and fuel used. Assumptions were, however, consistent with the literature (Zhang *et al.*, 2011). Moreover, SimaPro databases that supplied data to the background system (Electricity, energy, and waste) are also subject to technological know-how, which varies with geographical location (Du and Karoumi, 2014). However, European databases were employed for this study within the SimaPro, and are fairly representative of the UK context.

Finally, selected maintenance actions for concrete and steel are not interchangeable (i.e. cannot be used in place of one another), except for those of masonry. For example, sprayed concrete and near surface reinforcement can be used in place of one another. More so, saddling activities (for masonry) could address several defects at the same time and no other repair would be required. The knowledge strengthens the environmental integrity of masonry bridge from maintenance view point (considering that, 120 years was taken as a reference point for all methods to occur), yet, it would be advantageous to explore other substitutable methods for concrete and steel bridge and conduct similar LCA analysis on them. Such results would equally complement the LCA results derived in chapter 6.

9.3 Conclusion from Research Findings

Based on the set research questions, four main conclusions are drawn from the study.

- The environmental aspect of sustainability is minimally considered in bridge design, and sustainability itself is only appraised in five major areas, which does not effectively account for detailed environmental issues. The five areas are; need for the bridge, access to future maintenance, use of quality materials, consideration for long life with little amendment, and cost saving options.
- The environmental impacts of bridge maintenance solutions are rarely considered, whilst protection of flora, fauna, watercourses, and surrounding environment are the main environmental checks undertaken for maintenance solutions. In fact, only nine drivers determine the choice of a maintenance solution. These are; finance, speed of completion, funding choices, functionality, buildability, maintainability, minimal disruption to traffic, construction technique, and constructability. This excludes environmental emissions such as CO_2, NO_2 and other GHG emissions associated with the actual maintenance actions.
- LCA is a useful environmental assessment tool, and can be applied to bridge maintenance methods, as demonstrated in this study. However, LCA awareness amongst bridge designers is limited, much less its implementation in design.
- Masonry bridge is more environmentally sustainable from a maintenance viewpoint. Though good news for industry experts, there are major constraints that limit the industry moving towards constructing new ones. These are; initial construction cost, span limitation, and speed of completion.

9.4 Implications of the Research Findings

Choices made at the design stage affect the long-term performance of the bridge. Findings from the LCA analysis can, therefore, sharpen the choice of bridge design solutions, as evident in this study.

In the sense that clients will be happy to build bridges which require limited maintenance, the result provided in this study provides a useful guidance. In addition, the LCA findings can contribute towards the achievement of EMS (Environmental Management System) certification for a bridge design company, as it can be used to demonstrate commitment towards environmental improvement based on the ISO 14001 policy requirement. Although many UK construction companies strive to achieve EMS certification (Uren and Griffiths, 2000), not much success has been recorded for the bridge industry. It is mostly the case, as the interviews revealed, that sustainability is still a "tick box exercise" for the bridge industry, and not much environmental detail is considered. Moreover, a company should fulfil legal and regulatory requirements, which encompass environmental policy, planning, implementation and operation, checking and corrective action, and management review (ISO, 1996; Christini, 2003). The LCA findings can draw the attention of decision makers to implementing mitigation plans, which can be included in the environmental mission statement as part of their sustainability approach, thereby improving their competitive advantage, as companies are more likely to trade with eco-friendly organisations.

Besides, the pathway to research findings and the findings themselves are elements for achieving CEEQUAL assessment and rating awards. Currently, designers, clients and contractors are being rewarded for demonstrating commitment to a wider sustainability agenda (CEEQUAL, 2017). Towards this, consideration for the environmental impact of maintenance work is equally essential. Eligibility for an award is demonstrated on the basis of nine criteria (CEEQUAL, 2017). These are;

- Client contract strategy
- Project or contract management
- People and communities
- Land use and landscape;
- The historic environment
- Ecology and biodiversity

- Water environment (fresh and marine)
- Physical resources use and management
- Transportation.

Mainly, the LCA result findings derived from this study allow four of the nine areas to be demonstrated on account of environmental considerations (that is, ecology and biodiversity, water environment [fresh and marine], physical resources use and management, and transportation). Note that CEEQUAL does not include the necessary tools to demonstrate these nine elements. Therefore, projects need to employ necessary tools to demonstrate the attainment of these nine criteria. LCA can be a useful tool in this regard.

9.5 Contributions to the Body of Knowledge

The research makes useful contributions to theory, methodology, and practice, which are revealed in sections 9.5.1, 9.5.2 and 9.5.3, respectively.

9.5.1 Theoretical Contribution

Chapter two revealed shortage of literature on sustainable bridge design, as well as the environmental impact of bridge maintenance methods. At the same time, no detailed recommendation is available to guide the integration of LCA in bridge design which could improve the sustainability of bridge design while revealing the environmental impact of bridge maintenance methods. The current study bridges this gap by developing recommendations to help integrate LCA into bridge design. Though LCA has been applied to bridges, it has not been effectively explored for bridge maintenance methods, as demonstrated in this study. Even more important, LCA is rarely applied in bridge design. Recommendations emerging from this study set the platform for wider applicability of LCA in bridge design. The study therefore achieves a theoretical contribution in this area.

9.5.2 Methodological Contribution

Chapter three revealed that LCA data are gathered from secondary and primary sources, while some are derived from the commercial databases in available LCA software. Many of these databases lack precision, and realistic data are strenuous to obtain, especially for bridges (Thiebault, Du and Karoumi, 2013; Du and karoumi, 2014). Therefore, LCA results are subjective to the data collected. The data utilised in this study were verified by a wider audience of bridge experts, which improved the reliability of the secondary sources (literature data). Consensus among the experts on the literature data ensured the reliability of the data that informed the LCA analysis. Only data that reached consensus criteria were utilised in this study. The use of online questionnaire survey for verification of literature is relatively new in bridge LCA studies. It is, therefore, argued that online questionnaire survey could be applied in other bridge LCA studies where secondary data is lacking, following the success achieved in this study. This was taken as the study's methodological contribution.

9.5.3 Practical Contributions

Emergent recommendations from this study are not only applicable to bridge design, but can also be an environmental agenda checklist for the wider bridge industry, particularly towards achieving EMS certification or CEEQUAL award. The recommendations can: (a) prompt the bridge industry to adopt some environmental impact benchmarks for bridge projects; (b) allow staff training sessions to be conducted, towards raising awareness for LCA; and (c) enhance the proposal of an integrated team of LCA experts and bridge designers, if required.

9.6 Recommendations

Findings presented in this study allowed key recommendations to be made to; policy makers, researchers, designers, and bridge owners.

9.6.1 Recommendations for Policy Makers

Infrastructural assets such as bridges are vital for economic prosperity. However, their longevity and serviceability are dependent on continuous monitoring and maintenance. The study identifies the limitations to consideration of environmental impact in bridge maintenance actions. On the other hand, failure to consider the environmental impact of bridge maintenance actions undermines the industry's holistic effort towards achieving carbon dioxide reduction. A cultural change can be achieved, should government consider regulating the life-cycle emissions of bridge maintenance or rehabilitation works. With this, environmental agencies can be empowered to enforce more environmental safeguards for bridge maintenance actions before sanctioning a proposal.

9.6.2 Recommendations for Future Research

Recommendations for future research have emerged from the limitations identified in the study. One limitation draws attention to the benefits of conducting an LCA analysis on the construction and end-of-life phases of similar bridges (perhaps with a similar span). The result of such analysis will complement that of this research, and allow emergence of holistic knowledge regarding the life-cycle environmental impact of these bridges.

9.6.3 Recommendations for Designers and Bridge Owners

Recommendations derived in chapter eight largely concern bridge designers and bridge owners. However, the government will play a major role in their implementation. For instance, the recommendation that detailed CO_2, NO_2 and other GHG emissions should be considered as a design criterion will only be taken seriously (by designers and bridge owners) if a bill is passed on that matter, otherwise it will be business as usual. The same goes for the recommendation, "LCA awareness should be increased amongst bridge designers".

The question is, how will this be implemented, and who will fund awareness programmes and relevant trainings? Will the government do this, or bridge owners? Government can possibly facilitate training through Public-private Partnership (PPP) schemes, as the bridge owners are confronted with limited budgets for bridge maintenance, let alone LCA trainings.

9.7 Conclusions

The study aimed at improving environmental sustainability in bridges by investigating the possibilities of integrating LCA of bridge maintenance methods into the bridge design process. Based on the findings, consideration of LCA of bridge maintenance methods in design is limited, as the LCA methodology itself is rarely applied in bridge design. The current situation necessitated development of some recommendations to help guide the incorporation of LCA of bridge maintenance methods into bridge design for sustainable design choices. This set of recommendations will enlighten decision makers, government, and bridge owners on the scope for integrating LCA as a whole in bridge design. Other discoveries also emerged from the overall research approach, which led to four major conclusions presented in section 9.3 of this chapter. On a concluding note, the study has achieved its original aim of improving sustainability of bridge design, through the development of tailored recommendations to help incorporate LCA of bridge maintenance into bridge design.

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APPENDIX 1

Consent form

Identity of researcher

Teslim Bamidele Balogun (PhD researcher)

Tel: +447508733711,

Email: Teslim2.Balogun@live.uwe.ac.uk

Title of project: "Integrating bridge maintenance life cycle assessments into bridge management systems for improved bridge maintenance decision making"

The purpose of the research

The purpose of the research is to propose a model to incorporate environmental impacts from bridge maintenance methods into existing Bridge Management Systems (BMS) to help bridge managers with decision making. In order to develop the model, I need to assess a range of typical bridge maintenance activities in terms of materials used for concrete, steel and masonry bridges.

The purpose of the validation sheet

The purpose of this data validation sheet is to validate data on the quantities of material that I have obtained from the literature to use in my model. The quantities of materials are estimated for a selection of key bridge repair methods in the sheet below. I am requesting you to use your expertise to validate the data I have presented in the sheet below to allow me to feed accurate data into my model.

Why you have been selected to participate

You have been invited because you are a bridge inspector, site engineer or foreman or an expert directly involved in bridge maintenance operations. I would like you to use your expertise to validate the data I have obtained from the literature for some bridge maintenance material quantities to allow me to feed accurate data into a proposed model.

Harms and benefits

There are no harms associated with participating in this research. However, it is an opportunity to be involved in an academic research which can enhance effective bridge decision making with regard to sustainably consideration.

Privacy, anonymity and confidentiality

All collected data will be securely stored and destroyed after the completion of the research. Information collected will only be used for academic purpose and would not be made available to third parties to maintain confidentially. No personal information such as name, phone number, date of birth etc. is collected to maintain anonymity.

Information dissemination

The output of this research will be published in academic journals, conference papers and articles within bridge management and life cycle assessment domain. The complete thesis will be available in UWE repositories for reference.

Right to withdraw from participation

Your participation is completely voluntary and you may at any time withdraw from participating in the survey, if you wish to do so, but your participation will be much appreciated.

Participant declaration

I have read and understood the information sheet giving details of the project. I have also read and understood this consent form. I hereby give my consent to participate in this research.

Respondent/participant name ……………………………………………………………………

Respondent/participants' signature……………………………………………………………

Date dd/mm/yyyy ………………………………………………………………

APPENDIX 2

Information sheet for Survey

Introduction

I am a PhD research student in the Faculty of Environment and Technology (FET) at the University of the West of England in Bristol and undertaking research into the life-cycle appraisal of bridge maintenance methods using currently available life-cycle assessment tools.

What can I do?

You are invited to take part in this study by completing a data validation sheet, estimated to take 15 minutes. This is voluntary, but your participation will be much appreciated.

Why have I been invited to take part?

You have been invited because you are a bridge inspector, site engineer or foreman or an expert directly involved in bridge maintenance operations. I would like you to use your expertise to validate the data I have obtained from the literature for some bridge maintenance material quantities to allow me feed accurate data into a proposed model.

What happens to the information I give you?

All information collected will be securely stored. Individual participant will never be identified as identity will be completely anonymous.

Can I withdraw?

Returning the data validation sheet will be taken as your consent to participate. However, you may at any time withdraw from participating in the survey, if you wish to do so, but your participation will be much appreciated.

What happens next?

If you are happy to proceed, please read the invitation letter and proceed to answer the questions in the data validation sheet.

Researchers contact details

If you wish to discuss the research or potential outcomes of the research, please contact Dr Colin Booth (Director of study), Colin.Booth@uwe.ac.uk or Teslim Balogun (Researcher), Teslim.Balogun@uwe.ac.uk. Also, if you do not wish to complete the validation sheet now, but would prefer to do so later, please contact the researcher and a copy of the validation sheet would be emailed to you directly.

APPENDIX 3

UWE Bristol | University of the West of England

Invitation to participate in a Survey

DATA VALIDATION SHEET

DATE: JANUARY 2016

PROJECT TOPIC: "Integrating bridge maintenance life cycle assessment into bridge management systems for improved bridge maintenance decision making"

Dear Sir/Madam

I am a PhD research student in the Faculty of Environment and Technology (FET) at the University of the West of England in Bristol and undertaking a research into the life-cycle appraisal of bridge maintenance methods using currently available life-cycle assessment tools.

The purpose of the research is to propose a model to incorporate environmental impacts from bridge maintenance methods into existing Bridge Management Systems (BMS) to help bridge managers with decision making. In order to develop the model, I need to assess a range of typical bridge maintenance activities in terms of materials used for concrete, steel and masonry bridges.

I am inviting you to participate because you are a bridge inspector, site engineer or foreman or an expert directly involved in bridge maintenance operations. The purpose of this data validation sheet is to validate data on the quantities of material that I have obtained from the literature to use in my model. The quantities of materials are estimated for a selection of key bridge repair methods in the sheet below. I am requesting you to use your expertise to validate the data I have presented in the sheet below to allow me feed accurate data into my model.

For the purpose of individual anonymity, the sheet collects no personal information such as name, address, date of birth or phone number. The validation sheet is estimated to take about 15 minutes and information provided will be treated in strict confidence and would be used for academic purpose only. Your participation is completely voluntary and you may at any time withdraw from participating in the survey, if you wish to do so, but your participation will be much appreciated.

Your responses will make a valuable contribution to this research.

Yours sincerely,

Teslim Bamidele Balogun.

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Questions are divided into two parts; the first part addresses respondent's experience and the second part addresses quantities of material obtained from the literature that needs to be validated.

PART ONE

1. What is your role in the construction industry?

- Site Engineer ☐
- Bridge Inspector ☐
- Foreman ☐
- Bridge Manager ☐
- Construction Engineer ☐
- Bridge Engineer ☐
- Others ……………………………………………………………..

2. What is your highest qualification?

- Secondary /College certificate ☐
- National Diploma ☐
- Higher National Diploma ☐
- BSc Degree ☐
- Master's Degree ☐
- PhD or Higher ☐
- Professional qualification if any ....

3. Have you been involved in bridge maintenance work?

☐ **Yes** ☐ **No (If No, please proceed to question 7 in PART TWO)**

4. How long have you been involved in bridge maintenance?

☐ **<5years** ☐ **5-10years** ☐ **11-15years** ☐ **16-20 years** ☐ **over 20 years**

5**.** Please indicate any professional membership you are affiliated with.

- ICE (Institute of Civil Engineers) ☐
- CIHT (Chartered Institution of Highway & Transportation) ☐
- CIOB (Chartered Institute of Buildings) ☐
- RICS (Royal Institution of Chartered Surveyors) ☐
- IStructE (Institute of Structural Engineers) ☐

Others please specify ……….…………………………………………………….

PART TWO

6**.** This question provides material quantities – obtained from the literature – for some selected concrete, steel and masonry bridge repair methods. Quantities have been expressed in terms of m^2 **(one square meter effective bridge deck area).** Hence, the quantities provided in Table 1.1 are quantities required for one square meter effective depth area - during a single repair of the bridge. Can you please indicate your agreement or disagreement with this data by ticking 'agree' or 'disagree' respectively? In case you have disagreed with the figures provided, could you suggest an improved quantity based on your experience in the box marked 'suggested weight' - It is understood that quantities will vary from project to project and all values are approximate. Can you please also provide in the box marked 'suggested frequency' the number of times these repairs would occur during the life time of the bridge (120 years), based on your experience.

Table 1.1 Literature data validation

Bridge type	Repair methods	Materials	Quantity of materials potentially required to repair "1m² of a bridge deck area" – in one single repair				
			Literature data		Agree	Disagree	Suggested weight (tons)
			Frequency	Weight (tons)			
Concrete bridge	**Grout**	Cementitious grout	1	0.14			
	Overlaying	Concrete	1	2.5			
		Asphalt	1	0.27			
		Bitumen	1	0.3			
	Bearing renewal	Reinforcement	1	0.25			
	Expansion joint renewal	Reinforcement	1	0.25			
	Deck replacement	Concrete	1	2.5			
		Asphalt	1	0.27			
		Reinforcement	1	3			
		Bitumen	1	0.3			
Steel bridge	**Structural painting**	Epoxy paint	1	0.054			
		Polyurethane paint	1	0.105			
		Zinc coating (Per deck area)	1	0.366			
	Pavement repair	Asphalt	1	0.27			
		Bitumen	1	0.3			
	Deck re-waterproofing	Concrete	1	0.1			
		Reinforcement	1	0.1			
	Bearing renewal	Reinforcement	1	0.25			
	Expansion joint renewal	Reinforcement	1	0.25			
Masonry arch bridge	**Saddling**	Concrete	1	2.5			
		Asphalt	1	0.27			
		Reinforcement	1	0.25			
		Bitumen	1	0.3			
		Fill	1	2			
	Radial pinning	Cementitious grout	1	0.12			
		Dowel reinforcement	1	0.12			
	Waterproofing	Concrete	1	0.1			
		Reinforcement	1	0.1			
		Mastic seal	1	0.1			
	Near-surface reinforcement	Cementitious grout	1	0.152			
		Reinforcement	1	0.203			
	Sprayed concrete	Concrete	1	0.4			
		Reinforcing mesh	1	0.1			

7. Extra comments and suggestions relating to any of the maintenance methods can be provided in the space below;

………
………
………
………
………
………
………
…………………………………………………………………………

8. In your opinion what can be done to improve sustainability in bridge maintenance.

………
………
………
………
………
………
……………………………………………………………………………………………

9**.** Will you be interested in receiving the research findings?

☐ Yes ☐ No (If yes, please send an email to the researcher on Teslim.Balogun@uwe.ac.uk requesting the findings of the research)

Thank you for taking time to complete this data validation sheet.

APPENDIX 4

UWE Bristol | University of the West of England

Invitation Letter

DATE: August 2016

PROJECT TOPIC: "Integrating bridge maintenance life cycle assessments into bridge design for improved sustainable decision making"

Dear Sir/Madam

I am a PhD research student in the Faculty of Environment and Technology (FET) at the University of the West of England in Bristol, undertaking, research into the life-cycle appraisal of bridge maintenance methods.

The research intends to make recommendations for the integration of environmental impacts of bridge maintenance methods during the design of new bridges. This stems from the fact that design decisions are made early in the design process and have far reaching environmental implications in the later life of the bridges. Towards this, life-cycle analysis of typical bridge maintenance activities for concrete, steel and masonry bridges have been conducted to determine their life-cycle environmental impact.

I am inviting you to participate in an interview because of your valuable knowledge and experience about bridges. The purpose of the interview is to allow you comment on the Life-cycle assessment findings derived from assessing concrete, steel and masonry bridges and to indicate the potential usefulness of the results during the design of new bridges.

For the purpose of individual anonymity, no personal information such as name, address, date of birth or phone number will be stored. The interview is estimated to take about 15-20 minutes and information provided will be treated in strict confidence and would be used for academic purpose only. Your participation is completely voluntary and you may, at any time, withdraw from participating in the interview, if you wish to do so, but your participation will be much appreciated.

Returning the signed copy of the consent letter will indicate your agreement to participate in the interview. Please read the information sheet for more information.

Your contribution will make a valuable contribution to this research.

Yours sincerely,

Teslim Bamidele Balogun.

Architecture and Built Environment
UWE, Bristol (Frenchay campus, Room 4Q58)
Coldharbour lane Bristol,
BS16 1Q
Contact No: +44(0)1173286494
Email:Teslim.Balogun@uwe.ac.uk
Teslim2.Balogun@live.uwe.ac.uk

Director of Studies (DOS)
Colin Booth
Colin.Booth@uwe.ac.uk
Tel: 01173283998

APPENDIX 5

UWE Bristol | University of the West of England

Information sheet

DATE: August 2016

PROJECT TOPIC: "Integrating bridge maintenance life cycle assessments into bridge design for improved sustainable decision making"

Introduction

I am a PhD research student in the Faculty of Environment and Technology (FET) at the University of the West of England, Bristol, undertaking research into the life-cycle appraisal of bridge maintenance methods.

What can I do?

You are invited to take part in an interview, estimated to take 15-20 minutes. This is voluntary, but your participation will be much appreciated.

Why have I been invited to take part?

You have been invited because of your valuable knowledge and experience about bridges. Your contact details were obtained through - Linkedin or an official company website. I would like you to comment on the results I have derived from assessing the life-cycle environmental impact of typical bridge maintenance activities of concrete steel and masonry bridges.

What happens to the information I give you?

All information collected will be securely stored in accordance with data protection regulations. All information is collected anonymously and you will not be identified.

Can I withdraw?

Returning the signed copy of the consent letter will indicate your agreement to participate in the interview. However, you may, at any time, withdraw from participating in the interview, if you wish to do so, but your participation will be much appreciated. Data already provided will be removed and destroyed should you withdraw from the interview at any point.

If you have any complain?

If you have any questions or concerns about the research or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact: Dr Colin Booth (Director of Studies), University of the West of England, Frenchay Campus, Coldherbour Lane, Bristol BS16 1QY; Telephone: 01173283998; Email: Colin.Booth@uwe.ac.uk

What happens next?

Please proceed to read the consent letter if you are happy to participate in the interview.

Researchers contact details

If you wish to discuss the research or potential outcomes of the research, please contact Teslim Balogun (Researcher). Also, if you do not wish to take part in the interview now, but would prefer to do so later, please contact the researcher who would be able to invite you for an interview on a preferred date. The researcher's contact details are; Email: Teslim.Balogun@uwe.ac.uk; Contact No: +44(0)1173286494.

APPENDIX 6

UWE Bristol University of the West of England

Consent Form

DATE: August 2016

Project Title: "Integrating bridge maintenance life cycle assessments into bridge design for improved sustainable decision making"

The purpose of the research

This research intends to make recommendations for the integration of environmental impacts of bridge maintenance methods during the design of new bridges.

The purpose of the interview

The purpose of the interview is to allow you to comment on LCA research findings derived from assessing the life-cycle environmental impact of typical bridge maintenance activities of concrete, steel and masonry bridges.

Why you have been selected to participate

You have been selected because of your valuable knowledge and experience about bridges. Your contact details were obtained through - Linkedin or an official company website.

Harms and benefits

There are no known harms associated with participating in this research. Moreover, it is an opportunity to be involved in a piece of academic research, which can enhance effective bridge decision making with regards to sustainability targets.

Privacy, anonymity and confidentiality

All collected data will be securely stored and destroyed after the completion of the research. Information collected will only be used for academic purpose and will remain confidential. No personal information such as name, phone number, date of birth etc. is collected to maintain anonymity.

Information dissemination

It is anticipated that the output of this research will be published in academic journals, conference papers and articles within the bridge management and life cycle assessment domain. The complete thesis will be available in UWE repositories for reference. You will remain anonymous in all documents.

Right to withdraw from participation

Your participation is completely voluntary and you may withdraw at any time (before, during and after) from participating in the interview, if you wish to do so, but your participation is much appreciated. Data already provided will be removed and destroyed should you withdraw from the interview at any point.

Researchers contact details

If you wish to discuss the research or potential outcomes of the research, please contact Teslim Balogun (Researcher). Also, if you do not wish to take part in the interview now, but would prefer to do so later, please contact the researcher who would be able to invite you for an interview on a preferred date. The researcher's contact details are; Email: Teslim.Balogun@uwe.ac.uk; Contact No: +44(0)1173286494

Participant declaration of consent to participate

I have read and understood this information sheet giving details of the project. I have also read and understood this consent form. I hereby give my consent to participate in this research.

Respondent/participant name …………………………………………………………………

Respondent/participants' signature…………………………………………………………….

Date dd/mm/yyyy ………………………………………………………………

APPENDIX 7

<u>Interview schedule</u>

Section A

1. Can you tell me about your role and professional experiences within the bridge design industry?

Section B

2. In your experience how and to what extent is sustainability embedded in bridge design and construction.
3. In your experience what influence do expected bridge maintenance schedules have in sustainable design of new bridges?
4. What do you know about LCA and its role in bridge design?

Section C (Presentation of LCA results of bridge maintenance methods)

5. What will be the usefulness of this results/information when designing a new bridge?

Interview schedule

Themes/issues	**Questions**	**Follow up questions**	**Probes**
Professional experience and related background.	1. Can you tell me about your role and professional experiences within the bridge design industry?	• What was your main responsibilities • What sort of information/data would you require before commencing a design • What did you mostly design for	• Please tell me more about…
Perception of sustainability in bridge design.	2. In your experience how and to what extent is sustainability embedded in bridge design and construction.	• How do you factor in sustainability during design • What will be a sustainable approach	• And… • Can you tell me more
Role of post-maintenance plans in sustainable bridge design.	3. In your experience what influence do expected bridge maintenance schedules have in sustainable design of new bridges?	• In what way does future maintenance plans affect new bridge design • How is future maintenance plans integrated into new bridge design	• Please tell me more about
Awareness of Life-cycle assessment (LCA) and environmental impact.	4. What do you know about LCA or the role of environmental impacts of bridge maintenance during bridge design?	• In what way do you consider environmental impact bridge maintenance during bridge design • Have you considered/tried LCA	• Please tell me more about… • Go on.
The usefulness of LCA results in bridge design.	5. What will be the usefulness of this LCA results/information – of bridge maintenance methods during the bridge design process and its potential to improve their sustainability	• In what way will the LCA results influence your design options • What kind of decision will these results help you make • What type of result would be relevant	• Go on.

APPENDIX 8 Matrix coding results for **(Sustainability)** major themes

Table 8A1

	A: Sustainability in bridges
1: Need for the bridge	20
2: Access to future maintenance	19
3: Use of quality material	15
4: Consideration for long life	17

Table 8A2

	A: Environmental consideration
1: Protection of flora	19
2: Protection of fauna	17
3: Protecting the environment	21
4: Protection of water courses	15
5: Inspections	4

Table 8A3

	A: Environmental indicators
Consideration for CO_2 emissions	18

Appendix 8B Matrix coding results for **(Structural design)** major themes

Table 8B1

	B: Structural and maintenance decisions
1: Clients are decision makers	16
2: Cost driven	21
3: Construction cost	15
4: Maintenance cost	19

Table 8B2

	B: Drivers for maintenance solutions
1: Finance	16
2: Speed of completion	21
3: Functionality	15
4: Buildability	19
5: Maintainability	21
6: Minimal disruption to traffic	17
7: Construction method	18
8: Constructability	15

Table 8B3

	B: New approaches
1: Integral bridges	16
2: Weldering steel	15
3: FRP	14

Appendix 8C Matrix coding results for **(LCA awareness)** major themes

Table 8C1

	C: LCA amongst designers
1: LCA Awareness	4
2: No awareness	19

Appendix 8D Matrix coding results for **(LCA results)** major themes

Table 8D1

	D: Usefulness of the result
1: Masonry bridge as least impactful	18
2: Expansion joint as most impactful	19
3: Paying attention to material consumption	16

Table 8D2

	D: Complimenting the result
1: Associated maintenance cost for similar bridges	14
2: Associated construction cost for similar bridges	16

Table 8D3

	D: Challenges with masonry bridges
1: Initial construction cost	15
2: Span limitation	20
3: Speed of completion	19