

UNIVERSITY OF BIRMINGHAM

A Reliability Risk-Based Methodology for Highway Bridge Maintenance Decision Making

by

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ABSTRACT

Bridges are known to be crucial structures, which assist in the overall transportation infrastructure systems. They continue to serve for a long period of time and thus, they are usually subjected to multiple loadings in addition to several risks in their service life. Therefore, they require a great deal of maintenance in order to preserve their functionality. Risk management of bridges is particularly important for understanding the likelihood of extreme events and service distribution along with the consequences of service disruption. Thus, this thesis is concerned with developing and providing a detailed reliability risk-based methodology for the decision making of highway bridges made of concrete and steel. This research was aimed on delivering a successful tool which can provide a safety risk analysis for bridge structures. A review of the relevant literature was first carried out which assisted in providing a detailed background on bridges. This included discussing studies exploring bridge accidents in order to understand the reasons behind such accidents. Next, the aim of this study was successfully achieved by basing the proposed tool on a numerical model, which is relevant to the maintenance of bridge structures. The goals of this research were satisfied by reviewing, analysing and utilising the Fuzzy Reasoning Approach (FRA), Fuzzy Analytical Hierarchy Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) techniques. A new safety risk model applicable for bridges was then proposed. Three input parameters, Consequence Severity (CS), Failure Frequency (FF) and Weight Factor (WF) were introduced and then used for assessing the risks from components levels all the way to system level. Moreover, the Consequence Severity Criteria (CSC) parameter is introduced as the multi-consequences parameter, which takes into consideration eight factors that are

considered significant for the risk analysis of bridges. The eight factors, which are, functionality, safety, value for money, environment, traffic delay, time, reputational damage and socio-economic consequences are discussed in detail. Three case studies were used for validating and verifying the reliability of the proposed risk assessment and safety management model. Overall, for the first time, this work has carried out research as well as propose a safety model for risk assessment of highway bridges. In the case of no available information or risk data, it is possible to use subjective estimations with the proposed risk model. This is because the model permits the use of imprecise as well as vague descriptors for directly capturing experts' judgements. While there are certain complexities associated with the application of FAHP, the proposed risk assessment model uses an enhanced version of FAHP, which needs only a few expert judgements. The developed model is based specifically on highway bridges. Hence, the benefits of the model can be summarised in its ability to combine engineering judgements as well as expert knowledge with various risk information for the assessment of highway bridges in a reliable approach.

DEDICATION

To My Lovely Family

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practicable
ASCE	American Society of Civil Engineers
BMS	Bridge Management System
CS	Consequence Severity
CSC	Consequence Severity Criteria
EI	Expert Index
EMV	Expected Monetary Value
ER	Evidential Reasoning
ETA	Event Tree Analysis
FAHP	Fuzzy Analytical Hierarchical Process
FF	Failure Frequency
FAHP	Fuzzy Analytical Hierarchical Process
FMEA	Failure Mode and Effect Analysis
FRA	Fuzzy Reasoning Approach
FTA	Fault Tree Analysis
FTOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution
HAZOP	Hazard and Operability study
MCDM	Multi-Criteria Decision Making
MF	Membership Function
NIS	Negative Ideal Solution
NTSB	National Transportation Safety Board

OSP	Operational Safety Performance
PIS	Positive Ideal Solution
PO	Probability of Occurrence
RBS	Risk Breakdown Structure
RL	Risk Level
RRL	Road Research Laboratory
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UFN	Uniform Format Number
WF	Weight Factor

CHAPTER 1: INTRODUCTION

1.1 Motivation and Background

Bridges are known to be important structures in the transportation industry, which form a fundamental element of any road network. Bridges are usually treated as an everlasting construction and can act as a vital hub for land transports. As a result, bridges tend to have a direct impact on the economic and social developments (Yang et al., 2017). Hence, bridges are known to be one of the most complex building structures. Since bridges are known to serve for a long period, they are usually subjected to multiple loadings in addition to several risks in their service (Kodur and Naser; 2013). Hence, they require a great deal of maintenance in order to preserve their functionality.

Once constructed, maintenance and risk assessment of bridges is very crucial in dealing with real-world problems. Statistical investigations have shown that numerous bridge failures were triggered due to a number of issues including corrosion, traffic accidents, vehicle collisions, fire, structural instability, safety considerations, time, costs and overall poor risk management. These accidents have undoubtedly resulted in serious causalities as well as damages (Wardhana and Hadipriono, 2003; Liu et al., 2004; Tam et al., 2004; Sharma et al., 2008; Zhang et al., 2013; Kiviniemi and Jones, 2017; Zhou and Li, 2018).

Assessment and management of bridges involve the use of data and analysis for improving decision-making. This process is aimed at ensuring that the bridge can provide its desired level of service using the most cost-effective techniques. Therefore, an adequate Bridge Management System (BMS) would involve the application of

bridge inventories and conditions' data for assessing the benefits as well as costs of preservation, risk mitigation along with replacement activities. This can assist in supporting the decision-making processes.

Risk management is a widespread approach utilised not only in economic, but also in industrial and public safety areas to decrease uncertainty and accident rates. Risk management is concerned with the risk management planning, identification, analysis, responses, monitoring and controlling project risks. Thus, it can be stated that risk analysis is an evaluative procedure that determines the extent of risks in a project. Management and risk assessment of bridges is particularly important for understanding the likelihood of extreme events and service distribution along with the consequences of service disruption. Precisely, hazards such as vehicle collisions, extreme temperatures, wildfires, floods, high winds, storm surges, landslides or earthquakes are all triggered by short-duration events. These are abrupt, unexpected and unusual at any given location. Hence, they are known to have unavoidable safety consequences (Thompson, 2017; Powers et al., 2018). However, other events such as the occurrence of a flood may happen with some early warning. This allows for operational practices to take place that can potentially enhance safety aspects. Nevertheless, this would mean that both, mobility and costs would be affected. Adequate control along with operational practices can ensure that the likelihood of service disruption remains unaffected by an extreme event. While certain events are unavoidable, these can be managed. This would involve the development of programmatic decisions as well as the allocation of adequate resources. For instance, avoiding earthquakes may not be possible but instead, bridges can be made resilient enough to resist earthquakes (Jaimes et al., 2015). In addition, several sources may be able to provide information on the likelihood of extreme events

by providing geographically referenced data. This includes obtaining data from seismic monitors and early warning systems for earthquakes. Furthermore, human-caused extreme events can also be managed with available information of earlier incidences that can help gain insight on the overall hazards. This can help in managing issues such as vehicle collisions, over-height truck, and overloads. In terms of the likelihood of service disruptions, this refers to the probability of a service being affected, based on the occurrence of a hazardous event. As a result, service disruption may have corresponding consequences (Thompson, 2017).

Overall, the maintenance and safety of bridges are very important because of the increased number of accidents, injuries and fatalities resulting from inadequate safety risk management of bridges. Precisely, risk, in this industry can be described with the incidents and accidents that occur and lead to such injuries as well as fatalities. Therefore, there is an immense need for better safety management along with increased awareness (Bhattacharya, 2016). To do so, information on the nature and causes of such accidents is required. Risk analysis, thus, has a key role in the bridge safety and management framework. Such an analysis is required to establish if a particular risk has a low, medium or high risk level. Risks with negligible or low risk values, no significant action is needed but the relevant data must be recorded for auditing purposes (An et al., 2008). In case, the corresponding risk level is high, then adequate risk-reduction measures should be implemented along with reconsidering the maintenance and operation. This can assist in reducing the probability of occurrence of an event along with controlling the resulting potential consequences. Risk analysis of highway bridges is a complex topic due to the several related risks (Decò and Frangopol, 2011). As a result, it is not possible to depend on just one person's judgements to consider all the

features of a project. A group of relevant staff such as engineers, experts and project managers is required to make cumulative decisions. Moreover, useful information that is obtained through the risk estimation stages can be employed for assisting the relevant bodies such as engineers and risk analysts in making crucial decisions regarding the safety and maintenance of bridge infrastructure (Vidivelli et al., 2017).

Although several risk assessment techniques are currently available for use, in most circumstances, such as in the maintenance and safety of highway bridges, these methods may not cope well with the uncertainties in the available information. Often, due to lack of statistical data, expert knowledge and judgements are needed. Hence, risk analysts are usually faced with issues concerning incomplete risk data or increased levels of uncertainties in the risk data involved (An et al., 2011). Therefore, the development of innovative methods for risk analysis is needed for identifying major hazards as well for assessing the corresponding risks in the safety assessment of bridges. To do so, Fuzzy Reasoning Approach (FRA) along with other fuzzy techniques can be utilized such as Fuzzy Analytical Hierarchical Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). These approaches, based on the principles of fuzzy logic and sets, are advantageous in systematically measuring information qualitatively and quantitatively. This can assist in simplifying the risk analysis and reducing the corresponding, subjectivities, uncertainties, ill-defined problems, and dealing with vague information efficiently.

1.2 Problem Statement

Bridges are crucial structures, which assist in the overall transportation infrastructure systems. Since bridges are subjected to multiple loadings at a regular basis, risk

management is very important in order to preserve their functionality. Risk management of bridges is particularly important for understanding the likelihood of extreme events and service distribution along with the consequences of service disruption. Thus, this thesis is concerned with developing and providing a detailed reliability risk-based methodology for the decision making of highway bridges made of concrete and steel.

1.3 Aim and Objectives

This study is aimed at delivering a successful tool that can provide safety risk analysis for bridge structures. This aim will be achieved by basing the tool on a numerical model formed on mathematical calculations, relevant to the maintenance of bridge structures. To elaborate, the goals of this research will be satisfied by reviewing, analysing and utilising the various fuzzy logic based approaches (FRA, FAHP and TOPSIS) to define the risk factors for the highway bridges. This involves reviewing a number of cases such as accidents, which have occurred in the bridge structures. Addressing structure failures leading to bridge collapses and accidents can help understand the possible solutions to bridge failures.

The main research objectives of this study are:

1) To study and examine the current safety-related issues and investigate the types of risk present in the bridge industry.
2) To undertake an extensive literature review in order to form a deeper understanding of the current safety issues, which exist along with the corresponding types of risks in the bridge safety industry.
3) To identify the most critical elements of the chosen type of bridge.

4) To develop a risk model to assess the failure modes of the bridge structures based on the collected outcome of studies.
5) To develop a cost estimate model for maintenance cost analysis of the bridges.
6) To develop a risk-cost model to optimise the risk reduction and maintenance costs for the best maintenance solution.
7) To validate and verify the reliability of the risk assessment and safety management model with the assistance of case studies. Case studies will assist in illustrating the implementation of the suggested safety risk management model.
8) To produce an overall efficient and effective safety risk assessment and management framework, applicable to the highway bridges.
9) To provide recommendations for improvement of the bridge maintenance strategy.

1.4 Thesis Layout

The structure and contents of this thesis are organised as follows:

Chapter 1 provides an introduction to the study by providing the motivation for performing this study. In addition, the thesis objectives are provided in this chapter.

Chapter 2 provides a description of the research methodology adopted in this study. The chapter aims to highlight the significance of known important steps in performing the current research and describing research methods applied in this study, which can be utilised for developing and improving a safety risk management model for highway bridge safety risk analysis.

Chapter 3 presents a review of the relevant literature by first providing a detailed background on bridges. The chapter then discusses case studies concerning bridge accidents in order to understand the reasons behind such accidents. The chapter also discusses the problem of corrosion in highway bridges in detail along with providing the description of risk analysis and possible solutions to bridge failures.

The review includes an appraisal of current deterioration models cost estimate optimisation methods, theories and models that can be modified and adapted to be used in this research. A review of fuzzy reasoning techniques, FRA, FAHP and FTOPSIS is also provided in this chapter followed by the application of these techniques to bridge structures.

Chapter 4 presents the new safety risk model applicable for bridges. Three input parameters, CS, FF and WF are introduced and then used for assessing the risks from components levels all the way to system level. The Consequence Severity Criteria (CSC) parameter is introduced as the multi-consequences parameter, which takes into consideration eight factors that are considered significant for the risk analysis of bridges. The eight factors, which are, functionality, safety, value for money, environment, traffic delay, time, reputational damage and socio-economic consequences are discussed in detail. The fuzzy techniques, FRA, FAHP and FTOPSIS are discussed in detail along with explaining their contribution to the current study and the proposed safety model.

Chapter 5 presents a discussion of the three case studies utilized in this work, which are relevant to the safety aspects of bridges. In addition, the chapter provides the corresponding risk responses for each case study discussed.

Chapter 6 presents a discussion on the evaluation model by discussing the results from the three case studies used. In addition, the chapter also discusses the advantages and disadvantages of the application of the developed model. The advantages, as well as disadvantages of using FRA, FAHP and FTOPSIS are also discussed. Further possible improvements to the model are also suggested.

Chapter 7 presents a summary of the key findings of the research, the research novelties, the main conclusions drawn and recommendations for future studies are made.

1.5 Publications and Presentations

Almutairi, H. H., Baniotopoulos, C., and An, Min. (2020). Risk Assessment Model for the maintenance of highway bridges. Under Review.

Almutairi, H. H., Baniotopoulos, C., Ali, W. and An, Min. (2019). Bridge Risk Assessment Based on Fuzzy Reasoning and Analytical Hierarchy Process. Under review in Advances in Structural Engineering Journal.

Almutairi, H. H., Baniotopoulos, C., Ali, W. and An, Min. (2017). New Risk Assessment Model for Bridge Maintenance. Coordinating Engineering for Sustainability & Resilience. CESARE'17. Dead Sea, Jordan.

Almutairi, H. H., Baniotopoulos, C and An, Min. (2016). New Risk model for bridge maintenance. Civil Engineering Student Conference. Birmingham, UK. (*Winner of First Prize*).

CHAPTER 2: RESEARCH METHODOLOGY

2.1 Introduction

This chapter provides a description of the research methodology adopted in this study. The chapter aims to highlight the significance of known important steps in performing the current research and describing research methods applied in this study, which can be utilised for developing and improving a safety risk management model for highway bridge safety risk analysis.

The proposed management model is be based on the combination of FRA (Fuzzy Reasoning Approach), FAHP (Fuzzy Analytical Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods with the aim of improving the overall bridge safety risk model along with decision-making. In order to achieve this, a set of tasks needs to be established and undertaken. This chapter describes these stages of the development of the research model, the model-testing and the case studies.

2.2 Research Outline

The design of a research topic must be well planned and suitable enough to be able to respond adequately to the research questions. These research questions are the first active step of the project. Therefore, it is vital to understand how exactly the research will be carried out in order to create an organised and chronological pattern for the research methodology. This organisation can help one in being able to form a useful link between the obtained data and the information already presented in the chapter of

literature review. Hence, this can further assist in the post-processing of the data and analysis of the results obtained.

A critical review of the contemporary thinking in research methodologies is important for developing and improving a safety risk management model for highway bridge safety risk analysis. As Dainty (2008) explained, an ideal research methodology must be based around the reasoning and logical assumptions which form a particular study. A research strategy is able to investigate a problem while determining the research design, which is governed by the data collection, analysis and interpretation stages, as mentioned earlier in this thesis.

Three main approaches that are commonly adopted in such researches are the quantitative, qualitative and mixed methods (Panas and Pantouvakis, 2010). While qualitative methods are widely sued, it is best to use a mix of each of the two techniques, i.e. the qualitative and the quantitative methods in order to carry out a quality research. Therefore, this study utilises a combination of the two methods, which is the mixed method approach for data elicitation and analysis. This will be helpful in confirming the known safety risk factors and determining other useful features for safety risk management. The concept of uncertain risk is used for indicating the ambiguity about the existence or presence of risks.

The research methodology comprises of a number of steps, which are shown below in Figure 2.1. With the help of this research structure, the overall outline of the thesis will be discussed in the following sections, in which each step of the research project is explained.

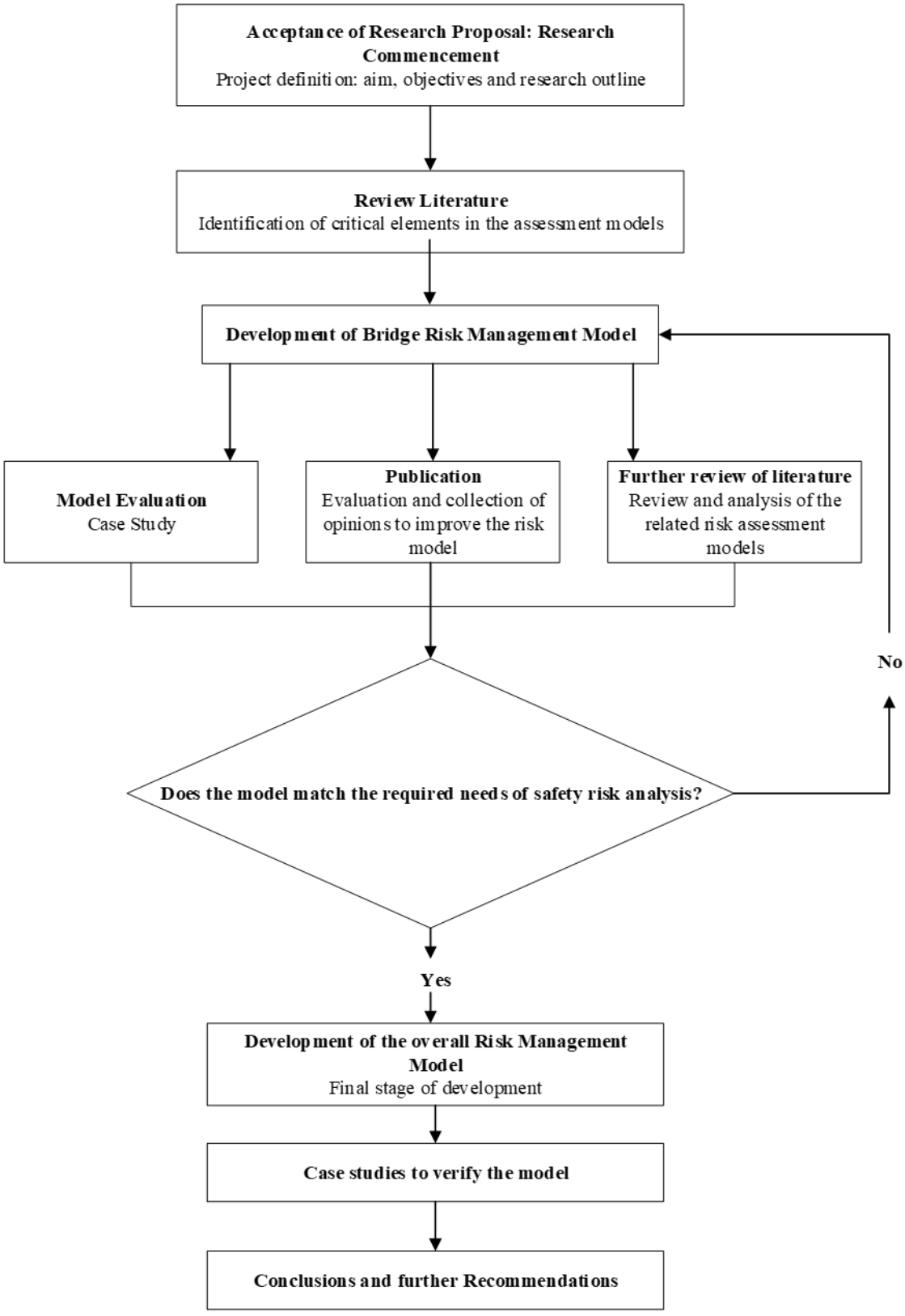


Figure 2.1: Study methodology

2.2.1 Research Objectives

As mentioned previously, this research is aimed on delivering a successful tool which can provide a safety risk analysis for bridge structures. This aim will be achieved by basing the tool on a numerical model, which is relevant to the maintenance of bridge structures. To elaborate, the goals of this research will be satisfied by reviewing, analysing and utilising the FRA, FAHP and TOPSIS techniques. This involves reviewing a number of cases such as accidents, which have occurred in the bridge structures. Addressing structure failures leading to bridge collapses and accidents can help understand the possible solutions to bridge failures.

In terms of the overall structure of this study, as shown in Figure 2.1, an extensive literature review is firstly carried out to form a deeper understanding on the current safety issues, which exist along with the corresponding types of risk. This aids in establishing a research strategy to complete the research effectively. Next, a bridge-related safety risk management model is developed based on the collected outcomes of other studies. Various works from the past will be moderated to assess the levels of the safety risk model. A review of a case study along with a publication and evaluation of other academic and non-academic sources will assist with this phase of the research. If the proposed model matches the safety requirements, further data will be analysed before the finalisation of the overall risk management model for bridges. This would mark the final step of the research, which will be concluded by verifying the reliability of the model and thus making any suggestions for further improvements to the study.

The following section provides a brief description of each of these steps in the research outline.

2.2.2 Literature Review

A review of the relevant literature for this study will be performed as it will help bring together useful knowledge from earlier studies which have mainly focused on studying the risk management models, specially related to bridge structure safety such as the operation and repair of bridges. While this step of the study will allow the researcher to form a deeper understanding of the subject, it will also allow for the identification of possible gaps in knowledge that can potentially be bridged through the works of this current research. The literature review in this study focuses on the existing safety problems and the associated risk factors which are concerned about bridge structure safety. This involves reviewing a number of cases such as accidents, which have occurred in the bridge structures. Useful information in form of data is collected from such sources through publications, journal papers and industrial reports. All these can be studied to strengthen the current research's objectives. This study will also review several hazard identification techniques. For instance, this includes the identification of key structural and hazard variables and the overall characterisation of hazards. These will be relative to the various bridges in operation in order to be able to comprehend how safety risks are assessed in these structures. The literature review sheds lights on the earlier works and their research methodologies so that any possible weaknesses can be addressed. It is worth mentioning that while various amounts of literature already exist on the safety management of bridges, the risk mitigation efforts are still challenging to address. Further, one of the main parts of this literature review also involves the thorough scrutinization of relevant techniques such as FRA, FAHP and TOPSIS to understand their respective mathematical models and concepts. The literature review would not only assess the existing risk models, but also consider the

various cost-based optimisation theories and models, which can be modified to be used in this research. The relevant bodies through which information will be attained include the Highways Agency, Network Rail, Department of Transport, ICE Library, American Society of Civil Engineers (ASCE) and Road Research Laboratory (RRL). Furthermore, the identification of critical elements in the assessment models will involve studying both, the quantitative and qualitative methods of assessments. It will be ensured that this is in accordance with the current standards for the assessment of highway bridges.

2.2.3 Development of the Conceptual Bridge Risk Model

A conceptual model for this study would be a depiction of a scheme, made up of the composition of concepts and ideas, which can be utilised to assist the understanding and simulation of the current subject and the presented model. The mathematical model will be formed through the data collected by reviewing several sources, especially for bridge related projects. This will assist in establishing a solid basis for developing appropriate modelling techniques. Critical analysis of the achieved data will help in the prediction of safety risks of bridges, both during - operation and maintenance. Such an analysis will help in defining the qualitative descriptors used in the risk model while allowing the proposed risk model to take into account the quantitative risk data. Any associated uncertainties can also be addressed through this model.

Hazard is a term which can be described as “likelihood of occurrence of an event in terms of maximum intensity” as stated by PIARC (2005). Whereas, risk can be defined as “quantitative expression of uncertainties and harmful consequences associated with a hazard” (Jannadi and Almishari, 2003; KarimiAzari et al., 2011; Tangtinthai, 2016). Precisely, parameters used in safety risk analysis include are probability of occurrence

(PO) and severity of consequences, which refers to a multi-consequences parameters. The multi-consequence parameters can be expressed in terms of several factors, which include the safety, functionality, value for money, environment, traffic delay, time, socioeconomic and reputational damage. An organized and thorough assessment of all risks is required in order to assist with the decision making and cost effectiveness in a project.

Moreover, the FRA, FAHP and TOPSIS approaches will also be incorporated for the development of a new safety risk management model, specifically designed for bridges. The use of FRA techniques in safety risk management has become very popular (Chan, Chan and Yeung, 2009). FRA techniques refer to fuzzy concept, which comprise of fuzzy set, fuzzy logic, and hybrid fuzzy techniques. Precisely, fuzzy is extensively acknowledged as a division of modern mathematics when compared with traditional mathematics. It must be noted that the use of FRA in combination with FAHP will assist in the proposition of the safety risk model in the current study. It is also well-known that the use of such fuzzy techniques can help in overcoming the trials of decision-making (Chan et al., 2013).

In addition, a cost estimate model will also be incorporated which can assist with the cost effectiveness. For instance, repair costs, labour costs as well as renewal costs are taken into consideration in order to search an optimal maintenance option. Undoubtedly, the developed model will be designed with the aim of prioritising safety through the most cost-effective options. This combination of the risk assessment model with the cost estimate model will help in optimising an overall risk-based maintenance model for highway bridges.

2.2.4 Model Evaluation

This particular stage of the study would involve the model being piloted prior to being introduced more widely. This will help ensure the effectiveness of the model and will be done mainly using case studies. The possibilities of such a test are either resulting in a satisfactory or unsatisfactory outcome. In case of an unsatisfactory result, the model will be revaluated and perhaps redesigned and modified until a satisfactory outcome is achieved. This will then be followed by testing the model to confirm its effectiveness and efficiency. To do so, the model will be validated and verified with the help of an actual case study or even industrial data. It is also probable to use other legitimate sources in the data collection step. Next, an academic publication will help in communicating, interacting and discussing with a wider audience within the same field. The obtained feedback will be valued and used to further expand as well as improve the model.

2.2.5 Review of Relevant Case Studies

This stage of the study would involve reviewing relevant case studies for obtaining the necessary data required in this thesis. These case studies offer a demonstration of the model as the model will be further developed by using those factors which were not addressed in the earlier model. In case, if any of the multi-consequences parameters is not satisfied based on the existing data, it will be judged through expert analysis. Interpretation of case studies can help in identifying key situations and can be utilised as a mode for facilitating the enlightenment of issues pertaining safety of bridge structures.

In general, case studies provide an in-depth examination and analysis of a known case. As Yin (1989 and 2003) explains, case studies are conducted with the aim of responding to the common “How” and “why” questions, which are an illustration of real-life cases. Case studies have been classified as vital research strategies in several areas. In the investigation of complex situations such as the safety of bridge structures, the use of case studies has been proven reliable. This is due to their ability to enable the researcher to encapsulate the useful information for necessary investigation. To elaborate, case studies allow the investigators to retain the all-inclusive and expressive features of real-life situations (Sutrisna and Abbott, 2007). They can then further use the existing information to perform further research.

The use of case studies in this work can particularly help with the verification of the dependability and consistency of the developed bridge risk assessment and safety management model. Any existing bridge-related issues shall be identified through this step. It is well-known that the designing and construction of bridges is an entirely complex process. Hence, it is probable that key details are easily overlooked if a proper construction strategy is not adopted (Hadipriono and Tahir, 1990). The analysis of a case study in this work can help understand the common issues which occur in regard to the safety of bridges. It is then intended that such a review of a case study will help in mitigating the risks incurred due to inaccurate designing and planning. Also, the main reasons for failures relevant to the current field will be identified. While the proposed model will be piloted on a number of actual bridges prior to proper use, the case study materials will be gathered from Highways Agency and its managing agents. However, this requires collaboration and an agreement in principle with the HA.

2.3 Summary

This chapter provides complete details of the research methodologies adopted in this study. The purpose of such a research methodology is that it will help in answering the various research questions of this study. The chapter also describes the approach used in this study which can aid in bridging any existing research gaps. An effective research methodology involves the resolution of existing issues related to risk management models specific to the bridge structures.

The proposed management model will be based on the understanding and applications of FRA, FAHP and TOPSIS methods with the aim of improving the overall bridge-safety risk model along with decision-making. In order to achieve this a set of tasks needs to be undertaken. This chapter describes these stages for the development of the research model. These stages mainly include the setting of the project's aim and objectives, carrying out a literature review relevant to the current study, the development of the conceptual bridge risk model, the collection of data for validation and the overall application of the proposed model. The case study materials will be gathered from Highways Agency and its managing agents. This will then be followed by the final summarisation of the research performed in this study. The outcomes of this research can be utilised to make additional recommendations will, which can help mitigate future risks and offer the chance to identify any research areas for further works. Finally, the overall purpose of setting such a research methodology is to enable the researcher to produce quality research, which can help maintain the safety and structural integrity of bridges and related structures for a longer period of time in terms of their maintenance, repair and improvement works.

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction

This chapter presents a review of the relevant literature on the study of the current maintenance models for highway bridges, which exist across the world. The literature review will provide a general background on the bridges and their importance in today's world. Next, the review will identify the shortfalls in current practices and methods of maintenance related to bridges.

An extensive literature review is carried out in this study to form a deeper understanding of the current safety issues, which exist along with the corresponding types of risk. This aids in establishing a research strategy to complete the research effectively. Such a review can help bring together useful knowledge from earlier studies, which have mainly focused on studying the risk management models, especially related to activities such as the operation, maintenance and repair of bridges. While this step of the study will allow the researcher to form a deeper understanding of the subject, it will also allow for the identification of possible gaps in knowledge that can potentially be bridged through the works of this current research. The literature review in this study focuses on the existing safety problems and the associated risk factors which concern bridges. This involves reviewing a number of cases such as accidents, which have occurred in the bridge structures. Useful information in form of data is collected from such sources through publications, journal papers and industrial reports. All these can be studied to strengthen the current research's objectives. This study will also review several hazard identification techniques. For instance, this includes the

identification of key structural and hazard variables and the overall characterisation of hazards. These will be relative to the various bridges in operation in order to be able to comprehend how safety risks are assessed in these structures. The literature review sheds light on the earlier works and their research methodologies so that any possible weaknesses can be addressed. It is worth mentioning that while various amounts of literature already exist on the safety management of bridges, the risk mitigation efforts are still challenging to address.

Further, since the proposed management model in this thesis will be based on the understanding and applications of FRA (Fuzzy Reasoning Approach), FAHP (Fuzzy Analytical Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods, this chapter will also include a general review of these methods. The careful scrutinization of these techniques will be performed to understand the respective theory behind the creation of such methods and their respective mathematical models along with concepts. It is aimed that such a review and critical analysis of the literature and specifically these methods can assist in making the necessary modifications to the current optimisation methods, theories and models. This would then allow for the existing models to be adapted and integrated for use in the current research. In addition, the literature review would not only assess the existing risk models but also consider the various cost-based optimisation theories and models, which can be modified to be used in this research.

The relevant bodies through which information will be attained include the Highways Agency, Network Rail, Department of Transport, ICE Library, American Society of Civil Engineers (ASCE) and Road Research Laboratory (RRL). Furthermore, the identification of critical elements in the assessment models will involve studying both,

the quantitative and qualitative methods of assessments. It will be ensured that this follows the current standards for the assessment of highway bridges.

3.2 Background Research on Bridges

Bridges are known to be crucial structures, which assist in the overall transportation infrastructure systems. Transportation systems are required to be well-organised in order to ensure the consistent and efficient flow of people, goods and services (Decò, Bocchini and Frangopol, 2013). Today, bridges are known to play a fundamental role in road networks. Bridges not only connect important roads but may also be a mean of connecting important cities. These highway bridges may be constructed of either steel or concrete. Additional materials used in the construction of such bridges include iron, timber, asphalt, rubber and several other materials. It is worth mentioning that bridges are treated usually as an everlasting construction, hence they require a great deal of maintenance in order to preserve their functionality. They act as a vital hub for land transports and as a result, tend to have a direct impact on the economic and social developments (Yang et al., 2017). Hence, bridges are known to be one of the most complex building structures. The designing process of bridges includes a number of complex factors such as safety, aesthetics, integration and costs (Jakiel and Fabianowski, 2015). Since bridges are known to serve for a long period of time, they are usually subjected to multiple loadings in addition to several risks in their service (Kodur and Naser; 2013).

As Sinha et al. (2002) mention, transport engineering has three main aspects, which need to be addressed. The first part comprises the design, construction and maintenance of various infrastructures such as bridges. The second part involves the planning,

project development and the management of these infrastructures. Finally, the third part encompasses the operations, logistics and overall operations including business. A significant amount of research has been carried out in the past on the study of bridges, specifically from the point of civil engineering. However, even though the topic has been the center of current focus for a long time, it is also known that several accidents have occurred in the past, which concern the safety of these bridges in terms of their ageing, loss, structural deficiency and various other issues (Andric and Lu, 2016). As Duan and Chen (1999) mention, designing bridges is the key step in civil and structural engineering of infrastructure systems. In the discussion of infrastructure systems, the significance of bridge maintenance is emphasised. This is due to the associated causalities, which may occur because of any damages or collapses of bridges (Choi, Sun and Park, 2013).

Aftermaths of any type of extreme event can result in the unexpected decline of infrastructure systems. This may lead to possible traffic disturbances, economic losses (Decò, Bocchini and Frangopol, 2013) as well as public losses (Liu et al., 2017).

The following section provides a review of some of the accidents and mishaps, which have occurred concerning bridges, mainly due to the poor maintenance and associated risk factors.

3.2.1 Discussion of Major Accidents Concerning the Safety of Bridges

Assessing the risks associated with bridges is a vital step in preventing any safety accident of bridges while ensuring the safety of the public (Yang et al., 2017). Literature shows that 503 bridges had collapsed in the USA during the period of 1989-2000 (Wardhana and Hadipriono, 2003; Zou, Kiviniemi and Jones, 2017). Further studies

show that a huge amount of fatalities, accidents and unwanted hazards occur on construction sites every year (Liu et al., 2004; ILO, 2005; Zhang et al., 2013; Zou, Kiviniemi and Jones, 2017). All these problems are direct results of issues relating to safety, time and costs, which are commonly observed due to poor risk management (Tam et al., 2004).

A detailed statistical investigation during the period of 1996-2005 showed that nearly 210 bridge failures were because of vehicle collisions (Sharma et al., 2008; Zhou and Li, 2018). Vehicle collisions could be due to traffic congestions. This shows the direct impact of any unexpected physical activity on the bridges. Hence, it can be concluded from the results of this statistical investigation that most operational bridges in the mentioned period were not resilient to any strong unexpected loads.

Zou, Kiviniemi and Jones (2017) indicate in their study that the scope of risk is very broad. It thus comprises of matters involving damages, failures to infrastructures, injuries and losses to lives, economic issues and possible interruptions to construction times. All these can be triggered due to problems concerning designing deficiencies, material failures, inexperienced operatives and inadequate management.

As Yang et al. (2017) mention, the I-35 W Mississippi River Bridge, which was located in the United States collapsed in 2007. Investigation on the incident showed that reasons for the collapse were; load capacity issues, design issues, inadequate numerical analyses and modelling along with undersized and corroded gusset plates. Mainly, design and construction errors had contributed to such a failure of the bridge. While corrosion worsened the state of the bridge, the National Transportation Safety Board (NTSB) declared that the lack of proper routine checks to the safety aspects of the bridge was the main contributor to the incident. Hence, it can be stated that the sole reason for such an

accident was the absence of maintenance and repair of the bridge. Yang et al. (2017) also mention some bridge failures, which occurred in China, were mainly due to damages and losses to the relevant structures.

Furthermore, a recent study (Oh, Deshmukh and Hastak, 2013) commented on the importance and criticality of key infrastructures in transportation systems such as bridges. The study mentioned that it is very crucial that bridges are stable in normal and hazardous situations, both. For instance, in the event of any unexpected natural event such as earthquakes, bridges can have a role in sustaining communities and providing emergency response for supporting activities to bring life to normal at the soonest. Hence, examining the functional and structural stabilities of such crucial infrastructures is very important. Also, a rapid emergency response is capable of limiting any further consequences and can assist in restoring functionality (Decò, Bocchini and Frangopol, 2013).

Kodur and Naser (2013) mention the factors which can influence the fire performance of bridges. They state that the level of vulnerability of structural components to a fire decides a particular bridge's performance under fire. Also, the resulting impact of any such event is based on traffic functionality. Geometric features are also one of the several key factors which can have an impact on the fire performance of the bridge. To elaborate, if a bridge is made of concrete, the cover thickness to internal reinforcement of steel tends to have a direct bearing on the fire response of reinforced structures. Hence, the materials used in the construction of bridges can also have a huge role. Moreover, the critical nature of a bridge is another important factor in terms of fire hazards. Both, bridge locations and traffic densities are able to determine this critical nature of bridges. Other factors which need to be addressed while dealing with the

maintenance of bridges include the traffic demand, traffic delays, times expected for repair works and the associated costs needed. In addition, other factors also include the economic consequences as well as the environmental damages resulting from any major bridge accidents.

Elaborating on the major causes of bridge accidents, Akkeson (2014) provided several critical factors, which have an influence on bridges. These include the materials used, surrounding ambient conditions and receiving loads on the bridges in terms of traffic. These factors need to be addressed during the construction of bridges. However, further investigation after a number of accidents showed that miscalculations with any of these factors could have detrimental effects. Any negligence in any stage of designing, planning and construction can result in the collapse of bridge structures. As detailed above, lack of maintenance is the main reason for several bridge accidents occurring around the globe. It is worth mentioning that some events and incidents such as earthquakes or floods may result in possible damages to any of the parts of the bridges. Although this may not be visually evident, this can lead to the weakening of the bridge structure, internally. If the bridges are not examined regularly, such a defect can lead to an increase in the possibility of bridge failure. This also indicates the importance of immediate action and repair work, which must be performed on the bridge after any natural calamities (Akkeson, 2014).

Some studies have also shown that usually bridges collapse during the construction period. If this is the case, then the failure occurs at a primary stage and thus the reason may not be evident. Investigations on this have indicated that the main reason for such a bridge collapse is the use of inferior quality concrete materials. This further proves the

significance of each part of a bridge and the need for proper maintenance (Akkeson, 2014).

Further work by Liu et al. (2017) highlighted the damage by a collision or a leakage of any dangerous chemical substance on a highway bridge. They stated that such an incident may pose a huge risk to the safety of the bridges. It is also known that bridge traffic can be massively damaged by fire. In fact, a fire can also result in permanent damage to a bridge or in some cases it can also lead to a bridge failure. Previous studies (Astaneh-Asl et al., 2009; Bajwa et al., 2012) relating to fires on bridges have shown that the fire led to the melting and collapse of the steel girder, which further resulted in major destruction of the bridge structure. Other studies confirmed the increasing number of accidents leading to fires on bridges. This is now posing a huge risk to the bridge structures. Even though this subject has been the center of attention for most studies, there are presently no appropriate fire prevention schemes for bridge structures, in general (Garlock et al., 2012).

Scheer (2011) indicated that in some cases, the collapse of a bridge may be inevitable. This may be due to the faulty design of a bridge. Negligence in regard to any factors related to the bridge construction may lead to a disaster.

3.2.2 The Problem of Corrosion in Highway Bridges

Corrosion is a common natural problem encountered in bridges, especially with steel bridges. A review of relevant literature has shown that corrosion of bridges is the main cause for deterioration of the bridge structures. Hence, this study focuses on the problem of corrosion in highway bridges as this issue needs to be monitored and the relevant risks need to be managed in order to avoid any further accidents. The main

cause for any corrosion is the exposure of steel in bridges to the surrounding atmosphere. Thus, the overall performance of the bridges is strongly influenced by corrosion. Essentially, corrosion can result in a reduction in the load-bearing capacity of the bridge hence leading to a bridge collapse or failure. Corrosion may also result in life-threatening circumstances. Therefore, it is extremely important to address this problem for the relevant safety, environment and economic reasons (Cinitha, Umesha and Iyer, 2014). It is known that a highway bridge is classed as structurally deficient if any of its parts are regarded to be in a poor condition. For steel bridges, corrosion may take place after the protecting coat deteriorates. Currently, the coat is assessed with a visual aid and physical tests for the coating characteristics. Various parameters such as the adhesive properties, the thickness and colour are assessed based on the technical specifications. It is also important to perform regular coating examinations in order to spot any deterioration in the protective coating (Kreislova and Geiplova, 2012). Smith and Day (2013) have mentioned that the application of protective measures is often successful in overcoming the catastrophic bridge failures caused mainly by corrosion. In terms of concrete bridges, Kamaitis (2002) studied the effects of reinforcement corrosion. The study stated that it is very common for concrete bridges to deteriorate due to corrosion of the reinforcements. Concrete carbonation along with chloride penetration are the main reasons which may initiate such a type of corrosion (Pearson and Patel, 2002). When steel corrodes, the formation of cracks and spalls is observed in the concrete which can result in secondary damage due to the impact of aggressive agents. It is worth mentioning that if the risk of reinforcement corrosion is perceived at an early stage then a catastrophic failure can be prevented or probably be reduced by the adoption of safety countermeasures. However, if the corrosion has exceeded certain

limits resulting in cracks and spalls of the concrete, then the repair works become more complex and costlier.

In colder places such as the United Kingdom, the process of de-icing is very common, especially in the winters. However, this process results in the chloride-induced corrosion of the reinforcement bars. As mentioned above, this leads to a deterioration in the structure of the bridge. Other sources of chlorine contamination in bridges is due to the presence of chloride ions in concrete. Marine ambience along with exposure to any airborne chloride may also result in possible degradation of concrete bridges.

Studies have shown that corrosion in bridges and reinforced concrete structures mainly takes place due to: inadequate concrete covering, low-quality concrete material, the impact of harmful salts (Kamaitis, 2002), poor designs or specifications, failure of bridge expansion joints and cold joints (Wallbank, 1989), chloride content, concrete diffusive properties, chloride threshold values and other environmental factors (Hansson 1984; Wryers et al. 1993; Liu and Weyers 1998; Chen and Mahadevan 2008; Zhang et al. 2010).

In terms of the degree of corrosion, it is known that chloride corrosion is rapid as compared to corrosion due to carbonation in cold places such as the UK. Hence, this indicates that chloride corrosion is crucial to address in order to prevent the deterioration of concrete bridges. However, this is only true for places where de-icing salts are used. Otherwise, for places that do not make use of de-icing salts and where the production of Carbon dioxide is high, carbonation induced corrosion tends to be the governing factor. Therefore, it is necessary to take into account the appropriate corrosion factors in the proposed research model.

Pearson and Patel (2002) in their investigation stated that the Highways Agency oversees 9700 bridges. 80% of these bridges are concrete bridges. The investigation also stated that for the whole country, 38% of the bridges were made of concrete while the rest had variations in the type of bridge stocks used. It is anticipated that concrete bridges in the North degrade quicker as compared to those in the South due to differences in the temperature.

3.2.2.1 Corrosion Mechanism

As mentioned above, highway bridges are greatly affected by corrosion. In terms of corrosion of reinforcement steel, this is mainly due to an electrochemical reaction, which consists of anodic and cathodic processes (Hansson, 1984). While the anodic reactions lead to metal loss due to oxidation, the cathodic reactions tend to consume electrons from the anodic reactions.

There are several possible anodic and cathodic reactions that can occur in steel and concrete. In the absence of some factors, ferrous oxides produce passive protective layers. These can serve to avoid the iron cations from penetrating the concrete, thus preventing the oxygen from reaching the steel. Chloride ions, carbon dioxide, oxygen and moisture can all reduce the alkalinity of the concrete. If this happens then the passive layer of the steel will also reduce, thus resulting in corrosion in the reinforcement. In terms of threshold limits, some studies (Liu and Weyers, 1998; Pantazopoulou and Papoulia 2001) have mentioned that if stress levels on concrete surpass its tensile strength, then it is highly likely that cracks and spalls will develop along with degradation of the concrete.

In terms of reinforced concrete structures, corrosion is a major issue. Not only does corrosion in such a case result in the degradation of the strength but it also leads to serviceability losses. Several studies have been undertaken in order to understand the corrosion process in concrete structures such as bridges. These works have shown that the service life of reinforcement is dependent upon the degradation phases along with the tolerable damage levels. As Wryers et al. (1993) mention, chloride-based corrosion can be split into three phases. These are the initiation, period and propagation of the corrosion, as illustrated in Figure 3.1. To elaborate, once the corrosion starts to occur, there is some local pitting which takes place. This is then followed by the development of cracks where localised corrosion is usually observed. This stage can often be referred to as the first step of crack propagation. Later, general corrosion marks the second step of crack propagation (Zhang et al., 2010).

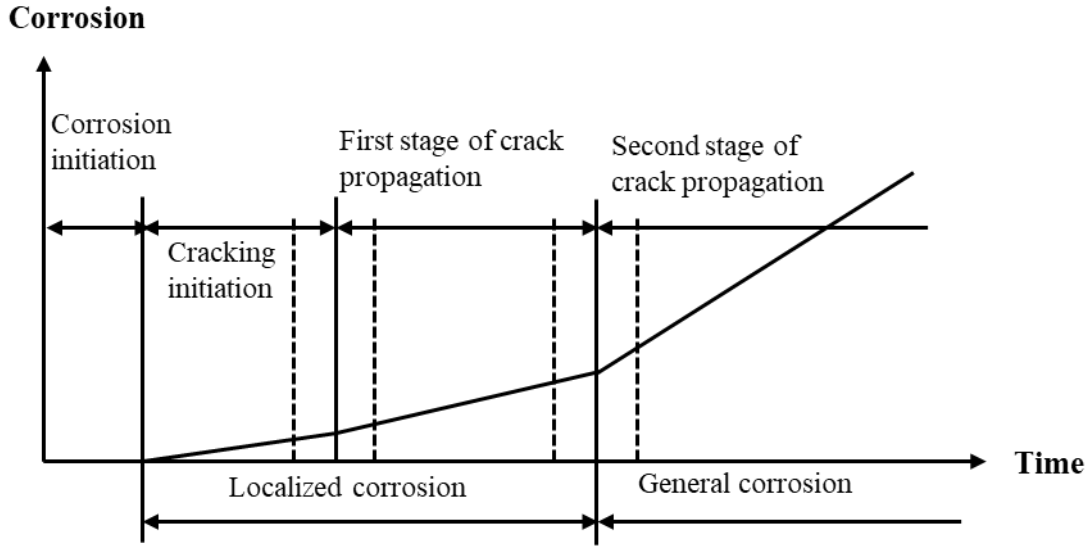


Figure 3.1: Chloride induced corrosion pattern (reproduced from Zhang et al., 2010).

3.3 Risk Analysis

3.3.1 Risk

Risk can be defined as the possibility of harm in a negative sense. In a positive sense, it can be defined as a chance to obtain something valuable. Human beings have always been risk-takers; the basis of survival is dependent on taking calculating risks. The same logic can be applied to project management. Projects come with risks that can define the course of actions to be undertaken to obtain a reasonable payoff. Risk is known to be intrinsic and thus a parameter which cannot be completely avoided.

Project risks or uncertainty come in a type that can be labelled as known unknowns and unknown unknowns. Zeng et al. (2005) mention that risk can be measured in terms of the probability of an undesirable event and its undesirable consequences. Risk perpetuates through all levels of project management or industry. Many factors can contribute to risks, but there exist certain definite factors that are always present. A lack of predictability and uncertainty related to project or business planning requires attention to manage and obtain a favourable outcome.

The art of risk management is to reduce these risks systematically while implementing good business practices. While risks cannot be completely avoided, they can be effectively managed. Risk management refers to a vital step in a project which could lead to adequate management and is a key for obtaining success. Managing risks is extremely important in any project such as the assessment of bridge structure safety as this field is known to be both, uncertain and complex (Aminbakhsh et al., 2013; Aven, 2016).

Figure 3.2 shows the typical four steps involved in managing risks (Mills, 2001; Zeng et al., 2005, 2007; Han et al., 2008; Winch, 2010; Nieto-Morote and Ruz-Vila, 2011). These four steps fall under two categories: risk analysis and risk mitigation, which are both the part of the implementation stage in a safety management system. To elaborate, the first step is the identification of risk, which aims to determine the potential risks associated with any project. To do so, several techniques such as brainstorming, check-list and HAZOP study could be carried out. The next step involves the assessment of the risk, which is also known as the risk analysis step. This stage helps in assessing the risks by the identification of any unwanted events, the probability of their occurrence and the consequences of such events. Figure 3.3 is a typical example of a risk matrix, which is commonly used for assessing and characterizing risks (Dyke et al., 2002; Rafele et al., 2005; Henselwood et al., 2006; Murray et al., 2011). Over here, the notations and colour coding of low (green), medium (yellow) and high (red) refer to the levels of risk. A low risk can be defined as an insignificant or easily controlled risk. A medium risk is tolerable; however, risk controls must be taken. A high risk is unacceptable regardless of whatever the benefits are with that kind of risk. Hence, it is must that adequate controls and actions are carried out for eliminating this risk.

The third step refers to the response planning where the risk is evaluated, and it is decided whether a particular risk is acceptable or not. In case the risk is considered acceptable, then the risk needs to be controlled only but not necessarily reduced. On the contrary, if the risk is considered unacceptable, then it is important to avoid or reduce it (Zeng et al., 2005). The final step involves risk monitoring and controlling. This step requires the adoption of appropriate action and can be referred to as the risk treatment

where the risks are either transferred, mitigated or controlled. In this step, feasible risk control options are also identified.

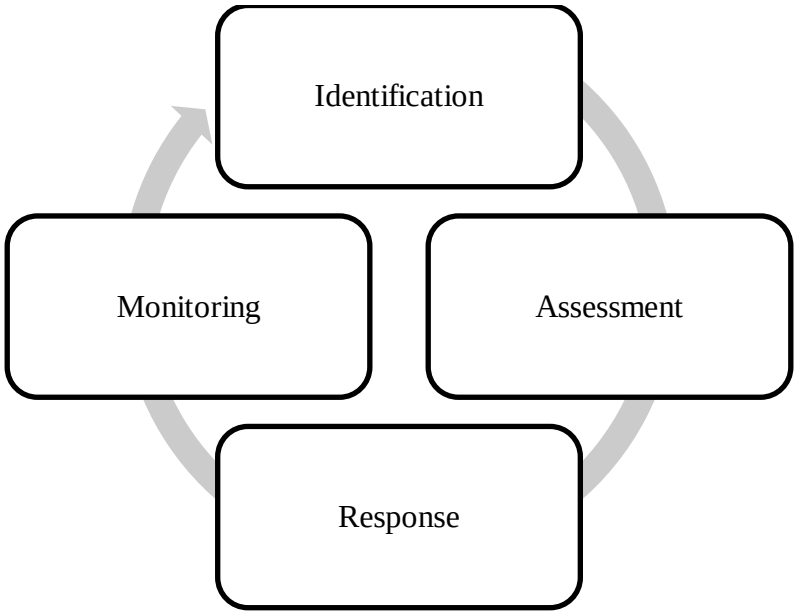


Figure 3.2: Four steps involved in the management of risks.

		Consequences				
		Not significant	Minor	Moderate	Major	Severe
Likelihood	Almost certain	Medium	High	High	High	High
	Likely	Medium	Medium	Medium	High	High
	Possible	Low	Low	Medium	Medium	High
	Unlikely	Low	Low	Low	Medium	Medium
	Rare	Low	Low	Low	Low	Medium

Figure 3.3: A typical example of risk matrix.

3.3.2 Types of Risk

There exist primarily three types of risk. The first risk, known as ‘pure and particular risk’ includes damage to personal property from fire, flood, collapse and several more factors. By law, clauses in contracts make it an obligation to obtain insurance to provide coverage against these risks. The next two types are defined to be out of control and

unexpected. A ‘fundamental’ risk is damage from external factors such as war, nuclear fallout, or even government taxes, malicious damage. These require no insurance cover and are subject to statutory liabilities. A ‘speculative risk’ is something can be apportioned in advanced and is subject to decisions by the parties involved. This may include time and money losses resulting from unexpected ground conditions, adverse weather, transit delays, etc. These risks are beyond control as stated before and require proper handling and timely resolution. The type of risk management implemented is dependent on its nature. Risk management is crucial to the growth of the commercial enterprise (Wood and Ellis, 2001; Aven, 2016). It is also worth mentioning that risks tend to vary through the lifecycle of a project. Hence, the controls are required to be matched accordingly.

3.3.3 Risk Analysis

Tools that can automate data searching and data management for various project phases can assist in risk analysis. Data sources such as statistics, existing documentation, inspection records and expert opinion can prove valuable to a project risk analysis. The risk analysis technique can be classified as qualitative or quantitative (Aven, 2016).

3.3.3.1 Qualitative Analysis

Qualitative risk analysis consists of presenting information like a description or recommendation. Occasionally it can be in the form of a score that can provide a scale for the probability and consequences of failure. They can be presented as a list, map or ranking. These analysis techniques can identify which risks have to be prioritized as high, medium or low. There exist a few analysis techniques and they are listed as follows (Aven, 2016):

- Brainstorming
- Delphi method
- Cause and affect diagram
- Checklist
- Event Tree Analysis (ETA)
- Risk Breakdown Structure (RBS)

3.3.3.2 Quantitative Analysis

Quantitative analysis techniques depend on numerical data to define the consequences of the risks. These can be presented in the form of the monetary value of property damage value. Quantitative analysis demands the data be numerically analysed using the following methods (Zio, 2007; Meyer and Reniers, 2013; Aven, 2015; 2016):

- Probability distribution
- Fuzzy logic
- Fault Tree Analysis (FTA)
- Expert judgement
- Expected Monetary Value (EMV)
- Decision Tree Analysis

3.4 Possible solutions to bridge failures

3.4.1 Background

Bridges are excellent structures that allow one to cross terrains of different elevations or obstacles such as bodies of water or debris. Bridges serve different functions and this, in turn, decides the material and design of the bridge. They are subject to critical engineering design in the modern era as they need to be safe, reliable and withstand the effects of the environment. This makes bridge construction very complex as there exist many different aspects of project planning. The complexity of bridge construction also creates risks that have to be accounted for, small mistakes such as a wrong type of bolt used can lead to fatal consequences in the future. The importance of vital infrastructure systems such as bridges is well known in both, normal and hazardous situations. Hence, it can be easily stated that bridges tend to have a crucial part in sustaining communities and industries.

3.4.2 Inspection of Bridge Structures

There is an immense need to inspect the functional and structural stability of bridges regularly (Oh, Deshmukh and Hastak, 2013). The strength and physical performance of bridges is required to be inspected on a regular basis to allow for the periodic assessment of the safety and maintenance of bridges (Wang and Elhag, 2008). To elaborate, an examination analysing the criticality of bridges must be carried out prior to the occurrence of any extreme and dangerous events, such as natural calamities. Such an examination would involve the use of a decision support scheme incorporating the vulnerability and severity assessments. This would help in providing useful details to appropriate organisations and specialists, which can assist with the facilitation of

improved disaster mitigation responses (Oh, Deshmukh and Hastak, 2013). In order to prevent any safety accidents, it is vital to perform the periodic assessment of bridges from time to time so that the required maintenance can be carried out ensuring the safety of everyone (Housner and Caughey, 1997; Wang and Elhag, 2008; Yang et al., 2017).

3.4.3 Design Considerations and Risk Assessment of Bridge Structures

Larger bridges need to take into account higher safety levels and factors into the design consideration as the scale of impact is consecutively larger. Risk management is crucial to a large bridge and is higher on the priority list of considerations. In addition, the process of bridge construction involves several risk factors which have the ability to affect the safety and quality of bridges in terms of the structures involved, the organization and occurrence of natural disasters (Li, 2014). These risk factors may carry on even after the construction of a bridge and thus bridges require careful maintenance. Repair works must be carried out regularly. In order to track the performance of bridges mainly in terms of their safety, relevant risk assessment models can be applied.

Usually, the process adopted in determining the bridge risks is in the form of risk scores. These scores for bridge structures are linked to various benchmarks. For instance, these standards include factors such as safety, functionality, sustainability and environment. Each criterion is grounded on the British Highways Agency (2004). Generally, bridge risks are examined by knowledgeable and skilled professionals and inspectors. They are needed for providing a measurable rating to the bridges based on the physical examination (Wang and Elhag, 2008). Physical examinations of bridges include assessing the structures for any physical deformities in terms of appearance,

cracks and so on. However, Yau et al. (2014) in their study mentioned the issues arising with recruiting physical examiners. It is highly possible that physical examiners are not able to make a correct decision in terms of the score rating. The assessors might be lacking the required information or expertise. Nevertheless, over the past few years, several researchers have proposed prediction models, which can be used for assessing bridge structures efficiently. Such prediction models are usually split into two types, i.e. with and without parameter learning.

To elaborate, in terms of the model with no parameter learning, a reliability-based method was proposed for assessing ageing in bridges. Risk scores along with life-cycle cost decision methods were used. This method proved successful in measuring bridge health and functionality (Stewart, 2001). Frangopol (2011) states that decisions regarding earthquake-resistant bridges must be reinforced by a life-cycle optimisation strategy while considering the likelihood of effective operations along with the predicted costs incurred on the whole.

Further, another work proposed a risk-based approach for determining an intervening scheme for bridges that experience various kinds of hazards (Adey, Hajdin and Bruhwiler, 2003). One study also made use of failure modes and effects analysis (FMEA) for constructing a system to choose the most suitable countermeasure for mitigating the scour effects. The study concluded that FMEA is a comparatively simpler and systematic approach for assigning risks (Johnson and Niezgoda, 2004). Overall, various models and tools have been used by researchers to deal with the abovementioned issues. Due to the uncertainties and inaccuracies associated with each method, the overall risk management process becomes quite challenging (Keshavarz-Ghorabaee et al., 2018).

A recent study by Andric and Lu (2016) adopted the combination of FAHP and fuzzy logic methods in an integrated manner. The study concluded that such an approach could be an efficient method for rapid hazard investigation. In fact, the use of fuzzy groups for making decisions has been used in the past as well for assessing bridge risks (Wang and Elhag, 2007; Wang, Liu and Elhag, 2008). Since bridge assemblies are multidimensional, the conceptual design procedure is classed as a Multi-Criteria Decision-Making (MCDM) process. As Keshavarz-Ghorabaee et al. (2018) mention, the logic of the fuzzy sets is considered to be one of the most effective methods for dealing with issues relating to uncertainties in the risk management models and MCDM. The TOPSIS approach is also well known for its successful applicability in MCDM issues and the fields of bridge construction.

Pearson and Patel (2002) indicated that it is important to repair deteriorated structures immediately and to do so an organised approach must be taken which comprises a mix of the available techniques, management and economics.

3.5 Review of FRA, FAHP and TOPSIS

3.5.1 FRA

Fuzzy Reasoning Approach (FRA) came into existence in 1979 by Lotfi A. Zadeh. The technique was introduced to provide a beneficial numerical methodology for reasoning that could deal successfully with uncertain and inaccurate data. In terms of the designing, building, operation and maintenance of projects such as those dealing with infrastructures, the overall process is known to be complex, which may suffer from high levels of risks and uncertainities. In addition, there is a great amount of difficulty in assessing risk and risk levels. Hence, the use of fuzzy-based systems, which rely on

risks can allow for the accommodation of experts' opinions and judgements. This can further assist contractors and relevant bodies for carrying out risk management for a particular project (Taylan et al., 2014).

In a study assessing the risks associated within the railway systems, the authors used the FRA technique for qualitative investigation (An et al., 2006, 2007, 2008, 2011, 2016). The investigators of the study suggested that FRA is a type of knowledge base which is initialised based on experts' knowledge. It works through the "if-then" rules that offer a systemic approach for converting the knowledge-based systems into non-linear mapping. Several researchers have stated the benefits of utilising the FRA technique showing that this approach has the capability of being adopted for assessing risks in engineering structures under controlled and uncontrolled environments, depending on the uncertainties in a project (Zeng et al., 2007; Nieto-Morote and Ruz-Vila, 2011).

FRA tends to be an effective option for managing projects with uncertainties, incompleteness, ambiguity and imprecision in terms of the received data (Majumder et al., 2013). For instance, in an engineering project or a follow-up study, it is likely that historical data such as the number of incidences, the severity of incidents, safety costs along with activities is incomplete or lacking some information. However, in such a case, the use of FRA assists the analyst and professional workers with safety management. To elaborate, fuzzy reasoning can transform linguistic parameters into quantitative parametres, which is needed for resolving issues that are fuzzy, vague, uncertain and imprecise for adequate decision-making problems. Hence, the FRA seems to be a successful technique for solving complex problems (Lam et al., 2001). Since it can handle vague data and unclear information, it is appropriate for use in the engineering sector, allowing for the linguistic description of nonlinear function

(Laarhoven and Pedrycz, 1983; Bojadziev and Bojacziev, 1997; Berredo et al., 2005; BS EN 50126-2, 2007).

3.5.2 FAHP

For solving complicated decision-making problems, Thomas Saaty developed a technique, which employed the use of hierarchical structures. The technique computed the decisions based on a quantitative analysis undertaken using mathematics. This technique is known as Analytical Hierarchy Process (AHP) (Saaty, 1980, 1994). Currently, this technique has been widely deployed across the different industries, businesses, health and safety industries (Jakiel and Fabianowski, 2015). This is because these areas of work regularly encounter multi-criteria decision-making (MCDM) problems on a regular basis to help set the priorities (Badri et al., 2012; Aminbakhsh et al., 2013).

Developing countries have a problem with effective project planning and development which includes transportation planning. This arises from the lack of accountability and the example of Departments of Transportation in the US should be an example of how to make the planning effective. Since the resources used belong to the public, consecutively the public is consulted to make final decisions. In turn, it has to be ensured that the public is provided with the right information. This forms the basis of good policymaking. Arslan (2008) provided an example of the integration of fuzzy logic with AHP (FAHP), which can provide an effective guideline. The ‘if-then’ rules of the model help reach a non-biased preference list that can be used to make less controversial policies. The transportation design concepts are subject to public approval and can be chosen to be municipally run or managed by private agencies.

Critical areas of work such as project risk assessment also deploy the use of AHP for weighting and identification of risks (Zeng et al., 2007, An et al., 2011; Nieto-Morote and Ruz-Vila, 2011). During its use, the structured technique computes the complex computations by evaluating the criteria on one to one pairwise comparison (Taylan et al., 2014).

The FAHP presented by Li et al., (2013) was used in a modular engineering project in Canada. The purpose of this model was to identify and eliminate risks and study the effects of these risks on the project cost and duration.

To calculate the subjective weights of individual risk factors, in a pairwise comparison, AHP has been used (Liu et al., 2015). This enabled the calculation of factor contributions for an evaluation criterion. Inherently, the risk analysis results computed became more consistent with the risk factors being calculated using AHP.

Along with the theory on the cost of safety, Aminbakhsh et al., (2013) implemented AHP to prioritise the key safety risks within an engineering project. This proved to be a robust method for generating a rational budget to implement accident prevention. This method revealed the possibility of implementing well-adjusted budgets during the planning and budgeting phase of the project. In Lithuania, Gudiene et al. (2014) applied AHP to list various success factors for engineering projects. These were mainly critical success factors. The findings clearly identified the prospects of employing AHP to rank critical factors for successful completion. Moreover, An et al. (2016) explained that even though FRA is able to accommodate imprecise data along with entailing assumptions in the process of risk assessment, in the safety management of railway systems, FRA alone seems to be an incompetent option. This is because each risk factor contributes differently in such a case, hence requiring to be considered for the overall

contribution to the risks of railways. Therefore, An et al. (2016) used a FAHP technique for risk analysis. This is based on the benefits of FAHP which allow for the determination of the related significance of risk factors in risk assessment.

FAHP appears to be an important technique which has been used in several sectors. These include: the designing and maintenance planning, reliability analysis, selection of most suitable alternates, resources allocation and several more (Van Laarhoven and Pedrycz, 1983; Bojadziev and Bojacziev, 1997; Herrera et al., 2001; Mikhailov, 2003; Fan et al., 2006; Gu and Zhu, 2006; An et al., 2011, 2016). Furthermore, FAHP has the ability to be combined with several other practices as well. Also, FAHP can assist in solving issues related to the loss of risk data in the hierarchical processes (An et al., 2006, 2016).

3.5.3 TOPSIS

Fuzzy logic has also been commonly employed in decision making processes. These processes are known to be full of complexity and difficulties, mainly when the best alternative is sought for. The Multi-Criteria Decision Making (MCDM) is a sub-discipline, which is a part of operations research and involves the use of mathematics and numerical tools for supporting the evaluation of decisions in different situations (Lootsma, 1999; Behzadian et al., 2012; Kuo, 2017). Amongst these several MCDM methods, over the last couple of years, a technique known as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has been commonly used for achieving reasonable outcomes. The technique was initially proposed by Yoon and Hwang in 1981. As mentioned above, the technique was considered as an approach for solving MCDM problems (Yoon and Hwang, 1981). Ever since, the technique has

known to aid in managing and handling complex circumstances (Tan et al., 2010; Zavadskas et al., 2010; KarimiAzari et al., 2011; Behzadian et al., 2012; Zhu et al., 2013; Khalili-Damghani et al., 2013; Goh et al., 2013; Doukas et al., 2014; Du et al., 2014; Kannan et al., 2014; Peng et al., 2015; Feia et al., 2016; Senouci et al., 2016; Kuo, 2017).

TOPSIS comprises of the six stages. These are: the normalization of decision matrices; computation of such matrices; determination of the Positive Ideal Solution (PIS) along with the Negative Ideal Solution (NIS); calculation of the separate alternatives of both, PIS and the NIS; calculation of the rank indices and the arrangement of these ranks in a downward order for obtaining the most suitable alternate (Kuo, 2017). Hence, TOPSIS is known to be a ranking-based methodology which is founded on the concepts of compromised solutions. In addition, the use of TOPSIS allows for choosing the most suitable alternate. This alternate would have the minimal distance possible from the Positive Ideal Solution while having the maximum possible distance from the Negative Ideal Solution. While PIS solutions deal with maximizing the benefits and minimizing the costs, NIS is vice versa. However, it is worth mentioning that, realistically, no PIS or NIS exist. If this was the case, then decision-making would be very simple. Hence, a balance is required (Li, 2009; Yami et al., 2017; Kuo, 2017).

Yousefi et al. (2014) studied the application of TOPSIS as an MCDM method for dealing with bridges and the criteria. They suggested that such a technique decreases the multiple alternative performances (i.e. bridges) in a single value (i.e. ranking scores) for facilitating the decision-making processes to determine the most appropriate bridges needed in retrofitting. The proposal was applied for an Isfahan highway network in Iran due to the region's seismic hazard characteristics.

Overall, TOPSIS is known to function well with producing satisfactory results in a wide range of sectors (Behzadian et al., 2012). In addition, the technique utilizes the achieved data completely to offer a fundamental rank for alternates (Chen and Hwang, 1992; Yoon and Hwang, 1995). Crisp numbers, non-obtainable and incomplete data are used to represent the traditional formulation of TOPSIS. However, in some realistic circumstances, decision makers tend to struggle in evaluating the precise weights of criteria along with the alternate rankings being studied. Hence, in such a case, researchers have proposed the extended fuzzy TOPSIS (FTOPSIS) technique. FTOPSIS is aimed at addressing fuzziness issues which are accompanied by evaluating problems full of complexity (Kuo et al., 2006; Yang et al., 2011). Yami et al. (2017) used AHP and FTOPSIS to achieve the weights of all criteria studied and for assessing the safety rankings to optimize the operational safety performance (OSP) in container ports.

Similar to Yami et al. (2017), Torfi et al. (2010) also used FAHP for obtaining the weights of criteria and FTOPSIS for the evaluation of alternative rankings, in a case where both, the criteria weights and performance rankings were considered unclear and imprecise. In Saudi Arabia, 30 engineering projects regarding structures were ranked by the use of FAHP and FTOPSIS. The techniques aided in carrying out the risk assessment of these projects which were mainly based on inaccurate and vague data.

Further, FTOPSIS has also been used for the risk assessment in projects concerning the operation and management of commercial centers (Tamosaitiene et al., 2013), dams (Haghshenas et al., 2016) and structures of railway culverts (Fabianowski and Jakiel, 2018). All these projects were known to have a fuzzy environment, nondeterminism, incompleteness and uncertain information.

Nevertheless, it is worth mentioning that one study (Junior et al., 2014) stated that even though the use of FAHP-FTOPSIS is considered reasonable for solving supplier selection issues, the use of FTOPSIS is proven as a better and more suitable option for solving issues related to supplier selection.

3.5.4 Application of Fuzzy Techniques to Bridge Structures

Since this current study is aimed at the use of fuzzy techniques for the risk-based optimization of highway bridges, this section provides a review of the relevant literature concerning the adoption of fuzzy techniques for bridge-related projects.

Designing bridges is a process full of complexity in terms of the structures involved, the technology used, and the architecture concerned. Such issues require careful handling by competent designers and experienced professionals. In fact, designing, construction and maintenance of highway bridges is an MC process, which is usually difficult to clearly define (Jakiel and Fabianowski, 2015).

Wang and Elhag (2008) argue that while assessment of bridges is usually performed by trained inspectors using subjective judgements including assigning numerical ratings, this process consists of some potential uncertainties. They state that such a method disregards the overall significance of the components involved in the bridges including elements such as superstructures, substructures and decks. These are mainly comprised of sub-elements and thus need to be considered as well as they may have a role as well. Also, the numerical ratings assigned to the various parts of bridges are simply assessment grades and not exact numerical values, where assessment grades should not be added. In addition, potential uncertainties with the ratings assigned by bridge inspectors are usually neglected, where it is known that imprecisions in decisions by humans are usually inevitable. Finally, the authors conclude in their review of the

literature that the overall evaluation of bridges is a basic process, which is unable to provide a full description of the bridges' conditions. Hence, the study by Wang and Elhag (2008) proposed and investigated an alternate method for the assessment of bridge conditions. They used the evidential reasoning (ER) approach to simulate the inaccuracies in bridge assessments. This method focuses on the theory of evidence and uses both, the qualitative and quantitative characteristics with a modelling outline. Each characteristic is ranked using collective assessment grades, uncertainties adapted to the probability theories, fuzzy uncertainties using sets of fuzzy linguistics variables and a combination rule for evidence. Such a technique is known to incorporate the significance of various bridge elements, where these can be evaluated to two adjacent grades for assessment. Also, the use of grades is more logical as compared to numerical ratings and thus the complete evaluation is a distributed one that can provide a fuller description of the condition of the bridge.

Furthermore, Tarighat and Miyamoto (2009) also highlighted the importance and cruciality of managing bridges along with stressing on the significance of showing the conditions of bridge elements. They also stated that results are usually imprecise and dependent on the inspectors' expertise. Hence, they introduced an innovative technique using fuzzy methods to manage the inadequacies resulting from uncertainties and vagueness in achieved data. The fuzzy technique involved using objective as well as subjective outcomes of current inspection practices. The model parameters were chosen as fuzzy inputs where they had an associated membership function. This function was achieved with statistic data. This helped in calculating the fuzziness using fuzzy rules intrinsic to the fuzzy expert system. The study also mentioned that fuzzy systems have

an advantage in that they can tolerate noise (that is uncertainties and vague data) hence making them ideal to deal with the existing indices for rating.

In a recent study by Lin et al. (2019), the authors stated the relevance of structural safety in the success of large-scale bridges. They mentioned that various indicators related to safety are used for risk warnings. However, these are usually used for pointing risks at specified points or locations. Hence, a method to assess the entire structure's safety is required. Therefore, for considering the various safety indicators, an analytic hierarchy process (AHP) is often adopted. AHP is known to provide a complete and balanced outline for arranging decision problems as well as for the representation and quantification of elements in the decision problems along with linking these elements to the overall goal(s) (Aminbakhsh, Gunduz and Sonmez, 2013). In addition, Lin et al. (2019) also elaborated that modeling problems as hierarchies allow for evaluating the weight of each node present using a sequence of pairwise judgements.

The use of FAHP is very popular for bridge-related issues concerning repair and maintenance works (Selih et al., 2008). However, even then, it is apparent that a major limitation arises from the proposed models' concerning bridges. This is that such models have limited applicability at a wider scale. Pan (2008) adopted FAHP for choosing the most appropriate bridge-construction method. However, the study was limited to only one bridge. Similarly, in a study by Chaphalkar and Shirke (2013), the issue of selecting an appropriate structure for a chosen site was considered. However, due to size limitations, only a few structure types could be taken into account. Hence, the results arising from any such studies are limited. Moreover, Salem and Miller (2006) used a methodology based on AHP to address the MC issues in the repair of existing bridges along with the creation of new structures.

Jakiel and Fabianowski (2015) in their investigative study used FAHP for presenting an approach that could be utilised for choosing a structural and technological version for a highway bridge. A group of criteria was considered in their study however, the proposed methodology was limited in terms of comparative data elaborations.

An interesting study by Andric and Lu (2016) proposed a disaster risk assessment model. This model was based on the integration of FAHP and fuzzy logics in a single approach. The study surveyed the past collapsed bridges to identify potential hazards. FAHP was then used to rank risk factors. This was due to FAHP being more systematic, accurate and effective as compared to AHP. Overall, the proposed methodology is practical and successful for a rapid risk analysis along with bridge assessment. The work also suggested that the total risks of engineering projects could be determined using fuzzy logics. To do so, the appropriate data such as risk indicators, probability and consequences information must be gathered from relevant bodies.

Yang et al. (2018) carried out research on determining safety factors which affect bridges. They used FAHP to analyse these factors for a bridge in China. The study successfully analysed and demonstrated various safety factors which need to be taken into consideration for the accurate evaluation of bridge safety models. The study further suggested that greater efforts need to be made in establishing and improving the regulations for ensuring the safety of bridges. Li (2014) also employed AHP and fuzzy logics to analyse and measure risk factors. The study introduced a successful and useful methodology for risk assessment in the bridge structures. The study also illustrated the features and requirements of risk assessment in such projects.

Wang and Elhag (2006) proposed a FTOPSIS based methodology for the risk assessment of bridges. Numerical examples were investigated. The study concluded that

the proposed FTOPSIS seems to function better as compared to other fuzzy versions of TOPSIS.

Cheng et al. (2019) explain the numerous possible risk factors associated with bridges, which possibly result in bridge collapses and failures. The study was focused on the use of a method founded on fuzzy logic. The method synthesizes FAHP based on a three-point scale, fuzzy sets and fuzzy logic. Their approach is able to structure and prioritise the wide variety of risks along with being able to manage inaccurate information. This concept was used successfully and effectively for the risk assessment of a bridge-suspension system in China. Even then, the study faces a common limitation, which is that it is limited to a specific case. Hence, it is recommended to take into consideration alternate risk factors as well for establishing enhanced hierarchical structures for the problem of risk assessment.

3.6 Summary

An extensive literature review is carried out in this study to form a deeper understanding of the current safety issues, which exist along with the corresponding types of risk. Bridges are known to be crucial structures, which assist in the overall transportation infrastructure systems. This chapter presents a review of the relevant literature on the study of the current maintenance models for highway bridges, which exist across the world. The literature review first provides a general background on the bridges and their importance in today's world. Next, the review considers some case studies, which are related to bridge accidents. The review then identifies the shortfalls in current practices and methods of maintenance related to the construction, maintenance and overall operation of bridges. In addition, corrosion is known to be a common problem that is encountered in bridges. Therefore, it is extremely important to address

this problem for the relevant safety, environment and economic reasons. Hence, the review provides general background on the issue of corrosion and also explains the mechanism of corrosion. The review then offers an evaluation of possible solutions to bridge failures. A review of the literature on risk management in the engineering industry is also provided.

In terms of the risk assessment techniques, several methods are available. This chapter also discusses the FRA, AHP, TOPSIS and the respective hybrids, FAHP and FTOPSIS techniques. Additionally, the chapter reviews these techniques in relation to bridge-related projects as well. Adopting FAHP and FRA, risk ranking matrices and implementing FTOPSIS model as risk-cost models can assist mainly in improving bridge maintenance systems and further help in optimising the life-cycle cost of the bridges.

Based on the review, it is known that the proposed model will be developed under an uncertain and fuzzy environment, which will thus make it applicable for use in the assessment of bridge structure safety.

While a significant amount of research is available in the literature on the maintenance of highway bridges, there is still an existing issue concerning the types of risk and the relevant risk scores for highway bridges. To clarify any such issues, based on the literature available, this work intends to study not four but eight multi-consequences parameters with the integration of the three fuzzy models, which are FRA, FAHP and TOPSIS. This integration is a novel approach towards the maintenance models of highway bridges.

CHAPTER 4: DEVELOPMENT OF SAFETY RISK MODEL FOR HIGHWAY BRIDGES

4.1 Introduction

This chapter is focused on the presentation of a new safety risk model for bridges. The model is developed based on three input parameters, Consequence Severity (CS), Failure Frequency (FF) and Weight Factor (WF). These are used for assessing the risks from components levels all the way to the system level. A Consequence Severity Criteria (CSC) parameter is introduced as the multi-consequences parameter, which takes into consideration eight factors that are considered significant for the risk analysis of bridges. Such a risk model would permit users and experts in the field to utilise fuzzy and numeric numbers along with linguistic values in the risk assessment. Risk categories along with scores are expected as outputs of the proposed risk model, which will mention the risk contributions as well. This will simplify and facilitate the risk assessment process of highway bridges, which is a complex topic.

4.2 Bridge Safety Risk Model

As Peters et al. (2006) mentioned, the term risk can be used to refer to the outcome of an error frequency multiplied by the severity of the consequence that results from its occurrence. Based on this, An et al. (2006; 2007) elaborated that in order to assess Risk Level (RL), two basic parameters can be used. These are the CS and FF risk parameters. These parameters help in the quantification and qualitative assessment of the magnitude of the risks. While CS is used to denote the amount of casualties with minor and major

injuries which are a result of a specific dangerous event, the FF denotes the frequency of an event over a known period (An et al., 2011).

Furthermore, as mentioned in Chapter 3 (Literature Review), assessing risks in highway bridges should incorporate a group of criteria for risk factors. Hence in order to successfully determine the risks associated with highway bridges, this study introduces a new risk parameter. This new risk parameter is referred to as the "Consequence Severity Criteria" (CSC) and can be split into eight factors. These are; safety, functionality, value for money, environment, traffic delay, time, socioeconomic and reputational damage. This multi-consequences parameter, CSC, is integrated with the FF in a fuzzy reasoning approach (FRA) in order to evaluate the RL of any dangerous incident. The incorporation of fuzzy reasoning allows for adequate risk analysis by modelling the associated risks in a project in addition to risks with insufficient data (An et al., 2006; 2007). Further, the use of membership function (MF) is regarded as a crucial element in the fuzzy reasoning approach. This is because the use of MF allows for handling uniformly the ambiguity and imprecision in data (Zeng et al., 2007). Hence, in the proposed method, several risk parameters along with the FRA approach is proposed as this is considered the most effective tool for risk analysis (Stergio and Kiremidjian, 2010).

In the safety assessment of highway bridges, each dangerous event is likely to be different, hence, the weight of each event must be considered individually in terms of its relative importance in the risk tree it belongs to. This assists in the accurate prediction of the RL of a highway bridge system as the contributing weight of each event is considered. Such a weight contribution is denoted by the Weight Factor (WF), which is employed in the proposed model. To elaborate, as discussed in Chapter 3, highway

bridges are prone to corrosion mainly due to environmental factors. Therefore, the proposed model takes into account the corrosion of different elements in a bridge. To do so, each element is assigned a WF that can be used to indicate the level of importance of the hazard.

Following the incorporation of the WF, the model then administers the Fuzzy Analytical Hierarchical Process (FAHP). FAHP not only helps in the calculation of the different WFs but also allows for solving issues concerning the loss of information in the hierarchical process. This method assists in carrying out the risk assessment of a typical highway bridge. Additionally, the components of RL are based on standards sets by experienced experts. This is possible as a significant amount of data is available related to bridges and can be used for assessing their respective safety and maintenance.

In terms of the risk assessment process, this is mainly a five-step process as An et al. (2007) describe. The process begins with an initial stage where a problem is defined. Next, relevant data is collected and analysed after which potential hazard(s) are identified. The risks are then estimated and finally, a risk response is provided. Such a process is able to provide an organised approach for identifying and controlling areas with high-risk levels. Moreover, a risk assessment model incorporating the fuzzy reasoning approaches is, in fact, more relevant, specifically for the safety assessment of highway bridges as it is deemed as an overall effective approach. With the inclusion of fuzzy reasoning, the five stages are (Wang, 2018):

1. Initial stage
2. Design stage
3. Estimation of fuzzy RA
4. FAHP risk analysis stage

5. Risk Response stage

These are detailed in Figure 4.1 below and the following sections discuss each of these stages in detail.

4.2.1 Initial Stage

Defining a problem marks the first step in a typical risk assessment. This stage involves the identification of the needs for safety in a project. Relevant safety rules along with safety requirements and regulations are part of this stage. In the current study, this stage comprises of defining issues and defects related to bridges. As a result, this incorporates the relevance and significance of safety rules, regulations and standards, which are practiced for RLs that are known by the "bridge level", "hazard group level" and "hazardous event level". As An et al. (2007; 2011) and Wang (2018) elaborated, this step takes into consideration the availability, reliability, maintainability, safety and criteria denoting the likelihood of a serious event taking place and its associated consequences which are likely to happen. Availability refers to the ability of keeping a functioning state in any provided situation whereas reliability refers to the ability of performing a specified function and can be denoted as operational reliability or design reliability. Maintainability can be explained as the ability to be timely along with being easily maintained while safety mainly concerns with the ability of not harming individuals, the surrounding environment and any assets during the entire life cycle of a project. These benchmarks are all devised and set by the classification society and national authorities.

Following on, with the identification of a problem being completed, the relevant data and information are looked for, collected and then analysed. Important sources of information are assessed based on their credibility. Hence, data is sought from useful

projects, databases and reports. However, it is highly likely that in some cases, the data is either incomplete or lacks useful information. In such cases, expert analysis and judgement are usually needed. Hence, in this study, this step involves the gathering of useful data on bridges and mainly highway bridges. Data achieved is sourced from bridge accidents and failures, which have taken place in the last couple of years, in order to form a deep and thorough understanding of the safety of bridges.

Collected data is described by qualitative descriptors and is linked with the relevant risk parameters, which are CS, FF and RL. In terms of the safety hazard identification process, this step allows for identifying all possible and likely hazardous events linked to the highway bridges and their respective operations. To elaborate, once an event is identified as hazardous then its resulting group level is identified in order to fully assess its effect on the safety of highway bridges. This process can be carried out with a mix or individual use of several techniques such as a HAZOP (Hazard and Operability) study, a 'what if' analysis, brainstorming approach, checklists along with a Failure Mode and Effect Analysis (FMEA) approach (Glossop et al., 2000; An et al., 2011; Liu and Tsai, 2012) for the safety analysis of highway bridges.

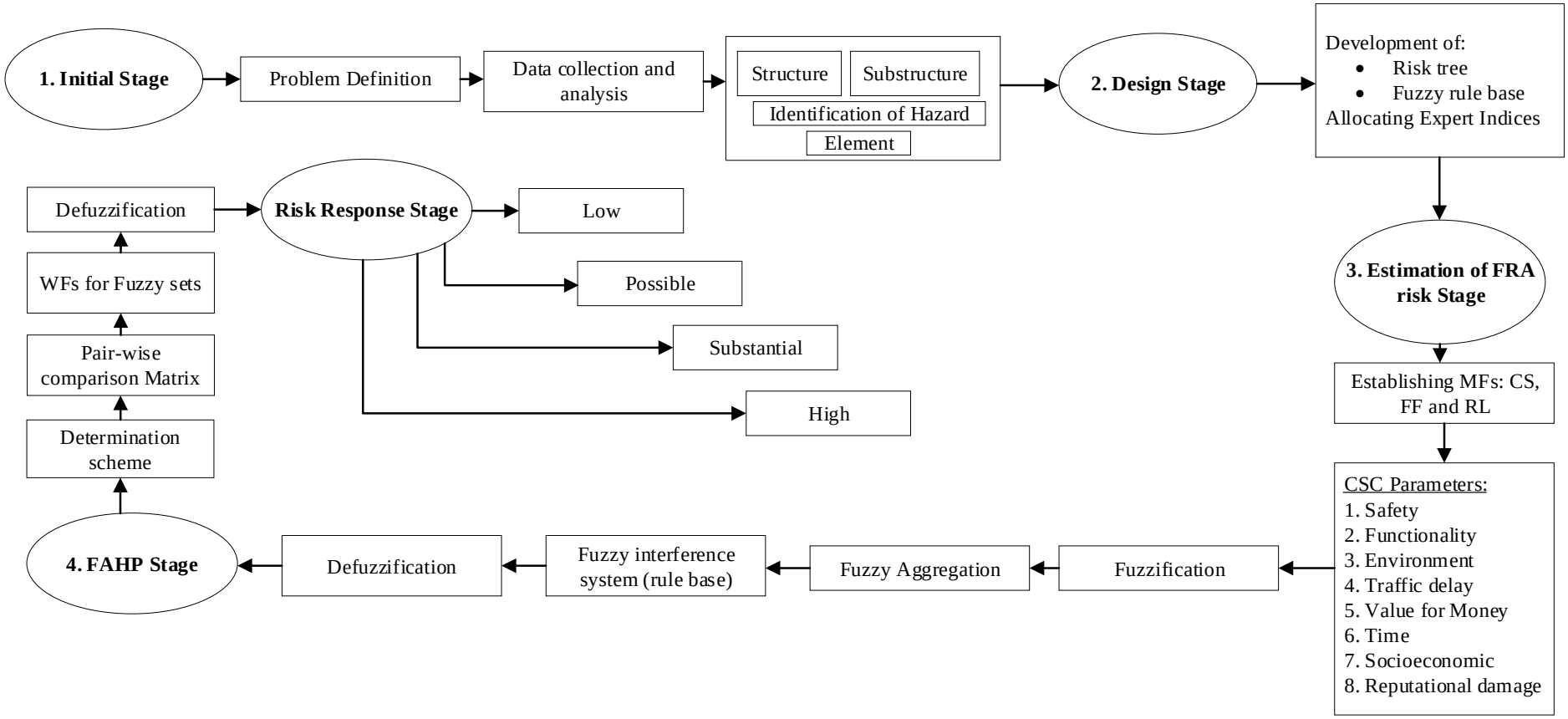


Figure 4.1: A schematic diagram of the five stages of a risk assessment mode

Precisely, a HAZOP study is known to be an ideal approach for identifying hazards in a project. It uses a structured and systematic approach and is based on an elaborate description of the problem. To do so, the problem is split into well-defined subsystems where each component in the system is reviewed and analysed carefully (Glossop et al., 2000). A 'what if' analysis is another widely used, useful technique for the identification of potential hazards. As the name suggests, this method is used to question the integrity of a project. Quite similar to the 'what if' analysis is the brainstorming approach which facilitates a discussion between a group of professionals and experts in the relevant fields. Such a technique assists in imaginative thinking and can help identify possible hazards that are missed during a systematic approach. Similarly, checklists are an excellent approach for identifying and reviewing potential hazards by listing them out based on past experiences as well as practitioners' thinking. However, since every project is different, a predesigned checklist may not be able to cover all types of hazards associated with a particular project. FMEA is another kind of hazard identification technique which has its own complexities. The technique investigates the models of failure for each element in a process. Complexities in this technique arise in the identification of those hazardous events which involve the failure of several process items.

Once the hazard identification is initialised, the process can be upgraded to the grouping level and the system levelled establish a risk tree diagram, as discussed in Section 4.2.2.

4.2.2 Design Stage

This step is the next stage in developing a risk assessment model. In this study, once the fundamental data is achieved regarding highway bridges, the design stage begins which

involves developing a risk tree diagram with the use of different MFs such as CS, FF and RL along with fuzzy rule bases (An et al., 2011).

4.2.2.1 Risk tree diagram development

As mentioned in Chapter 3 earlier, highway bridges are crucial structures which tend to have several safety concerns associated with them. Hence, developing and using a risk tree can assist the relevant bodies to assess the various risks associated with highway bridges efficiently. Such a risk tree can aid in the decomposition of the various risk contributors into useful pieces of information for successful risk assessment. A typical risk tree is shown in Figure 4.2. As illustrated by the diagram, the risk tree can be decomposed from a depot system into hazardous groups and event levels (An et al., 2011). In Figure 4.2, G denotes the hazard group level, S-G represents the sub-hazard group level and E represents the hazardous event level.

Problem definition marks the first step of any risk assessment. This step includes the identification of the need for safety. This involves the specified safety requirements that are needed at different levels, such as those represented by E, S-G and G in the Figure 4.2. For instance, at hazardous event level, hazardous events of E_1, E_2, …, E_n can have an influence at the sub-hazard group level, particularly on the risk level of S-G_1. As a result, the risk levels of S-G_1, S-G_2, …, S-G_n can contribute to the risk level of G_2 at hazard group level, where the risk levels of G_1, G_2, …, G_n can contribute to the overall risk levels of the bridge depot at a system level.

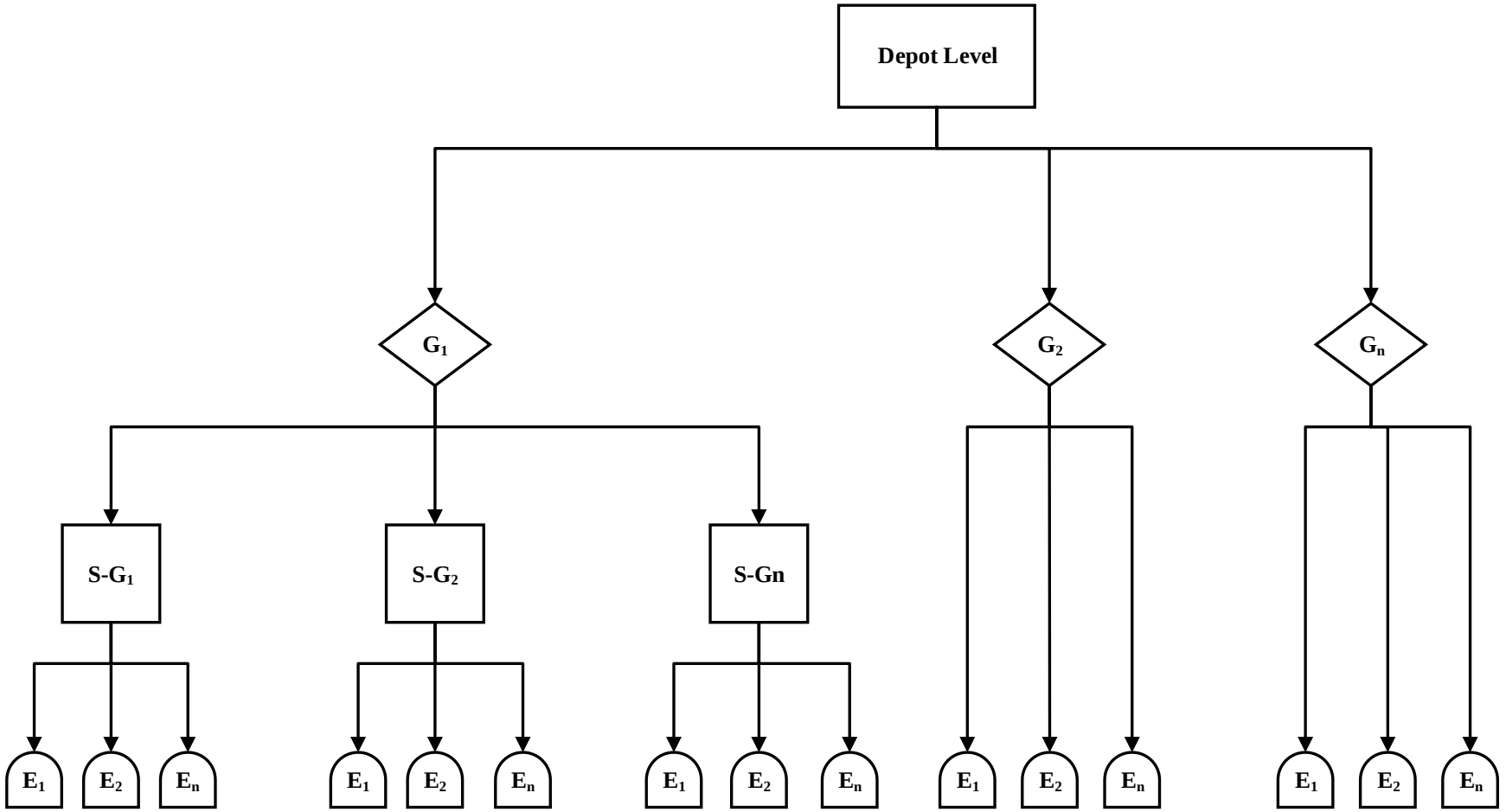


Figure 4.2: A typical risk tree diagram (Adapted by An et al., 2011).

4.2.2.2 Fuzzy rule base development

With the help of useful data on accidents, histories of incidences and thorough knowledge of engineering, it is possible to establish fuzzy rules. In fact, trained professionals tend to have excellent expertise in assessing risks and system behaviours in several kinds of failures based on their experiences. Both, CS and FF are treated as the inputs for the fuzzy rule bases while the RL is treated as the output. These parameters which form the fuzzy sets are sourced from previous experiences and information. Hence, the MFs are known to define these fuzzy sets. Also, a logic system comprising of three or more truth values is referred to as the many-valued logic (Ramakrishnan and Sabu, 2010). With such valuations, the many-valued logic can be expanded to permit for fuzzy premises based on which graded conclusions can be sources (Grattan-Guinness, 1975).

While these MFs can be either S-shaped, trapezoidal and triangular, it is known that trapezoidal and triangular MFs are commonly employed in the risk assessment of projects concerning highway bridges. In addition, empirical evidence also shows that trapezoid MFs are efficient in several engineering applications (Gholamy et al., 2019).

The CSC is defined as ‘Low’, ‘Medium’, ‘High’; FF is defined as ‘Very Low’, ‘Low’, ‘Medium’, ‘High’, ‘Very High’, and the RL is defined as ‘Low', ‘Possible', ‘Substantial', and ‘High'. For example, in bridge risk analysis, if CSC is ‘High’ and FF is ‘High’, then RL is ‘High’ as well (An et al., 2006; 2007; 2016).

4.2.2.3 Allocating Expert Indices

Risk analysis of highway bridges is a complex topic due to the several related risks. As a result, it is not possible to depend on just one person’s judgements to consider all the

features of a project. A group of relevant staff such as engineers, experts and project managers is required to make cumulative decisions. This, however, may lead to some disagreement between the involved individuals which may impact decisions. Hence, researchers introduced the concept of Expert Index (EI) for distinguishing the competency of experts. For instance, if in a decision making process there are *'n'* number of experts, then the *i*th expert's EI is achieved using the correlation (4.1):

$$EI_i = \frac{\mathrm{RI}_i}{\sum_{j-1}^{n} RI_j} \tag{4.1}$$

In (4.1), the numerator describes the *i*th expert's relevant important based on his experiences and expertise. This value can range from one to nine, where the former refers to the least importance and the latter refers to the greatest importance.

4.2.3 Estimation of fuzzy RA

This stage assesses risks based on the CS and FF of a hazardous event level for calculating RLs. However, as mentioned earlier, it is highly likely that risk analysts obtain insufficient data lacking important information as the risk analysis of highway bridges is a complex topic. As a result, increased levels of uncertainties may be associated with the obtained risk data. Therefore, An et al. (2006; 2008) discussed the proposition of a flexible approach, which can express expert judgments. This approach is known by the Uniform Format Number (UFN) and helps in capturing and converting individual decisions thus allowing for inaccuracies to be accommodated in the process of risk analysis with making the risk data practical. The six steps used for calculating RL at each hazardous event are listed and discussed as follows.

4.2.3.1 Step One: Input Parameters: CS and FF

With the help of useful data on accidents and failures along with histories of incidences, it is possible to obtain and gather useful input data. However, it is highly likely that this data is unavailable in some cases or consists of uncertainties. Therefore, for hazardous events, expert analysts can offer their personalised judgments based on their expertise and knowledge (Herrera et al., 2009; Garcia-Lapresta et al., 2009). Either an accurate numeric value, a range of values or even a linguistic term can be used for the input value. To elaborate, experts usually assign an accurate numeric value if sufficient data is available, however, in cases where there is an uncertainty in the data, then a range of numeric values is proposed. In addition, in such a case, fuzzy members or linguistic terms are also likely to be assigned (An et al., 2006, 2008; Alonso et al., 2009; Herrera et al., 2009; Garcia-Lapresta et al., 2009).

4.2.3.2 Step Two: Conversion of input values into a uniform format.

As mentioned in the description of step one, the input values are chosen based on the type of risk data available and are examples of crisp input data. In order to process a final decision, each input is required to be converted into a UFN, which is given as: A=$\{a, b, c, d\}$.

The 'degree of preference' is indicated by the UFN's resulting MF. This can be expressed as (4.2):

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & x \in [a, b], \\ 1 & x \in [b, c] \\ \frac{(x-d)}{c-d}, & x \in [c, d], \\ 0, & otherwise. \end{cases} \tag{4.2}$$

For a trapezoidal MF, its x-coordinates of the corners are determined using the real numbers in A, where a≤ b≤ c≤ d.

Possible judgments by experts and associated UFNs are shown in Table 4.1.

Table 4.1: Explanation of expert judgements and the associated UFNs (Adapted from An et al., 2011).

Description of judgements	Input values	Input types	UFNs
''...is a''	{a}	A numerical value	{a,a,a,a}
''...is between a and b''	{a,b}	A range of number	{a, (a+b)/2, (a+b)/2, a}
''...is between a and c and most likely to be b''	{a, b, c}	Triangular fuzzy numbers	{a, b, b, a}
''...is between a and d and most likely between b and c''	{a, b, c, d}	Trapezoidal fuzzy numbers	{a, b, c, d}
''...is RARE'	RARE	A linguistic term	RARE MF {a, b, c, d}

4.2.3.3 Step Three: Combination of UFNs

In this stage, a group of judgement is formed with the use of a suitable operator, which helps in combining several separate individual judgments. Aggregation of judgments can be achieved using a weighted trapezoidal averaging expression.

For instance, in a risk assessment involving '*m*' experts where '*n*' experts offer a non-zero judgment for a '*s*' hazardous event, the aggregated UFN, A^S can be given by (4.3):

$$A^s=\{a^s, b^s, c^s, d^s\} = \left\{ \frac{\sum_{y=1}^{m} a_y{}^s EI_y}{\sum_{y=1}^{n} EI_y}, \frac{\sum_{y=1}^{m} b_y{}^s EI_y}{\sum_{y=1}^{n} EI_y}, \frac{\sum_{y=1}^{m} c_y{}^s EI_y}{\sum_{y=1}^{n} EI_y}, \frac{\sum_{y=1}^{m} d_y{}^s EI_y}{\sum_{y=1}^{n} EI_y} \right\}$$

$$A_y^s = \left\{a_y^s, b_y^s, c_y^s, d_y^s\right\} \quad (4.3)$$

In (4.3), $a_y^s, b_y^s, c_y^s, d_y^s$, represent UFN numbers, respectively. A_y^s refers to the *y*th expert's judgement for 's'. Also, EI_y refers to the EI value of expert 'y'.

4.2.3.4 Step Four: Determination of fuzzy sets with the inclusion of UFNs

As discussed in Chapter 3, FRA is an excellent approach for modelling risks, specially in cases where there is either imprecise or approximate information. In this step, FRA assists with each UFN associated to each hazardous event. Fuzzy sets are established with the conversion of combined UFNs of CS and FF. Next, these are then introduced in a fuzzy interference system.

For example, in a hazardous event, 's', if the two UFNs of CS and FF are A_{CS}^s and A_{FF}^s, then the resulting fuzzy sets, $\tilde{A}_{CS}^s$ and $\tilde{A}_{FF}^s$ are (4.4 and 4.5):

$$\tilde{A}_{CS}^s = \left\{\left(q, \mu_{A_{cs}^s}(q)\right) |\ q \in Q = [0, q_n], \mu_{A_{cs}^s}(q) \in [0,1]\right\} \quad (4.4)$$

$$\tilde{A}_{FF}^s = \left\{\left(k, \mu_{A_{FF}^s}(k)\right) |\ k \in K = [0, k_n], \mu_{A_{FF}^s}(k) \in [0,1]\right\} \quad (4.5)$$

In (4.4 and 4.5), $\mu_{A_{cs}^s}$ and $\mu_{A_{FF}^s}$ are the trapezoidal MFs of A_{CS}^s and A_{FF}^s, respectively. Also, q and k are the respective input variables for Q and K of CS and FF.

4.2.3.5 Step Five: Process of Fuzzy Interference

As discussed in Step Four, the combined UFNs are aggregated to establish fuzzy sets. In the current step, these sets are introduced as inputs in the fuzzy interference process. This assists in determining and deciding on relevant rules suitable to the context of the study. Next, the fuzzy output of RL is calculated. This step is based on Mamdani's method (Lee, 2005; An et al., 2006). Rule bases are formed of collected rules that comprise of historic data and experts' judgements. 'If-then' rules are used to present the relationship between CS and FF (inputs) and RL (outputs).

For instance, if the *s*th rule is given as (4.6):

R_s: if q is $\tilde{T}_{cs}^{s}$ and k is $\tilde{T}_{FF}^{s}$then x is $\tilde{T}_{RL}^{s}$, s=1,2,…..,n (4.6)

Where k, q and x are variables denoting the K, Q and X of FF, CS and RL, respectively.

In addition, the qualitative descriptors of these MFs are $\tilde{T}_{FF}^{s}$, $\tilde{T}_{cs}^{s}$and $\tilde{T}_{RL}^{s}$.

The rule base for each consequence will be as follows:

1. IF (FF is VL) and (CS is L) then (RL is L)
2. IF (FF is VL) and (CS is M) then (RL is P)
3. IF (FF is VL) and (CS is H) then (RL is P)
4. IF (FF is L) and (CS is L) then (RL is P)
5. IF (FF is L) and (CS is M) then (RL is S)
6. IF (FF is L) and (CS is H) then (RL is S)
7. IF (FF is M) and (CS is L) then (RL is S)
8. IF (FF is M) and (CS is M) then (RL is S)
9. IF (FF is M) and (CS is H) then (RL is H)
10. IF (FF is H) and (CS is L) then (RL is S)
11. IF (FF is H) and (CS is M) then (RL is H)
12. IF (FF is H) and (CS is H) then (RL is H)
13. IF (FF is VH) and (CS is L) then (RL is H)
14. IF (FF is VH) and (CS is M) then (RL is H)
15. IF (FF is VH) and (CS is H) then (RL is H)

Where VL refers to very low, L refers to low, M refers to medium and H refers to high for FF and CS. For RL, L refers to low, P refers to possible, S refers to substantial and H refers to High.

The use of fuzzy intersection operation' is formulated below (4.7):

$$\alpha_s = \min\left[max\left(\mu_{A_{CS}^{s}}(q) \wedge \mu_{T_{cs}^{s}}(q)\right), max\left(\mu_{A_{FF}^{s}}(k) \wedge \mu_{T_{FF}^{s}}(k)\right)\right] \quad (4.7)$$

In (7), α_s denotes the fire strength for rule R_s. $\mu_{A_{CS}^s}(q)$ and $\mu_{T_{FF}^s}(k)$ are the MFs of $\tilde{A}_{CS}^s$ and $\tilde{A}_{FF}^s$, respectively. Similarly, $\mu_{T_{cs}^s}(q)$ and $\mu_{T_{FF}^s}(k)$ are MFs of $\tilde{T}_{cs}^s$ and $\tilde{T}_{FF}^s$, respectively.

Proceeding the fuzzy interference process, the resulting MF $\mu'_{T_{RL}^s}$ is given as (4.8):

$$\mu'_{T_{RL}^s}(x) = \alpha_s \wedge \mu_{T_{RL}^s}(x) \tag{4.8}$$

Following aggregation with fuzzy union (maximum) operation, the MF $\mu'_{T_{RL}}(x)$, which is the conclusion of rule R_s, is given as (4.9):

$$\mu'_{T_{RL}}(x) = q_{s=1}^{n} \mu'_{T_{RL}^s}(x) \tag{4.9}$$

In (4.9), n denotes the number of rules.

4.2.3.6 Step Six: Defuzzification

Defuzzification step is required for managing the fuzziness in the fuzzy sets received as outputs from the fuzzy interference process. The fuzziness is converted into a corresponding number, which is able to reflect the RL accurately. To do so, the 'centre of area' approach (Lee, 2005; An et al., 2006; 2011) is used. The risk level of a hazardous event, '*s*' can be determined by (4.10):

$$RL^s = \frac{\sum_{j=1}^{m} \mu'_{T_{RL}}(x_j) \cdot x_j}{\sum_{j=1}^{m} \mu'_{T_{RL}}(x_j)} \tag{4.10}$$

In (4.10), m represents the number of fuzzy sets' quantization levels and the output is assumed as $\tilde{T}'_{RL} = \left\{ \left(x, \mu'_{T_{RL}}(x) \right) | x \epsilon X, \mu'_{T_{RL}}(x) \epsilon [0,1] \right\}$.

4.2.4 FAHP Risk Analysis Stage

As mentioned before, each hazardous event contributes differently to the entire risk level. Hence, each event's weight must be considered individually. This would allow for

accounting the contribution of each hazardous event to the overall risk level of the bridge safety system. It is expected that FAHP can help in solving the issues of loss of risk data in the classification procedure, which helps determine the overall significance of each event in the decision-making scheme. As shown in Figure 4.2, the risk tree diagram for the current study will also evolve from a depot level of bridge safety systems to hazard group and sub-group levels before proceeding to the hazardous event levels. As stated in the literature review, FAHP is an expansion of the AHP technique, that makes use of an analogous structure as the AHP technique for conducting risk analyses. However, it is worth mentioning that in FAHP, the fuzzy ratios are used for replacing crisp ratios. FAHP is known to be flexible and thus can be combined with other methods as well. As a result, FAHP can help in generating WFs, which can accurately represent the main hazardous events in each classification. In order to calculate WFs, six steps are adopted, as discussed below (An et. al, 2011; Wang et al., 2018):

4.2.4.1 Step One: Setting a scheme for estimation

FAHP uses ‘pairwise comparisons’ which use an ‘estimation scheme’ for establishing the WFs for hazardous risk WFs. The scheme addresses the significance of WFs with the application of qualitative descriptors, which each have a triangular MF. Such MFs are used for allocating comparison matrices from expert judgements (An et al., 2007; 2011; 2016, Wang et al., 2018). To elaborate, if two risk factors do not have varying importance levels, they can be labelled as (1, 1, 2). The estimation scheme with the qualitative descriptors and their description along with the corresponding parameters for MFs is given in Table 4.2 below.

Table 4.2: FAHP estimation scheme

Intensity of importance in qualitative descriptors	Abbreviations	Explanation	Triangular fuzzy numbers	TranFNs
Equal significance	EI	Two risk factor contribute equally	(1,1,2)	[1.00,1.00,1.00,2.00]
Between equal and weak significance	BE&WI	When compromise is needed	(1,2,3)	[1.00,2.00,2.00,3.00]
Weak significance	WI	Experience and judgment slightly favor one risk factor over another	(2,3,4)	[2.00,3.00,3.00,4.00]
Between weak and strong significance	BW&SI	When compromise is needed	(3,4,5)	[3.00,4.00,4.00,5.00]
Strong significance	SI	Experience and judgment strongly favor one risk factor over another	(4,5,6)	[4.00,5.00,5.00,6.00]
Between strong and very strong significance	BS&VSI	When compromise is needed	(5,6,7)	[5.00,6.00,6.00,7.00]
Very strong significance	VSI	A risk factor is favored very strongly over the other	(6,7,8)	[6.00,7.00,7.00,8.00]
Between very strong and absolute significance	BVS&AL	When compromise is needed	(7,8,9)	[7.00,8.00,8.00,9.00]
Absolute significance	AL	The evidence favoring one risk factor over another is of the highest possible order of affirmation	(8,9,9)	[8.00,9.00,9.00,9.00]

4.2.4.2 Step Two: Comparison of risk factors

The risk contributors labelled in Figure 4.2, as ‘‘G_1’’, ‘‘G_2’’ and ‘‘G_n’’ represent the hazard groups in the assessment of risk levels for a bridge safety system. Based on Table 4.2, for instance, if there are two risk factors, G_1 and G_2, and G_1 has a greater significance comparatively, then a fuzzy number of (6,7,8) can be assigned to G_1. On the contrary, G_2 will be assigned a fuzzy number of (1/8, 1/7, 1/6).

4.2.4.3 Step Three: Converting the input data into UFNs:

FRA is reapplied to convert the 'crisp' values of risks into UFNs according to Table 4.1. Hence, a list of UFNs can be generated corresponding to the scales and scores of the defined risk contributors.

4.2.4.4 Step Four: Aggregation of UFNs:

Realistically, judgements and opinions can differ between the different experts in the risk evaluation process. Therefore, for concise results, the UFNs are gathered into a 'group UFN' for each risk factor.

4.2.4.5 Step Five: Use of Comparison Matrices for calculating Fuzzy WFs:

A comparison matrix can be constructed with the use of aggregated UFNs. The WFs are calculated using the geometric mean methods (An et al, 2011, 2016).

For instance, in a hazard group, '*p*', if the risk factors are known as B_1, B_2 and B_n, a pairwise comparison between B_i and B_j yields a $n \times n$ the matrix, which can be given as:

$$M=[K_{i,j}]=\begin{bmatrix} K_{1,1}\, K_{1,2} & \cdots & K_{1,n} \\ \vdots & \ddots & \vdots \\ K_{n,1}\, K_{n,2} & \cdots & K_{n,n} \end{bmatrix}, i,j = 1,2,\ldots..n \quad (4.11)$$

Where

$K_{i,j}=\{a_{i,j}, b_{i,j}, c_{i,j}, d_{i,j}\}$, $K_{j,i}=\{1/a_{i,j}, 1/b_{i,j}, 1/c_{i,j}, 1/d_{i,j}\}$

And $a_{i,j}, b_{i,j}, c_{i,j}, d_{i,j}$ are the $K_{i,j}$ UFNs and $K_{i,j}$ is the aggregated UFN, which represents the quantitative judgements on B_i.

Next, the WFs are calculated with the geometric mean technique, as set out by (Bojadziev et al., 1997). The geometric gravity center mean $\overline{K_i}$ of the *i*-th row of the comparison matrix is given as:

$$\bar{K}_i = \{\bar{a}_i, \bar{b}_i, \bar{c}_i, \bar{d}_i\} = \left\{\sqrt[n]{\prod_{j=1}^{n} a_{i,j}}, \sqrt[n]{\prod_{j=1}^{n} b_{i,j}}, \sqrt[n]{\prod_{j=1}^{n} c_{i,j}}, \sqrt[n]{\prod_{j=1}^{n} d_{i,j}}\right\} \quad (4.12)$$

$$W_i = \{a_i, b_i, c_i, d_i\} = \left\{\frac{a_i}{\sum_{j=1}^{n} d_j}, \frac{b_i}{\sum_{j=1}^{n} c_j}, \frac{c_i}{\sum_{j=1}^{n} b_j}, \frac{d_i}{\sum_{j=1}^{n} a_j}\right\} \quad (4.13)$$

Where W_i represents B_i's fuzzy WF.

4.2.4.6 Step Six: Normalisation and Defuzzification

The geometric mean method outputs are the Weight Factors for each hazard. Hence, a defuzzification is applied to change fuzzy-WFs to the corresponding 'crisp' numbers (Bojadziev et al., 1997). As a result, the crisp of w'_i is given as:

$$w'_i = \frac{a_i + 2(b_i + c_i) + d_i}{6} \quad (4.14)$$

To obtain the final WF of B_i, the following correlation can be used:

$$WF_i = \frac{w'_i}{\sum_{j=1}^{n} w'_j} \quad (4.15)$$

4.2.4.7 Step Seven: Determining RLs of Sub-Hazard Groups

The conciseness of performing risk evaluation is paramount, and this accuracy is achieved by calculating the RLs at each level. This section discusses the calculation of overall RL at 'sub-hazard group' level. This can be estimated for a S-G_i using the following formula:

$$RL_{S-G_i} = \sum_{i=1}^{n} RL_{B_i} WF_{B_i},\ i = 1,2,\ldots,n \quad (4.16)$$

The WF of both hazard and sub-hazard groups could be determined using steps 1 to 7. RL of hazard groups and the RL of the bridge safety system as a whole could be determined using (An, et al 2011, 2016):

$$RL_{SubstructureT_i} = \sum_{i=1}^{n} RL_{EB_i} WF_{EB_i} i = 1,2,\ldots,n \quad (4.17)$$

$$RL_{strucutre} = \sum_{i=1}^{n} RL_{ST_i} WF_{ST_i} \quad i = 1,2,\ldots,n \quad (4.18)$$

4.2.5 Risk Response Stage

Useful information that is obtained through the risk estimation stages can be employed in the current step for assisting the relevant bodies such as engineers and risk analysts in making crucial decisions regarding the safety and maintenance of bridge infrastructure. Moreover, in cases where high risks exist, immediate risk reduction actions can be implemented. In addition, in such cases, it is advised to reconsider the entire depot system and the associated risk tree. This can mainly help with reducing and controlling the failures and associated consequences.

4.2.6 Cost Model

The cost associated with any project is known to be a crucial factor. In terms of the safety of bridge infrastructures, the respective life cycle costs can be modelled with considering the performance review costs, maintenance costs, repair and renewal costs along with top failure events caused consequences. In order to model costs, certain simplified assumptions are made. These are:

- Any costs associated with the project are represented as the present value
- Any failure of subsystems or components is treated immediately with necessary repair works and this does not affect any other elements of the system
- Following repair and maintenance works, all components are in their original condition of state
- Spare equipment, as well as manpower, are enough for any maintenance and repair works
- The fundamental diagram for the analysis system is unchanged throughout the project

A bridge infrastructure system is open to various top failure events. These include bridge collapses, fire events and traffic accidents. All these events are likely to result in system breakdown as well as resulting in numerous fatalities such as injuries, deaths, damages and losses to properties as well as causing environmental issues. Hence, in terms of costs associated with top failure events, these compromise of those costs which are incurred as a result of the occurrence of failures in the bridges as well as losses in income which occur because of the system not being in operation. In addition, this also includes repair costs incurred due to top failure events in the bridge infrastructures. In terms of maintenance cost, these include spare part costs, labour costs as well as losses in income due to periods of inactivity in bridge operations because of maintenance required. It is also worth mentioning that in cases where main element of a bridge tends to fail, the overall bridge must be shutdown followed by immediate repair and maintenance works. Repair and renewal costs comprise of spare costs, labour costs and losses in income occurring as a result of the system not being in operation. As noted earlier, the fundamental system diagram remains unchanged throughout, hence, a performance review would comprise of the use of elements which are deemed reliable for reducing and eliminating failures. Hence, costs involved with performance reviews include spare part costs, labour costs and losses in income due to the system not being in operation. While higher initial investment costs can make a system very costly, they contribute massively to making the system more secure and safer as well as lowering the chances of any failure events occurring in the bridge system, which would consequently reduce expenses made on maintenance works.

A bridge-safety cost model can be given as:

Min: $$Cost = Cost_T(X) + Cost_R(X) + Cost_M(X) + Cost_P(X, Y) \quad (4.19)$$

Subject to: $Cost_{max} \geq Cost \geq Cost_{min}$

Where $Cost$ represents the overall safety related cost function; $Cost_T$ represents costs associated with top failure events occurring in a bridge system; $Cost_R$ represents the repair and renewal costs; $Cost_M$ represents costs associated with performance reviews following maintenance and repair activities. X refers to the respective cost variables associated with T, R and M whereas Y refers to the respective cost variables associated with P. $Cost_T(X), Cost_R(X)$ and $Cost_M(X)$ concern with policies of maintenance while $Cost_p(X,Y)$ considers both, the policies of maintenance as well as actions for performance reviews. Hence, such actions and policies are an integral part of the safety system as they assist in minimizing the safety-related costs.

4.2.7 TOPSIS

Fuzzy logic has also been commonly employed in decision making processes. These processes are known to be full of complexity and difficulties, mainly when a best alternative is sought for. The Multi-Criteria Decision Making (MCDM) is a sub discipline, which is a part of operations research and involves the use of mathematics and numerical tools for supporting the evaluation of decisions in different situations (Lootsma, 1999; Behzadian et al., 2012; Kuo, 2017). Amongst these several MCDM methods, over the last couple of years, a technique known as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has been commonly used for achieving reasonable outcomes. The technique was initially proposed by Yoon and Hwang in 1981. As mentioned above, the technique was considered as an approach for solving MCDM problems (Yoon and Hwang, 1981). Ever since, the technique has known to aid in managing and handling complex circumstances (Tan et al., 2010; Zavadskas et al., 2010; KarimiAzari et al., 2011; Behzadian et al., 2012; Zhu et al.,

2013; Khalili-Damghani et al., 2013; Goh et al., 2013; Doukas et al., 2014; Du et al., 2014; Kannan et al., 2014; Peng et al., 2015; Feia et al., 2016; Senouci et al., 2016; Kuo, 2017).

TOPSIS comprises of six stages. These are: the normalization of decision matrices; computation of such matrices; determination of the Positive Ideal Solution (PIS) along with the Negative Ideal Solution (NIS); calculation of the separate alternatives of both, PIS and the NIS; calculation of the rank indices and the arrangement of these ranks in a downward order for obtaining the most suitable alternate (Kuo, 2017). These steps are detailed below.

4.2.7.1 Step One: Normalization of decision matrices

This steps with the calculation of the normalized decision matrices. Under the *j*th criterion, for the *i*th alternative, the corresponding normalized value, $x_{i,j}$, can be obtained from:

$$x_{i,j} = \frac{a_{i,j}}{\sqrt{\sum_{i=1}^{m} {a_{i,j}}^2}}, i = 1, 2, \dots, m, j = 1, 2, \dots, n. \quad (4.20)$$

In (19), $a_{i,j}$ refers to the *i*th alternative's original value.

4.2.7.2 Step Two: Calculation of weighted normalized decision matrices

This step is used for the calculation of weighted normalized decision matrixes where under the *j*th criterion, for the *i*th alternative, the corresponding weighted normalized value, $y_{i,j}$, can be obtained from:

$$y_{i,j} = w_j \cdot x_{i,j}, i = 1, 2, \dots, m, j = 1, 2, \dots, n. \quad (4.21)$$

In (20), the weight of *j*th criterion is given by w_j and $\sum_{j=n}^{n} w_j = 1$.

4.2.7.3 Step Three: Determination of the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS)

This step comprises of the determination of the PIS, A^+, and NIS, A^-. To do so, the following correlations are used:

$$A^+ = \{y_1{}^+, y_2{}^+, \dots, y_j{}^+, \dots, y_n{}^+\} \tag{4.22}$$

$$A^- = \{y_1{}^-, y_2{}^-, \dots, y_j{}^-, \dots, y_n{}^-\} \tag{4.23}$$

In (21) and (22), $y_j{}^+$ and $y_j{}^-$ are the PI and NI values.

4.2.7.4 Step Four: Calculation of the separate alternatives of both, PIS and the NIS

This step involves calculating the separation measures with the help of n-dimensional Euclidean distance. Hence, separation of each alternative from the PIS can be obtained by:

$$D_i{}^+ = \sqrt{\sum_{j=1}^{n}(y_{i,j} - y_j{}^+)^2}, i = 1, 2, \dots, m. \tag{4.24a}$$

and from the NIS can be obtained by:

$$D_i{}^- = \sqrt{\sum_{j=1}^{n}(y_{i,j} - y_j{}^-)^2}, i = 1, 2, \dots, m. \tag{4.24b}$$

4.2.7.5 Step Five: Calculation of the rank indices

This step deals with the calculation of the relative closeness to the ideal solution, where the relative closeness for alternative, A_i, w.r.t A^+ is given by:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, i = 1, 2, \ldots, m. \quad (4.25)$$

As $D_i^+ \geq 0$ and $D_i^- \geq 0$, then, $C_i \in [0,1]$

4.2.7.6 Step Six: Arrangement of the preference order

This step deals with ranking the preference order where the basic fundamental of TOPSIS technique considered. TOPSIS is known to be a ranking-based methodology which is founded on the concepts of compromised solutions. In addition, the use of TOPSIS allows for choosing the most suitable alternate. This alternate would have the minimal distance possible from the PIS while having the maximum possible distance from the NIS. While PIS solutions deal with maximizing the benefits and minimizing the costs, NIS are vice versa. However, it is worth mentioning that, realistically, no PIS or NIS exist. If this was the case, then decision-making would be very simple. Hence, a balance is required (Li, 2009; Yami et al., 2017; Kuo, 2017).

4.2.8 Risk-Cost Model

Civil and structural engineers, risk analysts and project managers are usually faced with numerous contradictory aims in terms of the several maintenance options. To elaborate, their work involves maximising safety performances while minimising costs, which is basically minimising risks. As a result, based on these two critical factors, cost and safety, an integrated risk-cost model is projected based on the TOPSIS methodology. This helps in calculating the preference degree of maintenance options.

For instance, in a case where only maintenance costs are considered, the overall cost model is given as:

$$\text{Min} \quad Cost_i = Cost_L(A_i) + Cost_M(A_i) + Cost_E(A_i) + Cost_O(A_i) \quad (4.26)$$

And the risk-model is given as:

Min: $RL_i = RL_{system}(A_i)$ (4.27)

Where $Cost_i$ represents the overall costs associated with the *i*th maintenance option (A_i). $Cost_L$ represents costs associated with materials and parts while $Cost_E$ represents the costs associated with equipment use and $Cost_O$ represents costs associated with other activities such as losses in income due to the system not being in operation, fuel costs as well as management costs. RL_i refers to the risk level for the overall system after A_i has taken place.

It must be noted that all maintenance options should meet the safety constraints, which are set by relevant bodies such as national authorities and British Highway Agency. As mentioned earlier, an adequate safety model must assist in minimising maintenance costs. Hence, it is important to satisfy some constraints. As shown in the following expression, in reality, A_i comprises of finite options.

Subject to: $A_i \in \{A_1, A_2, \dots, A_m\}$ (4.28)

As mentioned previously, two important factors of a project are risk and cost. The current development of decision-making maintenance model based on risks, focuses on a balance between these two factors. The relationship between cost and risk is shown by Figure 4.3.

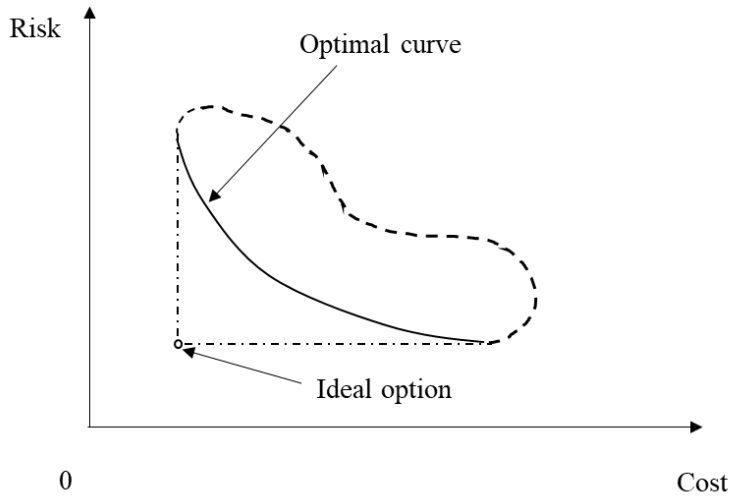


Figure 4.3: Risk versus Cost relationship (Adapted from Chen, 2012).

In terms of the risk-cost model based on TOPSIS, this is displayed in Figure 4.4. Considering the achieved risk assessment results, several maintenance options can be perceived for selection. The cost and safety risk models must be used for collecting and analyzing every single option concerning cost and risk information. This would assist in assessing the relevant risk reductions and cost estimations. The next step in the process of selection of maintenance options includes the preference evaluation stage. This must be implemented for producing the preference degrees for maintenance options. Such a process of preference evaluation comprises of typically six steps. The following sections discuss each of these steps briefly.

4.2.8.1 Step One: Calculation of normalized risk and cost values

This step calculates the normalized risk value, $x_{i,RL}$, and the cost value, $x_{i,cost}$, for A_i using the following correlation:

$$x_{i,RL} = \frac{RL_i}{\sqrt{\sum_{i=1}^{m} {RL_i}^2}}, i = 1, 2, \dots, m. \tag{4.29}$$

$$x_{i,cost} = \frac{Cost_i}{\sqrt{\sum_{i=1}^{m} {Cost_i}^2}}, i = 1, 2, \dots, m. \tag{4.30}$$

Where RL_i represents the risk model value and $Cost_i$ represents the cost model value, based on A_i.

4.2.8.2 Step Two: Calculation of weighted normalized risk and cost values

This step is used for the calculation of weighted normalized risk and cost values for A_i using the following correlations:

$$y_{i,RL} = w_{RL} \cdot x_{i,RL}, i = 1, 2, \dots, m. \quad (4.31)$$

$$y_{i,cost} = w_{cost} \cdot x_{i,cost}, i = 1, 2, \dots, m. \quad (4.32)$$

Where $y_{i,RL}$ refers to the normalized risk and $y_{i,cost}$ refers to the normalized cost values for A_i. The weights for risk and cost are w_{RL} and w_{cost}, respectively.

4.2.8.3 Step Three: Determination of the best A^+ and worst A^-

This step comprises of the determination of the best A^+ and worst A^- options depending on $y_{i,RL}$ and $y_{i,cost}$.

To do so, the following correlations are used:

$$A^+ = \{{y_{RL}}^+, {y_{cost}}^+\} = \{\bigcap_{i=1}^{m} y_{i,RL}, \bigcap_{i=1}^{m} y_{i,cost}\} \quad (4.33)$$

$$A^- = \{{y_{RL}}^-, {y_{cost}}^-\} = \{\bigcup_{i=1}^{m} y_{i,RL}, \bigcup_{i=1}^{m} y_{i,cost}\} \quad (4.34)$$

4.2.8.4 Step Four: Calculation of the separate distances

This step involves calculating the separation distances using best, ${D_i}^+$, and worst scenario options, ${D_i}^-$, respectively. Separation of A_i based on ${D_i}^+$ is defined as:f

$${D_i}^+ = \sqrt{\left(y_{i,RL} - {y_{RL}}^+\right)^2 + \left(y_{i,cost} - {y_{cost}}^+\right)^2}, i = 1, 2, \dots, m. \quad (4.35)$$

and separation of A_i based on ${D_i}^-$ is defined as:

$$D_i^- = \sqrt{\left(y_{i,RL} - y_{RL}^-\right)^2 + \left(y_{i,cost} - y_{cost}^-\right)^2}, i = 1, 2, \dots, m. \quad (4.36)$$

4.2.8.5 Step Five: Calculation of preference degrees

This step deals with the calculation of preference degrees based on D_i^+ and D_i^-. Hence, the preference degree, P_i, for A_i is obtained by:

$$P_i = \frac{D_i^-}{D_i^+ + D_i^-}, i = 1, 2, \dots, m. \quad (4.37)$$

4.2.8.6 Step Six: Arrangement of maintenance options

This step deals with ranking the maintenance options based on the preference degrees in a descending manner. It is worth mentioning that an increase in the preference degree results in an increase in the desirability of the maintenance option. Preference degrees tend to offer a comparison with each other for every maintenance option. With the achievement of all preference degrees, the best maintenance option having the greatest preference degree may be chosen.

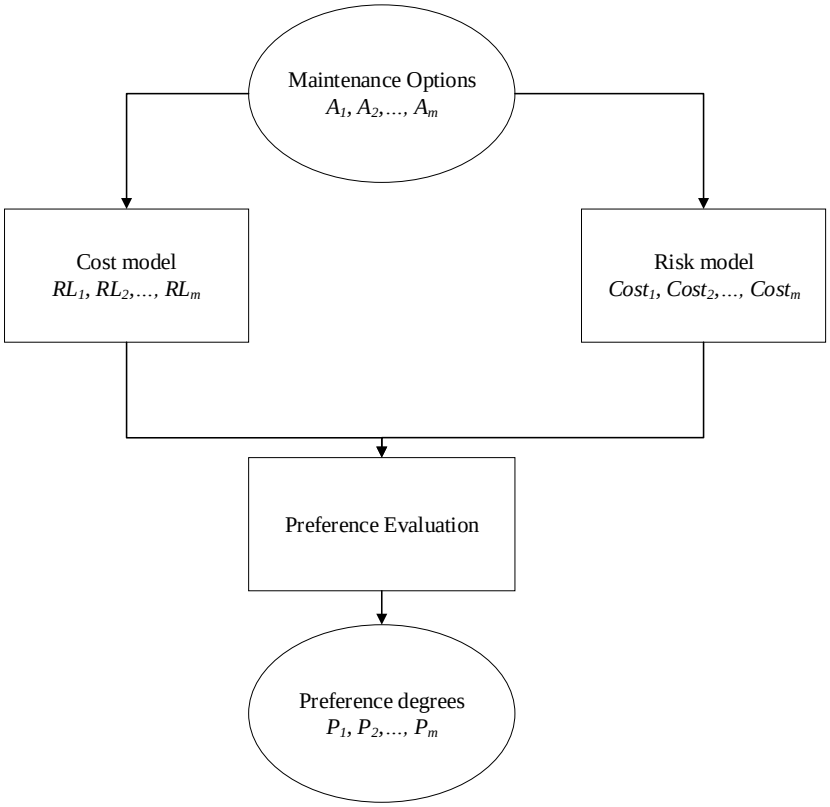


Figure 4.4: A schematic showing the process adopted for the selection of maintenance options (Adapted from Chen, 2012).

4.3 Description of the CSC Parameter along with FF and RL

The use of Consequence Severity (CS) and Failure Frequency (FF) is very common in evaluating risks (An et al., 2006; 2011). However, in terms of bridge safety maintenance, the researcher in the current study has devised a new parameter, which is known as the CSC (Consequence Severity Criteria).

This is an enhanced parameter based on the CS and is divided into eight factors, which are safety, functionality, value for money, environment, traffic delay, time, socioeconomic and reputational damage. Each of these eight consequence types are discussed briefly in the following section:

- Safety

In any project, it is mandatory to carry out a safety risk analysis and management prior to the commencement of the project and must be undertaken throughout the project completion. As bridge structures are dynamic in nature, the safety observations and inspections on these bridges is very important. This is because these inspections offer a way to detect sources which can cause harm. In terms of safety, the key concern is the structural collapse which must be avoided as it has the potential to result in a number of fatalities (Andrić and Lu, 2016).

- Functionality

In the event of a structural collapse, this could result in the closure of local routes. This can definitely have a negative impact on the daily bridge network as it might mean that operations are needed to be stopped. Often, a structural collapse is accompanied by other collapses as well and the need for closing strategic routes (Thompson, 2017).

- Value for money

With regards to finances of any project, it is very likely that any safety incident may result in an increased value for money. Failures or structural collapses would mean that repair works are needed and, in most cases, immediate repair works are required. This can result in the project incurring a huge cost. In addition, risk-based prioritisation of planned maintenance work is also essential for the achievement of value for money (Das, 1997).

- Environment

In the risk assessment of bridges, one key factor take into consideration is the environment. Any structural collapse could mean a direct impact on the environment. This is due to the pollution which will be spread because of such a collapse. As a result,

it can also be anticipated that further damage to the environment may also be probable. For instance, in the event of a bridge collapse, possible damages may happen to facilities storing hazardous chemicals (Das, 1997).

- Traffic delay

With bridge accidents, a massive delay to traffic is highly likely. Apart from the damages and issues incurred due to a structural collapse, traffic delays can last up to long hours. In addition, such traffic delays could also mean that other strategic routes are negatively impacted. Hence, an immediate solution must be devised to overcome such a critical issue. Usually, under major problems, it needs to be determined by relevant bodies whether the bridge is to be closed or kept often (Das, 1997; Sekine, 2006).

- Time

Time accounts for another critical parameter which is in fact linked to all other consequence types. In the event of any kinds of failures or damages to the bridge structure, a lot of valuable time may be lost. In certain cases, immediate solutions may be needed to save time lost (Zhu and Frangopol, 2016).

- Socioeconomic

Any kinds of bridge failures can have a huge influence on the socioeconomics. Often the socioeconomic costs are enormous. Thus, an adequate socioeconomic impact analysis is needed throughout a project to ensure the structure integrity is maintained (Andrić and Lu, 2016).

- Reputational damage

A bridge failure has a direct impact on the reputation. Recovery of trust, following a major incident, requires cost authorisations and risk demands. Assurance of public safety is a challenging task and may require further strategies to be adopted (Larkin, 2014).

Overall, each of these consequence types imply different consequences and deal with the corresponding risks. In addition, a single failure event can be responsible for triggering further events as the impact increases. These multi-consequences parameter, CSC, is integrated with the FF in a fuzzy reasoning approach (FRA) in order to evaluate the RL of any dangerous incident.

While CS and FF are commonly used, it is possible that a simple approach implying the use of these two methods may not be able to evaluate the risk effectively. It is possible that satisfactory results are not achieved. This may be due to a hazardous event having various consequence scenarios, which have varying severity levels. This results in increased amounts of uncertainties in the system of risk analysis. In terms of bridge safety, it is important to further improve the bridge safety risk assessment model. This can allow for identifying the potential hazards more efficiently and effectively.

CSC can be used for describing the magnitude of likely consequences. To elaborate, the CSC parameter considers the minor and major injuries along with fatalities, which occur due to particular hazardous events. The use of linguistic terms such as “Low”, “Medium” and “High” can be used to describe the different consequence types and their respective severity levels. Table 4.3 below lists the consequence types, their description and the respective MF parameters. Each consequence type has a corresponding

trapezoidal MF that is employed to transfer expert judgements into a comparison matrix (An et al., 2007).

Figure 4.5 below shows the plot for membership function employed to characterise CSC. In general terms, a MF for a fuzzy set "A" on the universe of discourse "X" is defined as μ_A:X → [0, 1]. Over here, each element of "X" is mapped to a value between 0 and 1. This particular value can be referred to as the degree of membership or membership value and is used to quantify the grade of membership of the element in "X" to "A". Thus, MFs permit the graphical representation of a fuzzy set. In Figure 4.5, the universe of discourse is represented by the x-axis, while the degrees of membership are represented by the y-axis in the [0,1] interval.

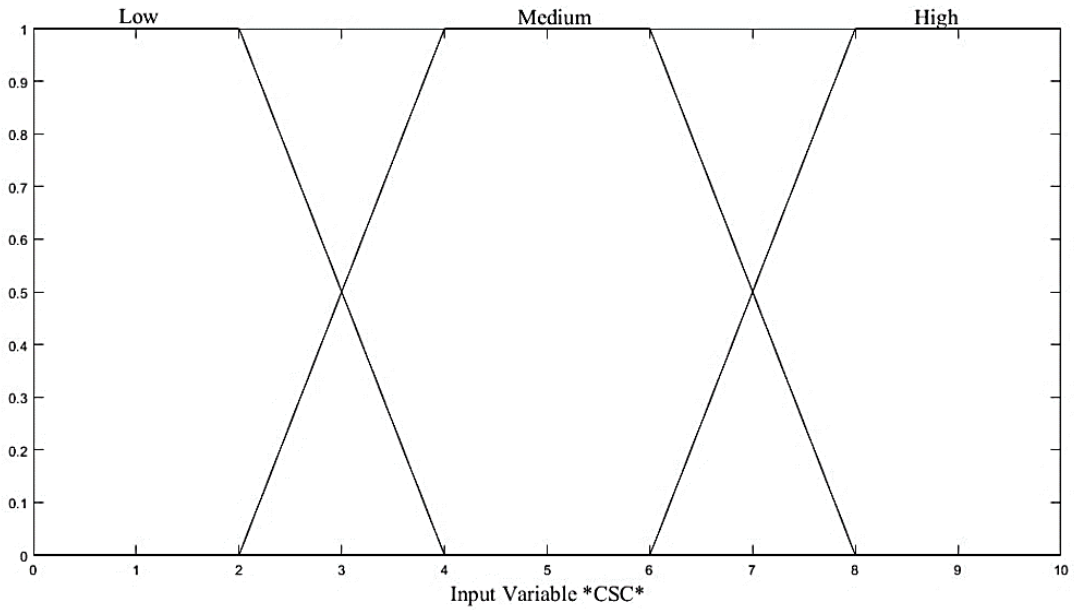


Figure 4.5: Membership Function of CSC

Table 4.3: Description of the CSC parameter

Consequence type	Consequence description	Description	Parameter MFs
Functionality	Low	Collapse of a structure resulting in the closure of a	0.0,0.0,.2.0.4.0

		local route.	
	Medium	Collapse of a structure resulting in the closure of a regional route. Collapse of a structure carrying major utility supply lines.	2.0,4.0,6.0,8.0
	High	Collapse of a structure resulting in the closure of a strategic route.	6.0,8.0,10.0,10.0
Safety	Low	N/A	0.0,0.0,.2.0.4.0
	Medium	Structural collapse with potential to result in small number of fatalities/high number of serious injuries e.g.-structure carries a very low traffic route or is a footbridge. Structure crosses a very low traffic route.	2.0,4.0,6.0,8.0
	High	Structural collapse with potential to result in high number of fatalities e.g. – structure carries a high/medium/low traffic route or is a busy footbridge. Structure crosses a high/medium/low traffic route, a passenger railway line or a populated public area.	6.0,8.0,10.0,10.0
Value for money	Low	Cause of failure (e.g. deterioration) is ongoing if not addressed within 3-4 years then extent and duration of work needed to repair will increase.	0.0,0.0,.2.0.4.0
	Medium	Cause of failure (e.g. deterioration) is ongoing if not addressed within 3-4 years then extent and duration of work needed to repair will increase significantly.	2.0,4.0,6.0,8.0
	High	Cause of failure (e.g. deterioration) is ongoing if not addressed within 3-4 years then extent and duration of work needed to repair will be excessive/unacceptable.	6.0,8.0,10.0,10.0
Environment	Low	Collapse where the period to repair/replacement would involve significant issues.	0.0,0.0,.2.0.4.0
	Medium	Structure collapse could result in pollution from utility/other supply lines carried. Collapse of a listed structure.	2.0,4.0,6.0,8.0
	High	Structure collapse could result in pollution of a conservation area, either from a utility/supply line carried by the structure, or from damage to an adjacent installation e.g. storage facility for hazardous chemicals.	6.0,8.0,10.0,10.0
Traffic Delay	Low	Between half an hour to one hour of traffic delay.	0.0,0.0,.2.0.4.0
	Medium	Between one hour to three hours of traffic delay.	2.0,4.0,6.0,8.0
	High	Above three hour of traffic delay.	6.0,8.0,10.0,10.0

Time	Low	The consequence of an accident is not necessary to be solved immediately.	0.0,0.0,.2.0.4.0
	Medium	The consequence of an accident can be solved in a given time but needs to be considered.	2.0,4.0,6.0,8.0
	High	The consequence of an accident needs to be solved immediately.	6.0,8.0,10.0,10.0
Reputational damage	Low	Trust is recoverable with little effort or at a nominal cost with resource allocation within budget – a major blip on the radar. Risk containable at sector level – Senior management to be kept informed.	0.0,0.0,.2.0.4.0
	Medium	Trust recovery demands cost authorisation above and beyond existing budgets. Risk containable at group sector level – senior management is involved.	2.0,4.0,6.0,8.0
	High	Trust severely damaged and full recovery questionable and costly. Risk demands attention of a board of group members and priority action.	6.0,8.0,10.0,10.0
Socio-Economic	Low	The benefit to Social and Economy is low.	0.0,0.0,.2.0.4.0
	Medium	The benefit to Social and Economic development of the affected region is intermediate.	2.0,4.0,6.0,8.0
	High	The benefit to Social and Economic development of the affected region is High from the planned work.	6.0,8.0,10.0,10.0

Failure Frequency (FF) is a representation of the number of times an event has taken place in a known period of time. For FF, the use of linguistic variables is common. These can be “Very Low”, “Low”, “Medium”, “High” and “Very High”. Figure 4.6 below shows the fuzzy FF set definition while Table 4.4 describes these linguistic variables and their respective MFs.

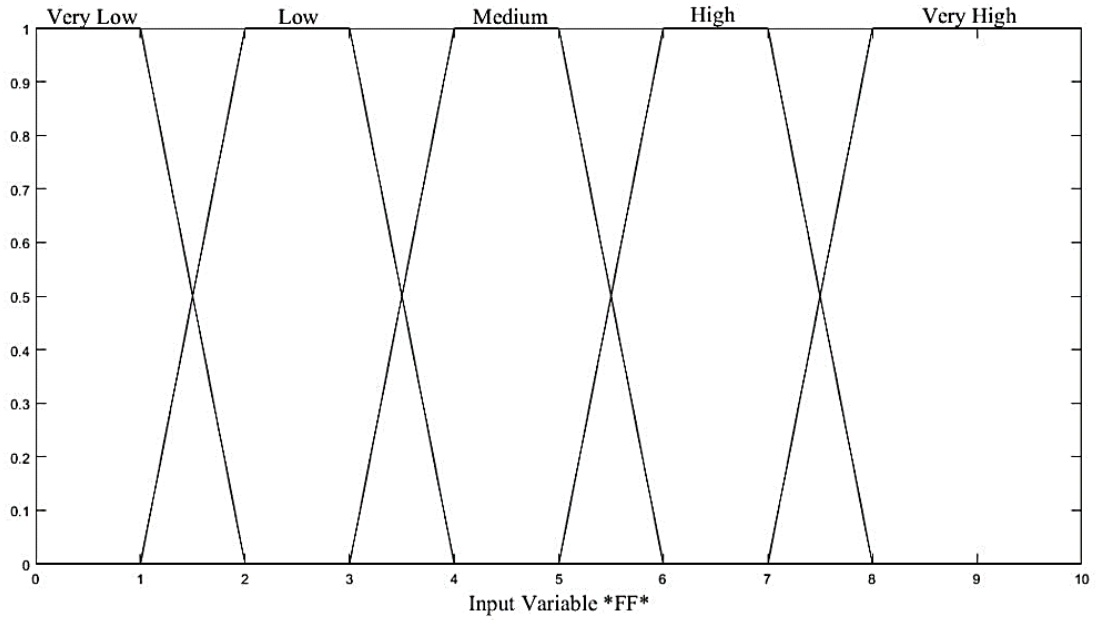


Figure 4.6: Membership Function of FF

Table 4.4: Failure Likelihood

Qualitative descriptors	Description	Parameter of MFs
Very low	Failure is unlikely	0.0,0.0,1.0,2.0
Low	Relatively few failures	1.0,2.0,3.0,4.0
Medium	Occasional failures	3.0,4.0,5.0,6.0
High	Repeated failures	5.0,6.0,7.0,8.0
Very High	Failure is almost inevitable	7.0,8.0,10.0,10.0

Similarly, the RL can be categorised into four regions, i.e. ‘Low’, ‘Possible’, ‘Substantial’, and ‘High’. These are further described in Table 4.5 and shown in Figure 4.7.

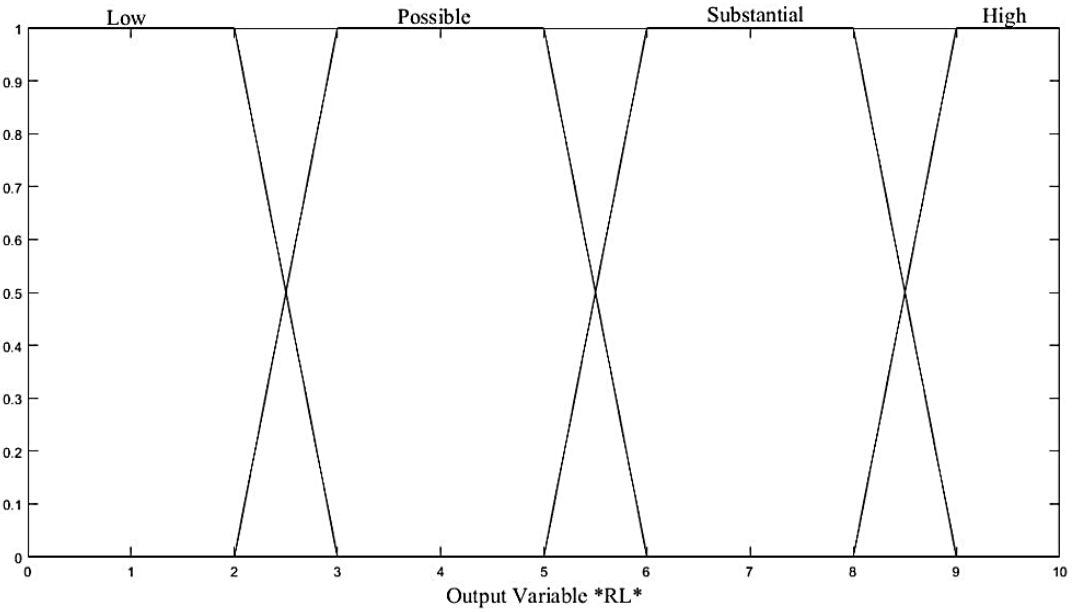


Figure 4.7: Risk Level MF

Table 4.5: Risk Level

Qualitative descriptors	Description	Parameters of MFs
Low	Risk is acceptable	0.0,0.0,2.0,3.0
Possible	Risk is tolerable but should be further reduced if it is cost effective to do so	2.0,3.0,5.0,6.0
Substantial	Risk must be reduced if it is reasonably practicable to do so	5.0,6.0,8.0,9.0
High	Risk must be reduced safe in exceptional circumstances	8.0,9.0,10.0,10.0

4.4 Summary

This chapter is focused on the presentation of a new safety risk model for bridges. The model is developed based on three input parameters, CS, FF and WF. These are used for assessing the risks from components levels all the way to the system level. CSC parameter is introduced as the multi-consequences parameter, which takes into consideration eight factors that are considered significant for the risk analysis of bridges. Such a risk model would permit users and experts in the field to utilise fuzzy

and numeric numbers along with linguistic values in the risk assessment. Risk categories along with scores are expected as outputs of the proposed risk model, which will mention the risk contributions as well. This will simplify and facilitate the risk assessment process of highway bridges, which is a complex topic. In addition, the chapter also discusses a risk-based maintenance decision-making model. This makes use of the TOPSIS methodology that helps integrate both, risk and cost into the bridge-safety process for making suitable and relevant maintenance decisions. Civil and structural engineers, risk analysts and project managers are usually faced with numerous contradictory aims in terms of the several maintenance options. Their work involves maximising safety performances while minimising costs, which is basically minimising risks. As a result, based on these two critical factors, cost and safety, an integrated risk-cost model is projected based on the TOPSIS methodology. This helps in calculating the preference degree of maintenance options. The model can be a useful tool which makes use of the relevant information regarding the safety of bridges.

CHAPTER 5: CASE STUDIES

5.1 Introduction

This chapter focuses on the presentation of three case studies for the risk assessment of highway bridges. Three case studies were used to validate and verify the reliability of the risk assessment and safety management model. In fact, case studies are used to assist in illustrating the implementation of the suggested safety risk management model. Thus, the three case studies utilized in this study are relevant to the safety aspects of bridges. The chapter provides in detail the corresponding risk responses for each case study. The case studies were collected from literature reviews of relevant sources.

5.2 Case Study 1

This risk assessment case study is performed for a single bridge structure to evaluate all the associated risks on this structure. The case study addresses the multiple needs of this structure. As detailed in Table 1 below, a strategic route with 50,000 AADT (Annual average daily traffic) is carried by this structure, which shows that the associated traffic rating is ranked “Medium”. The structure comprises of a five span viaduct in addition to an in-situ concrete slab. The latter is positioned on precast post-tensioned concrete beams. Piers along with reinforced concrete crossheads are used to support these beams at half joints. In terms of the structure’s geographical location, it crosses above a freight railway track, which is underneath one of the five spans. The remaining four spans cross open land and a river.

With regard to the structure’s physical condition, it has been reported that the structure is not in its best condition. To elaborate, the joints, which are non-structural, along with

the waterproofing system have both failed already. This failure has allowed chlorides as well as water to penetrate through the crossheads, beams, half joints and the deck slab. Such a failure undoubtedly puts the integrity of the overall structure at risk and this is evident by reports, which detail that the crossheads, beams, half joints and the deck slab are all showing signs of deterioration. In addition, concrete spalling has taken place as well. Reports have indicated corroded reinforcements also in the structure. Moreover, the freight railway track has been observed and it has also shown signs of spalling.

Investigators investigating the physical condition of the structure have mentioned that for the half joints which are closest to the reinforcement, these must be evaluated with a 0.8 condition factor. Although the structure passes this evaluation, it was concluded that if a condition factor lower than 0.75 was used, the structure would fail.

In terms of what could be done to preserve the structure and maintain its safety, two scheme options are proposed. The first option involves doing just the minimum. It would comprise of performing repairs on the concrete, specifically the railway span only. For the second scheme option, which appears to be a preferable option, this involves performing repairs on all spans of concrete. In addition, the failed joints, as well as the existing waterproofing system, must be replaced.

Furthermore, the resources have been collected from historical data and interviews. Five experts on this topic have been reached out to help on this study. The case study uses two primary parameters, Failure Frequency (FF) and Consequence Severity Criteria (CSC) of hazardous events. The risk assessment outputs are, hazard groups, risk levels and the overall risk level of a bridge structure with risk values varies from 0 to 10, characterised from ‘Low’, ‘Possible’, ‘Substantial’ and ‘High’ assigned with percentages. FRA is used to calculate the risks level of hazard groups based on the

aggregations of the results of each hazardous event that belongs to the particular hazard group which is then weighted by Fuzzy-Analytical Hierarchy processes methods. Historical data of hazards and databases have been noted over the past decade and further reviewed for bridge structures. The hazard groups are classified and with each group consisting of several hazardous events. The bridge structure data is shown in Table 5.1.

Table 5.1: Bridge structure data for Case Study 1

Strategic route:	50,000 AADT
Span bridge features:	A 5-span viaduct that has an in-situ concrete slab. The slab is positioned on post-tensioned precast concrete beams. These are further positioned using reinforced concrete piers as well as crossheads at half joints. One span is below freight railway line, while the other four cross a river and open land.
Component that fails:	Non-structural joints and waterproofing system
Condition of reinforcement factor:	0.8
Dropped factor:	Below 0.75.
Minimization:	Concrete repairs (railway span only).
Replacement:	Five spans concrete, joints and waterproof.
Risk Events:	• Non-Structural Component Failure (Waterproofing) due to deterioration • Concrete Spalling over the freight railway • Reinforcement Corrosion • Component failure (non-structural joints): Route serviceability may be affected, superstructure as well as sub-structures are deteriorating, which are below failed joints, half joints.

5.2.1 Risk Assessment

5.2.1.1 Safety Hazard Identification and Analysis

A safety risk management group is determined with the purpose of reviewing the safety risks on highway bridges. This group comprises of five experts and these experts must be able to demonstrate the adequate knowledge. As a result, each expert is allocated a contribution factor. This is demonstrated in Table 5.2.

Table 5.2: Allocation of Expert Indices

Experts	**Background**	**Contribution factor**
E1	Safety Manager	0.32
E2	Project Manager	0.24
E3	Senior Safety Officer	0.22
E4	Safety Officer with 15 years' experience	0.16
E5	Site Engineer	0.06

Step 1: Input FF and CSC.

Data available is taken from experts and is defined as a numerical number. The range and linguistics variable are shown in Table 5.3.

Table 5.3: Experts linguistics variable converted

Input type	**Description**	**Input values**	**Input values (FF)**	**STFN (FF)**	**Input values (CSC)**	**STFN (CSC)**
A numerical value	….is a ….is between *a* and *b*	*a* (a, b)	7 (8,9)	(7,7,7,7) (8,8,9,9)	6 (4,5)	(6,6,6,6) (4,4,5,5)
A range of	….is High	High About c	High About	(5,6,7,8) (7,8,8,9)	Medium About 6	(2,4,6,8) (5,6,6,7)

numbers A linguistic term #1 A linguistic term #2 A triangular fuzzy number	….is about c ….is between *a* and *c* and most likely to be *b*	(a, b, c)	8 (8,9,10)	(8,9,9,10)	(2,3,4)	(2,3,3,4)

Step 2: Convert inputs into UFNs.

The crisp numbers have been converted to UFNs according to Table 4.1. The numbers of FF and CSC of the elements are then aggregated.

$A_{FF(safety)}$=(8,8,9,9)-(7,7,7,7)-(7,8,8,9)-(8,9,9,10)-(5,6,7,8)

$A_{CSC(safety)}$=(4,4,5,5)-(6,6,6,6)-(5,6,6,7)-(2,3,3,4)-(2,4,6,8)

Step 3: Aggregating UFNs.

Equations 4.2, 4.3,4.4 and 4.5 are used for transferring to fuzzy sets UFNs as follows:

The data given by five expert judgments are aggregated by:

$FF_{safety} = \mu(x) = ((8,8,9,9) \times 0.32 + (7,7,7,7) \times 0.24 + (8,9,9,10) \times 0.22 +$

$(7,8,8,9) \times 0.16 + (5,6,7,8) \times 0.06)) = (7.42, 7.86, 8.24, 8.68)$

$$FF_{safety} = (x) = (7.42, 7.86, 8.24, 8.68)$$

Also, aggregated of CSC_{safety} can be obtained by:

$$CSC_{safety} = (x) = (4.08, 4.58, 5.02, 5.52)$$

Step 4: Transferring the UFNs into fuzzy sets as shown in Figure 5.2 and Figure 5.3.

FF_{safety}= (7.42, 7.86, 8.24, 8.68)

CSC_{safety}= (4.08, 4.58, 5.02, 5.52)

Step 5: Fuzzy inference process

The experiences and engineering judgments are used to produce 120 rules. The fire strength of every rule can be calculated by equation 4.7 for the input fuzzy sets, which is then moved to conclude the fuzzy sets of rule firing. The truncated MF can then be used by equation 4.8 for the conclusion of fuzzy sets of every rule. After aggregating the conclusion, equation 4.9 can be utilized using the fuzzy output of RL, which is represented to form a single fuzzy set to a failure mode. For example, the fuzzy set of Cs_{FF}, Cs_{CSC} is the input fuzzy sets and are found using the entire rules. In this example the four rules used are:

- Rule# IF $Concrete, safety_{FF}$ is high and $Concrete, safety_{CSC}$ is medium then RL is high.
- Rule# IF $Concrete, safety_{FF}$ is very high and $Concrete, safety_{CSC}$ is medium then RL is high.
- Rule# IF $Vandalism, safety_{FF}$ is low and $Vandalism, safety_{CSC}$ is low then RL is possible.
- Rule# IF $Vandalism, safety_{FF}$ is low and $Vandalism, safety_{CSC}$ is medium then RL is substantial.

The firing strength is calculated by equation 4.7:

$$\alpha_s = \min\left[max\left(\mu_{A^s_{FF}}(k) \wedge \mu_{T^s_{FF}}(k)\right), max\left(\mu_{A^s_{CSC}}(q) \wedge \mu_{T^s_{csc}}(q)\right)\right]$$

$$\alpha_i = \min[((0.4) \wedge (1)), ((0.6) \wedge (1))]$$

Max = ~~(L)~~,~~(P),~~ ~~(S),~~ (2H)

Step 6: Defuzzification.

The crisp number of fuzzy set output can be defuzzified by equation 4.10, through which the RL of Concrete spalling is obtained, as shown in Figure 5.4.

$$RL_{concrete,safety} = \frac{\sum_{q=1}^{n-1} z_q \, \mu(Z_q)}{\sum_{q=1}^{n-1} \mu(Z_q)} = \left(\frac{(0.4\times10)+(0.6\times10)}{0.4+0.6} = 10 \right)$$

$$(RL_{concrete,value\ for\ mony} = 10)$$

$$(RL_{concrete,enviroment} = 9.7)$$

$$(RL_{concrete,trafic\ delay} = 9.7)$$

$$(RL_{concrete,time} = 10)$$

$$(RL_{concrete,RD} = 9.6)$$

$$(RL_{concrete,EC} = 10)$$

In the same way, every RLs of elements can use the same equation to get the result as shown in Table 5.4.

Table 5.4: Results of risk assessment

Structure	**RL Substructure**	**Elements**	**FF(MF)**	**CS (MF)**	**Risk Score**	**Risk percentage**
Bridge RL(9.50)	Concrete Spalling RL(9.48)	Safety	(H0.4,VH0.6)	(M1)	10	100% High
		Value for money	(H0.4,VH0.6)	(M1)	10	100% High
		Environment	(H0.4,VH0.6)	(L0.8,M0.2)	9.7	97% High
		Time	(H0.4,VH0.6)	(H1)	9.7	97% High
		Traffic delay	(H0.4,VH0.6)	(L0.5,M0.5)	10	100% High
		Reputational damage	(H0.4,VH0.6)	(L1)	9.6	96% High
		Socio-Economic	(H0.4,VH0.6)	(M1)	10	100% High
	Deterioration (Reinforcement corrosion) RL(9.45)	Value for money	(H0.4,VH0.6)	(L0.5,M0.5)	9.7	97% High
		Environment	(H0.4,VH0.6)	(L1)	9.6	96% High
		Time	(H0.4,VH0.6)	(M1)	10	100% High
		Traffic delay	(H0.4,VH0.6)	(L1)	9.6	96% High
		Reputational damage	(H0.4,VH0.6)	(L1)	9.6	96% High
		Socio-Economic	(H0.4,VH0.6)	(L1)	9.6	96% High
		Value for money	(H0.4,VH0.6)	(L0.04,M1)	9.9	99% High

	(Waterproofing) RL(9.58)	Time	(H0.4,VH0.6)	(M1)	10	100% High
		Traffic delay	(H0.4,VH0.6)	(L0.48,M0.52)	9.7	97% High
		Reputational damage	(H0.4,VH0.6)	(L1)	9.6	96% High
		Socio-Economic	(H0.4,VH0.6)	(L1)	9.6	96% High
	Joints RL(9.64)	Value for money	(H0.4,VH0.6)	(M1)	10	100% High
		Time	(H0.4,VH0.6)	(H1)	10	100% High
		Traffic delay	(H0.4,VH0.6)	(M1)	10	100% High
		Reputational damage	(H0.4,VH0.6)	(L1)	9.6	96% High
		Socio-Economic	(H0.4,VH0.6)	(L1)	9.6	96% High

5.2.2 Risk Assessment of all Structure Levels

In this case, the fuzzy–AHP (FAHP) is used to achieve the element level and substructure level to find the WFs of each of them. According to the estimation scheme in Table 4.2, every expert judgment has to produce pairwise comparisons from the element level to the substructure level. The following process is carried out to obtain the WFs of the elements level and the substructure level. The calculation process is as follows:

Step 1: Establishing an estimation scheme.

The estimation scheme is made using the judgments recorded which were agreed upon by the experts. The estimation scheme can be used as shown in Table 4.2.

Step 2: Construct Pair-wise comparison factors in a risk tree

The relative differences between substructures and elements produced from expert judgments are shown in Table 5.9 and Table 5.10. Four comparisons have been taken

from each expert and are free to use any of the tables (numerical numbers, linguistic terms or fuzzy numbers).

Step 3: Converting inputs into UFNs.

The expert or engineering judgments used to make the decisions are shown in Table 4.1, which are then converted to UFN as shown in Table 5.9 and and Table 5.10.

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Step 4: Aggregate UFNs.

UFN numbers are aggregated in Table 5.9.

Table 5.10 mentions alongside the respective expert opinion in the Expert index. By using equation 4.3, Table 5.9 shows the comparison of each substructure level.

$$M_1 = \{a_1, b_1, c_1, d_1\} = \left\{\frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}\right\}$$

$$= \left\{\frac{(6\times0.32)+(7\times0.24)+(6\times0.16)+(6\times0.22)+(6\times0.06)}{(0.32+0.24+0.16+0.22+0.06)}\right\} = (6.24, 7.24, 7.24, 8.24)$$

Step 5: Based on comparison matrix, calculating fuzzy WFs.

An overall comparison matrix can be developed for the hazard group after performing steps 1 to 4. With the use of aggregated UNFs, detailed by equation 4.11, it is possible to establish the comparison matrix, *P*.

$$P=\tilde{A}=\begin{bmatrix} \tilde{a}_{1,1}\ \tilde{a}_{1,2} & \cdots & \tilde{a}_{1,n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n,1}\ \tilde{a}_{n,2} & \cdots & \tilde{a}_{n,n} \end{bmatrix}$$

The overall comparison matrix can be achieved as shown in Table 5.11 and Table 5.12.

$$S(x_a) = x_a^{1/log9}$$

Table 5.10 shows that converted entries are completed in the comparison matrix, *P*.

UFN geometric is U_a of the *a*-th row in the comparison matrix and is calculated by equation 4.12 as shown in Table 5.5.

$$U_a = \{a_a, b_a, c_a, d_a\} = \left\{ \sqrt[4]{\prod_{j=1}^{4} a_{1,j}}, \sqrt[4]{\prod_{j=1}^{4} b_{1,j}}, \sqrt[4]{\prod_{j=1}^{4} c_{1,j}}, \sqrt[4]{\prod_{j=1}^{4} d_{1,j}} \right\} =$$

$U_{Concrete\ Spalling}$ = (2.51, 2.94, 2.94,3.52)

$U_{Deterioration}$ = (0.98,1.09,1.09,1.28)

$U_{Wateproofing}$ = (0.50, 0.55, 0.55, 0.66)

U_{Joints} = (0.37, 0.51, 0.51, 0.60)

Table 5.5: Comparison matrix of a-th row

	A	**B**	**C**	**D**
Concrete Spalling	2.511000524	2.941085482	2.941085482	3.526179441
Deterioration	0.981998475	1.094759819	1.094759819	1.283462715
Waterproofing	0.503757433	0.558420351	0.558420351	0.66758037
Joints	0.376529506	0.517842061	0.517842061	0.605254642

Following on, the hazard fuzzy WF will be achieved using equation 4.13 as presented in Table 5.6.

$$W_A = \{a_a, b_a, c_a, d_a\} = \left\{ \frac{a_a}{\sum_{j=1}^{n} d_j}, \frac{b_a}{\sum_{j=1}^{n} c_j}, \frac{c_a}{\sum_{j=1}^{n} b_j}, \frac{d_a}{\sum_{j=1}^{n} a_j} \right\}$$

$$W_{Concrete\ Spalling} = \{a_a, b_a, c_a, d_a\} = \left\{ \frac{2.51}{6.08}, \frac{2.94}{5.11}, \frac{2.94}{5.11}, \frac{3.52}{4.37} \right\} =$$

$W_{Concrete\ Spalling} = (0.41,0.57,0.57,0.80)$

$W_{Deterioration} = (0.16,0.21,0.21,0.29)$

$W_{Waterproofing} = (0.08,0.10,0.10,0.15)$

$W_{Joints} = (0.06,0.10,0.10,0.13)$

Table 5.6: WF of hazard fuzzy

Fuzzy WFs				
Concrete Spalling	0.41282531	0.575317589	0.575317589	0.806299769
Deterioration	0.161447129	0.214150382	0.214150382	0.293477887
Waterproofing	0.082821097	0.109234856	0.109234856	0.152649605
Joints	0.061903974	0.101297173	0.101297173	0.138398141

Step 6: Defuzzification as well as normalisation.

For fuzzy WF, the associated crisp number can be easily obtained using equation 4.14. This is also demonstrated in Table 5.5.

$(W_{Concrete\ Spalling} = \frac{0.36+2(0.52+0.52)+0.75}{6} = 0.58)$

$(W_{Deterioration} = 0.21)$

$(W_{Waterproofing} = 0.11)$

$(W_{Joints} = 0.10)$

Table 5.7: Crisp number of fuzzy WF

Normalisation and Defuzzification	
Concrete Spalling	0.586732572
Deterioration	0.218587757
Waterproofing	0.112068355
Joints	0.100915135

For the hazardous WF, the final WFs can be found by equation 4.15, as Table 5.8 shows.

$WF_{Concrete} = \frac{w_c}{\sum_{i=1}^{4} w} = \frac{0.58}{(0.58+0.21+0.11+0.10)} = 0.57$

$(WF_{Deterioration} = 0.21)$

$(WF_{Waterproofing} = 0.11)$

$(WF_{Joints} = 0.09)$

Table 5.8: Final WFs of hazardous

Final WF	
Concrete Spalling	0.576186165
Deterioration	0.214658684
Waterproofing	0.110053947
Joints	0.099101204

Step7: Risk Level and Weight Factors.

Once the WFs of elements are obtained, the RL of the "bridge element" substructure RL can be found from the synthesis of element WFs.

$$RL_{structure} = \sum_{j=1}^{4} RL_j WF_j = RL_c \times W_c + RL_D \times W_D + RL_w \times W_w + RL_J \times W_J =$$

$$RL_{structure} = \sum_{j=1}^{4} RL_j WF_j = 9.48 \times 0.576 + 9.45 \times 0.214 + 9.58 \times 0.110 + 9.64 \times 0.09 = 9.50$$

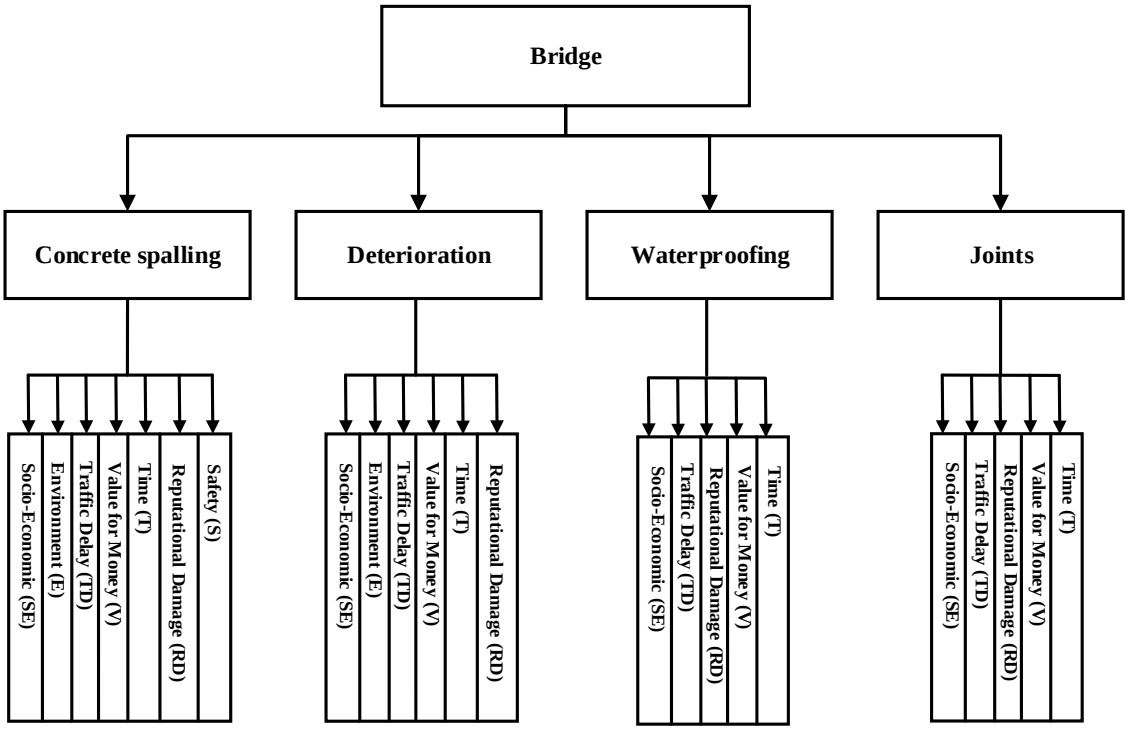


Figure 5.1: Risk tree for bridge risk analysis

Converting and Aggregate UFNs

Table 5.9: Expert judgments for substructure of bridge structure.

	Expert 1				Expert 2				Expert 3				Expert 4				Expert 5			
Comparison	0.32				0.24				0.16				0.22				0.06			
Concrete Spalling vs Deterioration	6	7	7	8	7	8	8	9	6	7	7	8	6	7	7	8	6	6	8	8
Deterioration vs Waterproofing	2	3	3	4	4	5	5	6	4	4	5	5	2	3	3	4	4	4	5	5
Waterproofing vs Joints	1.5	2.5	2.5	3.5	1	1	1	2	1	2	2	3	1.5	2.5	2.5	3.5	1	2	2	4

Table 5.10: Aggregation of Expert judgments.

Aggregate				
Concrete Spalling vs Deterioration	6.24	7.24	7.24	8.24
Deterioration vs Waterproofing	2.70	3.70	3.70	4.70
Waterproofing vs Joints	1	1.22	1.22	2.22

Table 5.11: Pairwise comparison matrix *P* established for bridge elements

	Concrete Spalling	**Deterioration**	**Waterproofing**	**Joints**
Concrete Spalling	1,1,1,1	6.24,7.24,7.24,8.24	16.84,26.78,26.78,38.72	16.84,32.68,32.68,85.97
Deterioration	0.12,0.13,0.13,0.16	1,1,1,1	2.7,3.7,3.7,4.7	2.7, 4.51, 4.51, 10.43
Waterproofing	0.02,0.03,0.03,0.05	0.21, 0.27, 0.27, 0.37	1,1,1,1	1,1.22,1.22,2.22
Joints	0.01,0.03,0.03,0.05	0.09,0.22,0.22,0.37	0.45,0.81,0.81,1	1,1,1,1

Comparison matrix calculating the fuzzy WFs

Table 5.12: Pairwise comparison matrix *P* established for bridge elements

	Concrete Spalling	**Deterioration**	**Waterproofing**	**Joints**
Concrete Spalling	1,1,1,1	2.46, 2.65, 2.65, 2.83	4.02, 5.06, 5.06, 6.07	4.02, 5.58, 5.58, 9
Deterioration	0.35, 0.36, 0.36, 0.40	1,1,1,1	1.63,1.90,1.90,2.14	1.63, 2.10, 2.10, 3.17
Waterproofing	0.14, 0.17, 0.17, 0.22	0.46, 0.52, 0.52, 0.61	1,1,1,1	1,1.10,1.10,1.48
Joints	0.10, 0.17, 0.17, 0.22	0.30, 0.47, 0.47, 0.61	0.67, 0.90, 0.90, 1	1,1,1,1

5.2.3 Maintenance Decision Making Option

The input of FF and CS of every failure mode can be measured by FRA to obtain the RL of every failure. The RL of the substructures is the result of the product of RL and WF of the elements. Finally, the RL of the structure is obtained by the substructure. The element, substructure and structure of the bridge are shown in Table 5.13.

Table 5.13: Risk assessment results

Structure	RL Substructure	RC	Elements	PC	Risk Score	Risk percentage
Bridge RL(9.50)	Concrete Spalling RL(9.48)	58%	Safety	28%	10	100% High
			Value for money	20%	10	100% High
			Environment	18%	9.7	97% High
			Time	8%	9.7	97% High
			Traffic delay	13%	10	100% High
			Reputational damage	7%	9.6	96% High
			Socio-Economic	6%	10	100% High
	Deterioration (Reinforcement corrosion) RL(9.45)	21%	Value for money	38%	9.7	97% High
			Environment	22%	9.6	96% High
			Time	10%	10	100% High
			Traffic delay	15%	9.6	96% High
			Reputational damage	8%	9.6	96% High
			Socio-Economic	7%	9.6	96% High
	(Waterproofing) RL(9.58)	11%	Value for money	47%	9.9	99% High
			Time	15%	10	100% High
			Traffic delay	18%	9.7	97% High
			Reputational damage	10%	9.6	96% High
			Socio-Economic	10%	9.6	96% High
			Value for money	47%	10	100% High
			Time	14%	10	100% High
			Traffic delay	18%	10	100% High

	Joints RL(9.64)	10%	Reputational damage	10%	9.6	96% High
			Socio-Economic	10%	9.6	96% High

As the RL of the structure of the bridge is 9.50, it is labelled as High. This reduces the risk in the transition region "As Low As Reasonably Practicable" (ALARP). It can be assumed that the requirement for safety corresponds to the system's overall RL, which should not be greater than 3. In terms of the overall maintenance budget, this is £500,000. In addition, Table 5.14, Table 5.15 and Table 5.16 show the detailed costs, that include costs for parts, materials, equipment, labour as well as any relevant costs. Four maintenance options can be supposed. Maintenance should reduce the RL of the Bridge structure, provided that either of the four maintenance options mentioned below is used. These are:

Option 1: maintain the Concrete Spalling.

Option 2: maintain the Joints and Waterproofing.

Option 3: maintain the Joints and Deterioration.

Option4: maintain the Waterproofing and Deterioration.

The RL of all of the structures is estimated after the implementation of matching optional maintenance. Table 5.15 shows the cost and RL of every option, and the best option can be identified using a decision making model.

Table 5.14: Maintenance costs

Structure	**Substructure**	**Risk Score**	**Final Cost with 10%**
Bridge RL(9.50)	Concrete spalling	9.48	(280,000+28,000) 308000
	Deterioration(Reinforcement corrosion)	9.45	(120,000+12,000) 132000
	Waterproofing	9.58	(160,000+16,000)

			176000
	Joints	9.64	(200,000+20,000) 220000

Table 5.15: Maintenance options costs along with associated RLs.

Options	Cost	RL
Option 1	308,000	5.40
Option 2	396,000	1.92
Option 3	352,000	2.85
Option 4	308,000	3.03

Normalised cost recommended, there are four options attached from cost and risk model.

$$x_{cost}=\frac{cost_1}{\sqrt{\sum_{i=1}^{m} {cost_1}^2}} = \frac{308000}{\sqrt{(308000)^2+(396000)^2+(352000)^2+(308000)^2}} = 0.4490$$

And normalised RL of structure for option 1 is:

$$x_{RL}=\frac{RL_1}{\sqrt{\sum_{i=1}^{m} {RL_1}^2}} = \frac{5.40}{\sqrt{(5.40)^2+(1.92)^2+(2.85)^2+(3.03)^2}} = 0.7625$$

The weighted cost is normalised for option 1. The cost and risks are equally significant and are calculated as:

$z_{1\,cost} = \ w_{cost} \times x_{cost}$ = 0.5× 0.4490 = 0.2245

The weighted RL structure is normalised for option 1 and can be calculated as follows:

$z_{1\,RL} = \ w_{RL} \times x_{RL}$ = 0.5× 0.7625 = 0.3812

Also, Table 5.16 shows the calculated of next options of the weighted RL and cost normalised. And the best option can be calculated as:

$O^+ = \{0.2245, 0.1355\}$

$O^- = \{0.2886, 0.3812\}$

The option 1 degree of preference can be detect as:

$D_1^+ =$

$\sqrt{(z_{1\,cost} - z_{1\,cost}{}^+)^2 + (z_{1\,RL} - z_{1\,RL}{}^+)^2} =$

$\sqrt{(0.2245 - 0.2245)^2 + (0.3812 - 0.1355)^2} = 0.2457$

$D_1^- =$

$\sqrt{(z_{1\,cost} - z_{1\,cost}{}^-)^2 + (z_{1\,RL} - z_{1\,RL}{}^-)^2} =$

$\sqrt{(0.2245 - 0.2886)^2 + (0.3812 - 0.3812)^2} =$

0.0641

$P_1 = \frac{D_1^-}{D_1^+ + D_1^-} = \frac{0.0641}{0.2457 + 0.0641} = 0.2069$

Table 5.16: The outcome of preference evolution at every option

Options	x_{cost}	z_{cost}	x_{RL}	z_{RL}	D^+	D^-	P	**Rank**
Option 1	0.449	0.2245	0.7625	0.3812	0.2457	0.0641	0.2069	4
Option 2	0.5773	0.2886	0.2711	0.1355	0.0641	0.2457	0.7930	1
Option 3	0.5132	0.2566	0.4024	0.2012	0.0731	0.1828	0.7143	2
Option 4	0.449	0.2245	0.4278	0.2139	0.0784	0.1791	0.6956	3

5.2.3.1. Calculation of Costs

Sensitivity Analysis

Depending on the changes in the maintenance cost of each component, a sensitivity analysis has been carried out. Maintenance costs of each component increased by 10% is demonstrated in Table 5.17 while Table 5.18 shows the calculated cost of each

maintenance option, based on the variances. Table 5.19 summarises the maintenance options' calculated preference rankings.

Maintenance costs

Maintenance costs ($Cost_M$) comprise of two individual costs; labour ($Cost_{MLab}$) and parts ($Cost_{MP}$).

$$Cost_M = Cost_{MLab} + Cost_{MP}$$

$$Cost_{MLab} = \sum_{n=1}^{M} Cost_{MLab} \times MT_n$$

$$Cost_{MP} = \sum_{n=1}^{M} Cost_{MP,n} \times MT_n$$

Maintenance work costs (*n-th)* can be split in the following manner:

$$Cost_M = Cost_{MLab} + Cost_{MP}$$

280,000 = 100,000+180,000

Where MT_n refers to the time needed for carrying out maintenance works while ensuring the structural integrity of the bridge stays in place.

Table 5.17: Maintenance costs increased by 10% for each component.

Substructure	**RL**	**Maintenance Cost**	**Maintenance Cost +10%**
Concrete spalling	9.48	280,000	(280,000+28,000) 308000
Deterioration (Reinforcement corrosion)	9.45	120,000	(120,000+12,000) 132000
Waterproofing	9.58	160,000	(160,000+16,000) 176000
Joints	9.64	200,000	(200,000+20,000) 220000

Table 5.18: Maintenance options' costs and the corresponding overall RL of the system based on the component cost variances by 10%.

Option	**Original Cost**	**Cost +10%**	**RL**
Option 1	(280,000+28,000)	(280,000+28,000) 308000	5.40
Option 2	200,000+160,000	396,000	1.92
Option 3	200,000+120,000	352,000	2.85
Option 4	160,000+120,000	308,000	3.03

Table 5.19: Preference rankings according to varying maintenance costs.

Option	**Original**	**Cost +10%**	**Rank**
Option 1	0.2069	0.2069	4
Option 2	0.7930	0.7930	1
Option 3	0.7143	0.7143	2
Option 4	0.6956	0.6956	3

Based on the results achieved in this section, it appears that the proposed cost-risk model is insensitive to the cost variances of each component. This is because the model does not have an influence on the preference degrees of maintenance options. Nevertheless, the model is sensitive to the risk contributions of each component and subsystem. This is demonstrated in Table 5.13 where the overall system's RL reduces significantly with the elimination of high risk contributors. In addition, since the risk-cost model's inputs are formed with combining the maintenance options, each option's combination will have a significant influence on the outcomes. Overall, based on the results presented in this section, it is apparent that the proposed risk-based decision-making model can greatly help asset management teams in comprehending the problem

and thus making effective decisions in terms of which risk reduction measures must be taken.

5.2.4 Results

Three fuzzy models, FRA, FAHP and TOPSIS are successfully used in the risk assessment of this case study. This was achieved in a step-by-step manner. The outcomes were then calculated in the process of risk assessment. Based on the results, it appears that option 2 is the most suitable one. This is because of this option's highest preference degree of 0.7930%. Additionally, option 2 also appears to be the best safety maintenance option. Moreover, the option with the highest preference degree can be considered as the most ideal option, based on the recommended risk-cost model.

Further, it is possible that the RL for the overall bridge system could be decreased from 9.50 (High 100%) to 1.92 (low 100%), if option 2 is used for carrying out the maintenance work. Also, the respective cost of the project would be around £396,000. This value appears to be in the budget. Thus, the best maintenance option is proposed, which highlights a suitable option for reducing the RL. As the RL of the structure of the bridge is 9.50, it is labelled as "High".

Figure 5.2, Figure 5.3 and Figure 5.4 show the FF, CSC and RL of Case Study 1.

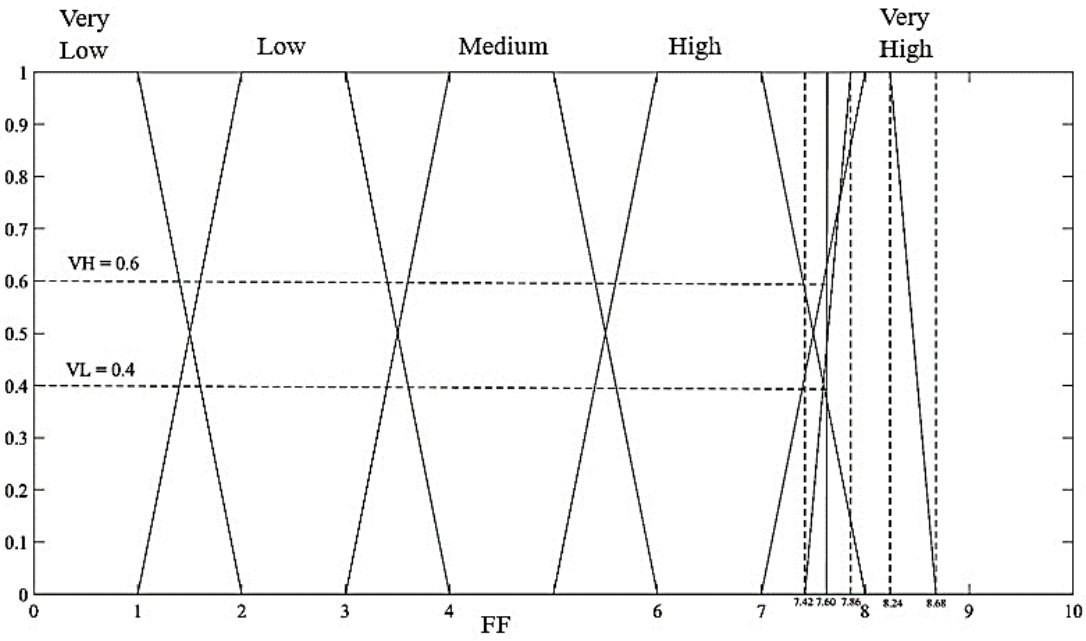


Figure 5.2: FF for Case Study 1

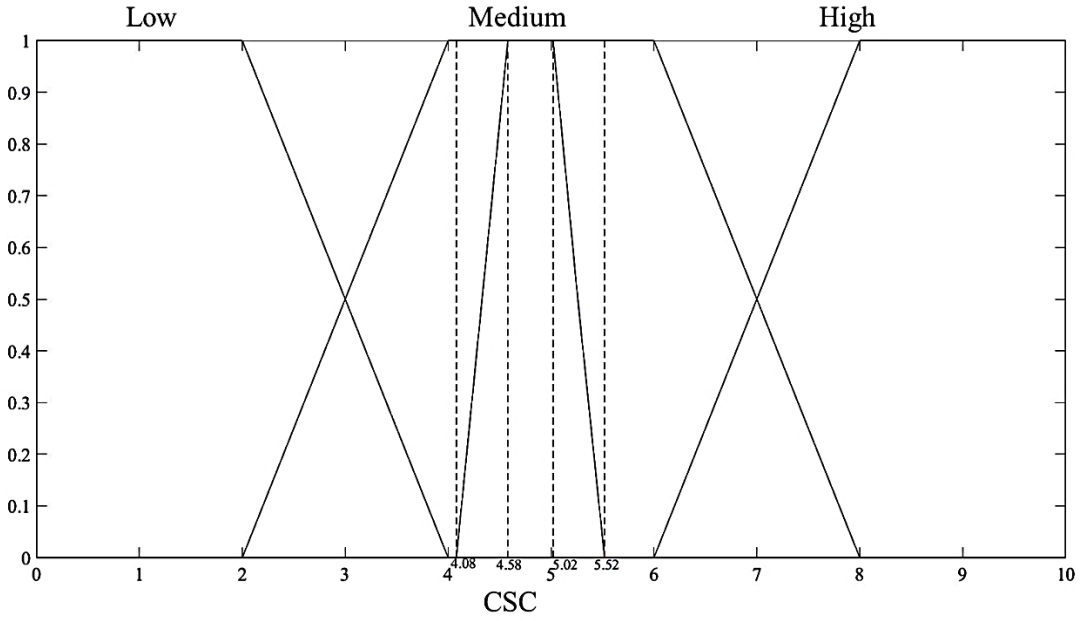


Figure 5.3: CSC for Case Study 1

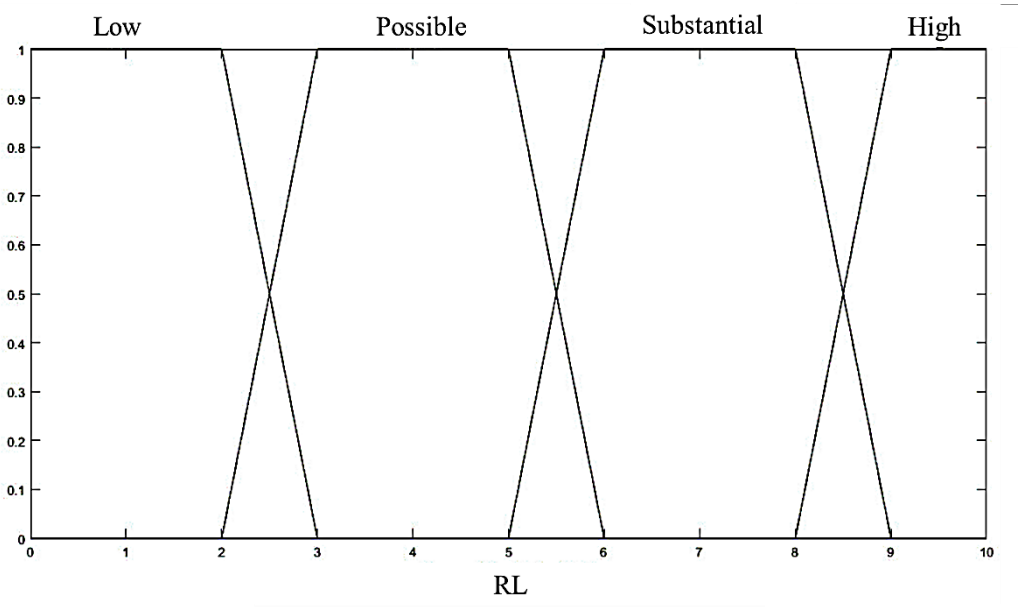


Figure 5.4: RL for Case Study 1

5.3 Case Study 2

This risk assessment case study is performed for a single bridge structure to evaluate all the associated risks on this structure. The case study addresses just a single need for this structure. A strategic route with less than 40,000 AADT is carried by this structure. Therefore, the associated traffic rating is ranked as “low”.

This case study involves replacing a substandard subway system. This is because the subway structure has failed its 40 tonnes Assessment. This was because of a change in the standards for shear reinforcement from the construction time. Formerly, the structure was subjected to a “Level 3” assessment. In this assessment, the structure demonstrated a 70% remnant strength for complete HA loading. Type HA loading is commonly used for the design loading of highway bridges in the UK. However, it is unlikely that an increased capacity is seen with a higher level of assessment. Overall,

the structure demonstrated signs of distress, hence, props were installed. In addition, the failure mode is probable to be brittle/sudden.

Furthermore, the installed props lead to slight chances of vandalism thus introducing breach of safeguarding. This may result in the existing subway collapsing completely. Such would be an example of a global collapse showing a major structural failure. However, at present, this is unlikely to happen.

While initial vandalism to the props could cause the propping systems to fail, this would only be initiated with a series of events taking place. Overall, it is unlikely that the subway system experiences all these events at once. The passing of an overweight vehicle over the structure may expose the structure to a low risk. Therefore, the chances of failure of the structure due to overloading effects are low. The reason behind the likelihood of having events of vandalism is explained by the poor lighting and no security system at the subway. For failure to take place, more than one prop would be vandalised, which is unexpected. Regarding the subway's operation, it is utilised by college students frequently. Thus, there may be a chance for some injuries or even fatalities.

5.3.1 Risk assessment

Step 1: Input FF and CSC.

Data available is taken from experts and is defined as a numerical number. The range and linguistics variables are demonstrated in Table 4.1.

Step 2: Creating UFNs by converting inputs.

According to Table 4.1, crisp numbers have been converted to UFNs. The numbers of FF and CSC of the elements are then aggregated.

$A_{FF(safety)}$=(1.27,1.27,1.27,1.27)

$A_{CSC(safety)}$=(2.71,2.71,2.71,2.71)

Step 3: Aggregating UFNs.

There lies no need for aggregating the judgements of experts as the achieved data is collected based on a single expert judgement. Therefore, the procedure shifts to step 4.

Step 4: Transferring the UFNs into fuzzy sets.

Equations 4.2, 4.3, 4.4 and 4.5 are used for transferring to fuzzy sets UFNs as following:

$$A_{FL}^{s} = \left\{\left(k, \mu_{A_{FL}^{s}}(k)\right) |\ k \in K = [0,10], \mu_{A_{FL}^{s}}(k) = \begin{Bmatrix} 1 & k = 1.27 \\ 0 & otherwise \end{Bmatrix}\right\} \quad (3)$$

$$A_{cs}^{s} = \left\{\left(q, \mu_{A_{cs}^{s}}(q)\right) |\ q \in Q = [0,10], \mu_{A_{cs}^{s}}(q) = \begin{Bmatrix} 1 & q = 2.71 \\ 0 & otherwise \end{Bmatrix}\right\} \quad (4)$$

Step 5: Fuzzy inference process

The experiences and engineering judgments are used to produce 120 rules. The fire strength of every rule can be calculated by equation 4.7 for the input fuzzy sets, which is then moved to conclude the fuzzy sets of rule firing. The truncated MF can then be used by equation 4.8 for the conclusion of fuzzy sets of every rule. After aggregating the conclusion, equation 4.9 can be utilized using the fuzzy output of RL represented to form a single fuzzy set to a failure mode. For example, the fuzzy set of Vs_{FF}, Vs_{CSC} is the input fuzzy sets and are found using the entire rules. In this example the four rules used are:

- Rule# IF $Vandalism, safety_{FF}$ is very low and $Vandalism, safety_{CSC}$ is low then RL is low.
- Rule# IF $Vandalism, safety_{FF}$ is very low and $Vandalism, safety_{CSC}$ is medium then RL is possible.
- Rule# IF $Vandalism, safety_{FF}$ is low and $Vandalism, safety_{CSC}$ is low then RL is possible.
- Rule# IF $Vandalism, safety_{FF}$ is low and $Vandalism, safety_{CSC}$ is medium then RL is substantial.

The firing strength is calculated by equation 4.7:

$\alpha_s = \min\left[max\left(\mu_{A^s_{FF}}(k) \wedge \mu_{T^s_{FF}}(k)\right), max\left(\mu_{A^s_{CSC}}(q) \wedge \mu_{T^s_{csc}}(q)\right)\right]$

$\alpha_i = \min[((0.73) \wedge (0.27)), ((0.645) \wedge (0.355))]$

Max = (1L), (2P), (1S), (H)

Step 6: Defuzzification.

Crisp number of fuzzy set output can be defuzzified by equation 4.10, through which the RL of vandalism is obtained.

$RL_{Vandalism,safety} = \frac{\sum_{q=1}^{n-1} z_q \mu(Z_q)}{\sum_{q=1}^{n-1} \mu(Z_q)} = \left(\frac{(0.645\times3)+(0.355\times6)+(0.27\times6)+(0.27\times9)}{0.645+0.355+0.27+0.27} = 5.26\right)$

$(RL_{Vandalism,functunality} = 5.11)$

$(RL_{Vandalism,enviroment} = 7.05)$

$(RL_{Vandalism,time} = 5.08\ )$

$(RL_{Vandalism,trafic\ delay} = 6.04)$

$(RL_{concrete,Reputational_damage} = 4.8)$

$(RL_{concrete,SocioEconomic} = 4.14)$

In the same way, every RLs of elements can use the same equation to get the result as shown in Table 5.20.

Table 5.20: Results of risk assessment

Structure	RL Substructure	Elements	F(MF)	CS (MF)	Risk Score	Risk percentage
Bridge RL(6.04)	Vandalism RL(5.50)	Safety	(VL0.73,L.27)	(L0.645,M0.355)	5.26	74% Possible 26%Substantial
		Functionality	(VL0.73,L.27)	(L0.725,M0.275)	5.11	89% Possible 11%Substantial
		Environment	(VL0.73,L.27)	(L0.695,M0.305)	7.05	100% Substantial
		Time	(VL0.73,L.27)	(L0.37,M0.63)	5.80	20% Possible 80% Substantial
		Traffic delay	(VL0.73,L.27)	(L0.25,M0.75)	6.04	100%Substantial
		Reputational damage	(VL0.73,L.27)	(L0.90,M0.10)	4.80	100% Possible
		Socio-Economic	(VL0.73,L.27)	(M1)	4.14	100% Possible
	Propping system RL(7.21)	Safety	(VL0.12,L0.88)	(L0.60,M0.40)	6.67	100% Substantial
		Functionality	(VL0.12,L0.88)	(L0.35,M0.65)	7.28	100% Substantial
		Environment	(VL0.12,L0.88)	(M0.80,H0.20)	8.41	59% Substantial 41% High
		Time	(VL0.12,L0.88)	(L0.15,M0.85)	7.76	100% Substantial
		Traffic delay	(VL0.12,L0.88)	(L1)	5.64	36% Possible 64% Substantial
		Reputational damage	(VL0.12,L0.88)	(L0.80,M0.20)	6.19	100%Substantial
		Socio-Economic	(VL0.12,L0.88	(L0.05,M0.95)	8.26	74% Substantial

						26% High
	Overweight vehicle RL(5.93)	Safety	(VL0.60,L0.40)	(L0.40,M0.60)	6	100% Substantial
		Functionality	(VL0.60,L0.40)	(L0.35,M0.65)	6.08	100% Substantial
		Environment	(VL0.60,L0.40)	(L0.645,M0.355)	5.57	43% Possible 57% Substantial
		Time	(VL0.60,L0.40)	(L0.15,M0.85)	6.57	100% Substantial
		Traffic delay	(VL0.60,L0.40)	(L0.695,M0.305)	5.45	55% Possible 45% Substantial
		Reputational damage	(VL0.60,L0.40)	(L0.37,M0.63)	6.05	100% Substantial
		Socio-Economic	(VL0.60,L0.40)	(L0.73,M0.27)	5.35	65% Possible 35% Substantial
	Structure overload RL(5.51)	Safety	(VL0.75,L0.25)	(L0.55,M0.45)	5.4	60% Possible 40% Substantial
		Functionality	(VL0.75,L0.25)	(L0.20,M0.80)	6.01	100% Substantial
		Environment	(VL0.75,L0.25)	(L0.75,M0.25)	5	100% Possible
		Time	(VL0.75,L0.25)	(L0.65,M0.35)	5.20	80% Possible 20% Substantial
		Traffic delay	(VL0.75,L0.25)	(L0.10,M0.90)	7.20	100% Substantial
		Reputational damage	(VL0.75,L0.25)	(L0.825,M0.175)	4.72	100% Possible
		Socio-Economic	(VL0.75,L0.25)	(L0.925,M0.075)	4.23	100% Possible

5.3.2 Risk Assessment of all Structure Levels

In this case, the fuzzy–AHP (FAHP) is used to achieve the element level and substructure level to find the WFs of each of them. According to the estimation scheme in Table 4.2, every expert judgment must produce pairwise comparisons from the element level to the substructure level. The following process is carried out to obtain the WFs of the elements level and the substructure level. The calculation procedure involves:

Step 1: Establishing an estimation scheme.

The estimation scheme is made using the judgments recorded which were agreed upon by the experts. The estimation scheme can be used as demonstrated in Table 4.2.

Step 2: In a risk tree, constructing Pair-wise comparison factors.

The relative differences between substructures and elements produced from expert judgments are shown in Table 5.25 and Table 5.26. Four comparisons have been taken from each expert, and are free to use any of the tables (numerical numbers, linguistic terms or fuzzy numbers).

Step 3: Creating UFNs from inputs.

The expert or engineering judgements used to make the decisions are shown in Table 4.1, which are then converted to UFN, as shown in Table 5.25 and Table 5.26.

Step 4: Aggregate UFNs.

UFN numbers are aggregated in Table 5.26 alongside the respective expert opinion in the Expert index. By using equation 4.3. Table 5.25 shows the comparison of each substructure level.

$$M_1 = \{a_1, b_1, c_1, d_1\} = \left\{\frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}\right\}$$

$$= \left\{\frac{(1\times0.45)+(1\times0.33)+(1\times22)}{(0.45+0.33+0.22)}\right\} = (1,1.67,1.67,2.67)$$

Step 5: Using the comparison matrix to calculate fuzzy WFs.

An overall comparison matrix can be developed for the hazard group after performing steps 1 to 4. With the use of aggregated UNFs, detailed by equation 4.11, it is possible to establish the comparison matrix, *P*.

$$P = \tilde{A} = \begin{bmatrix} \tilde{a}_{1,1}\ \tilde{a}_{1,2} & \cdots & \tilde{a}_{1,n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n,1}\ \tilde{a}_{n,2} & \cdots & \tilde{a}_{n,n} \end{bmatrix}$$

As shown in Table 5.27 and Table 5.28, the overall comparison matrix can be achieved.

$$S(x_a) = x_a^{1/log9}$$

Table 5.28 shows that converted entries are completed in the comparison matrix, *P*.

UFN geometric is U_a of the *a*-th row in the comparison matrix and is calculated by equation 4.12 as showing in Table 5.21.

$$U_a = \{a_a, b_a, c_a, d_a\} = \left\{\sqrt[4]{\prod_{j=1}^{4} a_{1,j}}, \sqrt[4]{\prod_{j=1}^{4} b_{1,j}}, \sqrt[4]{\prod_{j=1}^{4} c_{1,j}}, \sqrt[4]{\prod_{j=1}^{4} d_{1,j}}\right\} =$$

$$W_{vansalism} = (1.07,1.80,1.80,3.07)$$

$W_{Propping\ system} = (0.89,1.21,1.21,1.75)$

$W_{overweight\ vehicle} = (0.55,0.75,0.75,1.08)$

$W_{structure\ overload} = (0.34,0.60,0.60,0.92)$

Table 5.21: Comparison matrix of a-th row

	A	B	C	D
vandalism	1.078545	1.801781	1.801781	3.078705
propping system	0.894846	1.219909	1.219909	1.758322
overweight	0.554185	0.751761	0.751761	1.088943
structure overload	0.342078	0.605189	0.605189	0.927175

Following on, the hazard fuzzy WF will be achieved using equation 4.13 as presenting in Table 5.22.

$W_A = \{a_a, b_a, c_a, d_a\} = \left\{\frac{a_a}{\sum_{j=1}^{n} d_j}, \frac{b_a}{\sum_{j=1}^{n} c_j}, \frac{c_a}{\sum_{j=1}^{n} b_j}, \frac{d_a}{\sum_{j=1}^{n} a_j}\right\}$

$W_{Vandalism} = \{a_a, b_a, c_a, d_a\} = \left\{\frac{1.07}{6.85}, \frac{1.80}{4.37}, \frac{1.80}{4.37}, \frac{3.07}{2.86}\right\} =$

$W_{vansalism} = (0.15,0.41,0.41,1.07),$

$W_{Propping\ system} = (0.13,0.27,0.27,0.61),$

$W_{overweight\ vehicle} = (0.08,0.17,0.17,0.37),$

$W_{structure\ overload} = (0.04,0.13,0.13,0.32)$

Table 5.22: WF of hazard fuzzy

Fuzzy WFs				
vandalism	0.15738	0.411493	0.411493	1.072849
propping system	0.130574	0.278605	0.278605	0.61273
overweight	0.080866	0.171688	0.171688	0.379468
structure overload	0.049916	0.138214	0.138214	0.323097

Step 6: Defuzzification as well as normalisation.

Crisp number of fuzzy WF can be easily obtained using equation 4.14 as well as showing in Table 5.18.

$(W_{Vandalism} = \frac{0.15+2(0..41+.41)+1.07}{6} = 0.47)$

$(W_{Propping\ system} = 0.30)$

$(W_{Overweight\ vehicle} = 0.19)$

$(W_{Structure\ overload} = 0.15)$

Table 5.23: Crisp number of fuzzy WF

Defuzzification and Normalization	
vandalism	0.479367
propping system	0.30962
overweight	0.191181
structure overload	0.154311

Hazardous WF's final WFs can be found by equation 4.15, as Table 5.24 shows.

$WF_{Vandalism} = \frac{w_c}{\sum_{i=1}^{4} w} = \frac{0.47}{(0.47+0.30+0.19+0.15)} = 0.42$

$(WF_{Propping\ system} = 0.27)$

$(WF_{Overweight\ vehicle} = 0.16)$

$(WF_{Structure\ overload} = 0.13)$

Table 5.24: Final WFs of hazardous

FINAL WF	
Vandalism	0.422543
Propping system	0.272918
Overweight vehicle	0.168519
Structure overload	0.136019

Step7: Risk Level and Weight Factors.

Once the WFs of elements are obtained, the RL of the "bridge element" substructure RL can be found from the synthesis of element WFs by using equation 4.18.

$$RL_{structure} = \sum_{j=1}^{4} RL_j WF_j = RL_c \times W_c + RL_D \times W_D + RL_w \times W_w + RL_J \times W_J$$

$$= \sum_{j=1}^{4} RL_j WF_j = 5.50 \times 0.42 + 7.21 \times 0.27 + 5.93 \times 0.16 + 5.51 \times 0.13 = 6.04$$

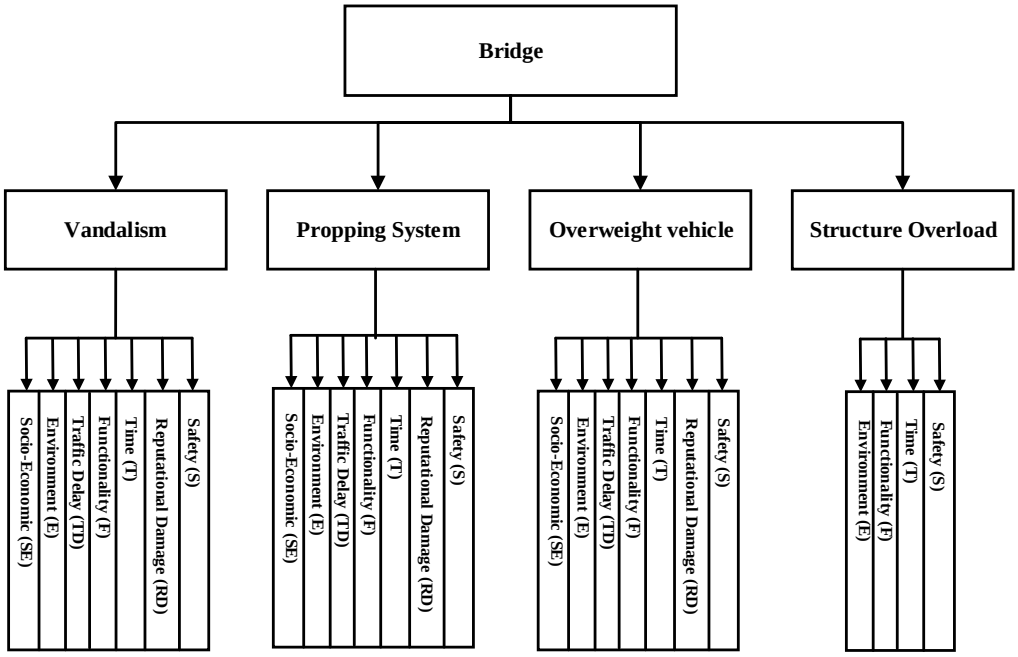


Figure 5.5: Risk tree for bridge risk analysis

Converting and Aggregate UFNs

Table 5.25: Expert judgements for substructure of bridge structure.

	Expert 1				**Expert 2**				**Expert 3**			
Comparison	0.45				0.33				0.22			
Vandalism vs Propping	1	2	2	3	1	1	1	2	1	2	2	3
Propping vs Overweight	1	2	2	3	1	1	1	2	2	3	3	4
Overweight vs Structure	1	1	1	2	1	2	2	3	1	1	1	2

Table 5.26: Aggregation of Expert judgements.

Aggregate				
Vandalism vs Propping	1	1.67	1.67	2.67
Propping vs Overweight	1.22	1.89	1.89	2.89
Overweight vs Structure	1	1.33	1.33	2.33

Table 5.27: Pairwise comparison matrix *P* established for bridge elements

	vandalism				**propping system**				**overweight vehicle**				**structure overload**			
vandalism	1.000	1.000	1.000	1.000	1.000	1.670	1.670	2.670	1.220	3.156	3.156	7.716	1.220	4.198	4.198	17.979
Propping system	0.375	0.599	0.599	1.000	1.000	1.000	1.000	1.000	1.220	1.890	1.890	2.890	1.220	2.514	2.514	6.734
overweight	0.130	0.317	0.317	0.820	0.346	0.529	0.529	0.820	1.000	1.000	1.000	1.000	1.000	1.330	1.330	2.330
structure overload	0.056	0.238	0.238	0.820	0.149	0.398	0.398	0.820	0.429	0.752	0.752	1.000	1.000	1.000	1.000	1.000

Comparison matrix calculating the fuzzy WFs

Table 5.28: Pairwise comparison matrix *P* established for bridge elements

	vandalism				**propping system**				**overweight vehicle**				**structure overload**			
vandalism	1.000	1.000	1.000	1.000	1.000	1.477	1.477	2.110	1.163	2.397	2.397	4.730	1.163	2.977	2.977	9.000
Propping system	0.474	0.677	0.677	1.000	1.000	1.000	1.000	1.000	1.163	1.623	1.623	2.241	1.163	2.016	2.016	4.265
overweight	0.211	0.417	0.417	0.860	0.446	0.616	0.616	0.860	1.000	1.000	1.000	1.000	1.000	1.242	1.242	1.903
structure overload	0.111	0.336	0.336	0.860	0.234	0.496	0.496	0.860	0.526	0.805	0.805	1.000	1.000	1.000	1.000	1.000

5.3.3 Maintenance Decision Making Option:

The input of FF and CS of every failure mode can be measured by FRA to obtain the RL of every failure. The RL of the substructures is the result of the product of RL and WF of the elements. Finally, the RL of the structure is obtained by the substructure. The element, substructure and structure of the bridge is shown in Table 5.29.

Table 5.29: Risk assessment results.

Structure	RL Substructure	RC	Elements	PC	Risk Score	Risk percentage
Bridge RL(6.04)	Vandalism RL(5.50)	42%	Safety	32%	5.26	74% Possible 26% Substantial
			Functionality	20%	5.11	89% Possible 11% Substantial
			Environment	15%	7.05	100% Substantial
			Time	10%	5.80	20% Possible 80% Substantial
			Traffic delay	8%	6.04	100% Substantial
			Reputational damage	7%	4.80	100% Possible
			Socio-Economic	7%	4.14	100% Possible
	Propping system RL(7.21)	27%	Safety	27%	6.67	100% Substantial
			Functionality	26%	7.28	100% Substantial
			Environment	16%	8.41	59% Substantial 41% High
			Time	12%	7.76	100% Substantial
			Traffic delay	8%	5.64	36% Possible 64% Substantial
			Reputational damage	6%	6.19	100% Substantial
			Socio-Economic	6%	8.26	74% Substantial 26% High
			Safety	29%	6	100% Substantial
			Functionality	24%	6.08	100% Substantial

	Overweight vehicle RL(5.93)	17%	Environment	15%	5.57	43% Possible 57% Substantial
			Time	12%	6.57	100% Substantial
			Traffic delay	9%	5.45	55% Possible 45% Substantial
			Reputational damage	6%	6.05	100% Substantial
			Socio-Economic	5%	5.35	65% Possible 35% Substantial
	Structure overload RL(5.51)	14%	Safety	26%	5.4	60% Possible 40% Substantial
			Functionality	23%	6.01	100% Substantial
			Environment	16%	5	100% Possible
			Time	14%	5.20	80% Possible 20% Substantial
			Traffic delay	9%	7.20	100% Substantial
			Reputational damage	6%	4.72	100% Possible
			Socio-Economic	6%	4.23	100% Possible

As the RL of the structure of the bridge is 6.04, it is labelled as Substantial. This reduces the risk in the transition region "As Low As Reasonably Practicable" (ALARP). It can be assumed that the requirement for safety corresponds to the system's overall RL, which should not be greater than 3. In terms of the overall maintenance budget, this is £300,000. In addition, Table 5.30, Table 5.31 and Table 5.32 show the detailed costs, that include costs for parts, materials, equipment, labour as well as any relevant costs. Four maintenance options can be supposed. Maintenance should reduce the RL of the Bridge structure, provided that either of the four maintenance options mentioned below is used. These are:

Option 1: maintain the Vandalism.

Option 2: maintain the Propping system.

Option 3: maintain the Overweight vehicle.

Option 4: maintain the Overweight vehicle and Structure overload.

The RL of all of the structures is estimated after the implementation of matching optional maintenance. Table 5.30 shows the cost and RL of every option, and the best option can be identified using a decision making model.

Table 5.30: Maintenance costs

Structure	Substructure	Risk Score	Final Cost with 10%
Bridge	Vandalism	5.50	(156,000+15,600) 171.600
	Propping system	7.21	(250,000+25,000) 275.000
	Overweight vehicle	5.93	(182,000+18,200) 200.200
	Structure overload	5.51	(183,000+18,300) 201.300

Table 5.31: Maintenance options costs with corresponding RL.

Options	Cost	RL
Option 1	171.600	2.31
Option 2	275.000	1.94
Option 3	200.200	1.00
Option 4	201.300	1.77

Normalised cost recommended, there are four options attached from cost and risk model.

$$x_{cost}=\frac{cost_1}{\sqrt{\sum_{i=1}^{m} {cost_1}^2}}=\frac{171.600}{\sqrt{(171.600)^2+(275.000)^2+(200.200)^2+(201.300)^2}}=0.3982$$

And normalised RL of structure for option 1 is:

$$x_{RL}=\frac{RL_1}{\sqrt{\sum_{i=1}^{m} {RL_1}^2}}=\frac{2.31}{\sqrt{(2.31)^2+(1.94)^2+(1.00)^2+(1.77)^2}}=0.6350$$

The weighted cost is normalised for option 1. The cost and risks are equally significant and are calculated as:

$z_{1\,cost} = \ w_{cost} \times x_{cost}$ = 0.5× 0.3982 = 0.1991

The weighted RL structure is normalised for option 1 and can be calculated as follows:

$z_{1\,RL} = \ w_{RL} \times x_{RL}$ = 0.5× 0.6350 = 0.3175

Also, Table 5.32 shows the calculation of next options of the weighted RL and cost normalisation. And the best option can be calculated as:

$O^+ = \{0.1991, 0.1375\}$

$O^- = \{0.3191, 0.3175\}$

The option 1 degree of preference can be detected as:

$D_1^+ =$

$\sqrt{(z_{1\,cost} - {z_{1\,cost}}^+)^2 + (z_{1\,RL} - {z_{1\,RL}}^+)^2} =$

$\sqrt{(0.1991 - 0.1991)^2 + (0.3175 - 0.1375)^2}$ = 0.1801

$D_1^- =$

$\sqrt{(z_{1\,cost} - {z_{1\,cost}}^-)^2 + (z_{1\,RL} - {z_{1\,RL}}^-)^2} =$

$\sqrt{(0.1991 - 0.3191)^2 + (0.3175 - 0.3175)^2} =$ 0.1200

$P_1 = \frac{D_1^-}{D_1^+ + D_1^-} = \frac{0.1200}{0.1801 + 0.1200}$ = 0.3999

Table 5.32: The outcome of preference evolution for every option

Options	x_{cost}	z_{cost}	x_{RL}	z_{RL}	D^+	D^-	P	**Rank**
Option 1	0.3982	0.1991	0.6350	0.3175	0.1801	0.1200	0.3999	3
Option 2	0.6382	0.3191	0.5333	0.2667	0.1763	0.0509	0.2239	4

Option 3	0.4646	0.2323	0.2749	0.1375	0.0332	0.1999	0.8576	1
Option 4	0.4672	0.2336	0.4866	0.2433	0.1113	0.1132	0.5043	2

5.3.4 Results

This case study shows the successful use of the three fuzzy models, FRA, FAHP and TOPSIS in a step by step manner. A risk assessment is carried out and the outcomes are calculated. Evidently, option 3 is the most suitable maintenance option due to its highest preference degree of 0.8576 %. Additionally, option 3 also appears to be the best safety maintenance option.

The ideal option appears to be the one with the highest preference degree, based on the proposed risk-cost model. In fact, the overall bridge system RL can be decreased from 6.04 (High 100%) to 1.00 (low 100%) if option 2 is used for carrying out maintenance work. Also, the associated costs of £200,200 will be within the budget. Thus, the best maintenance option is proposed, which highlights a suitable option for reducing the RL. As the RL of the structure of the bridge is 6.04, it is labelled as “Substantial”.

Figure 5.6,

Figure 5.7 and

Figure 5.8 show the FF, CSC and RL of Case Study 2.

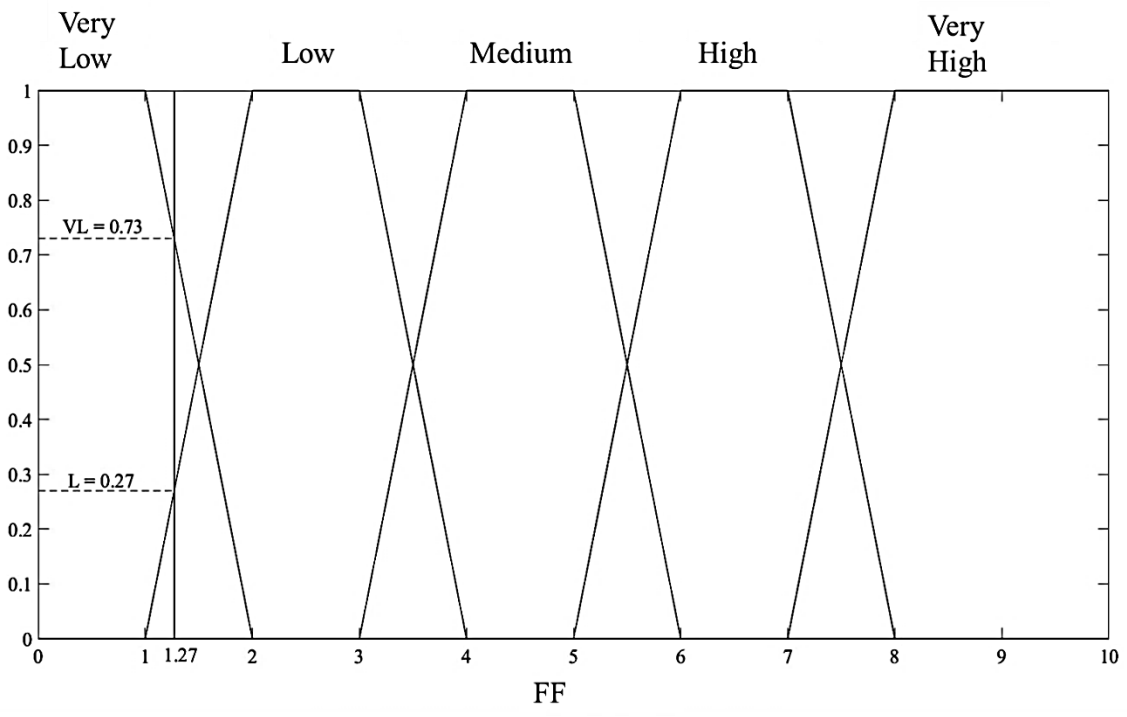


Figure 5.6: FF for Case Study 2

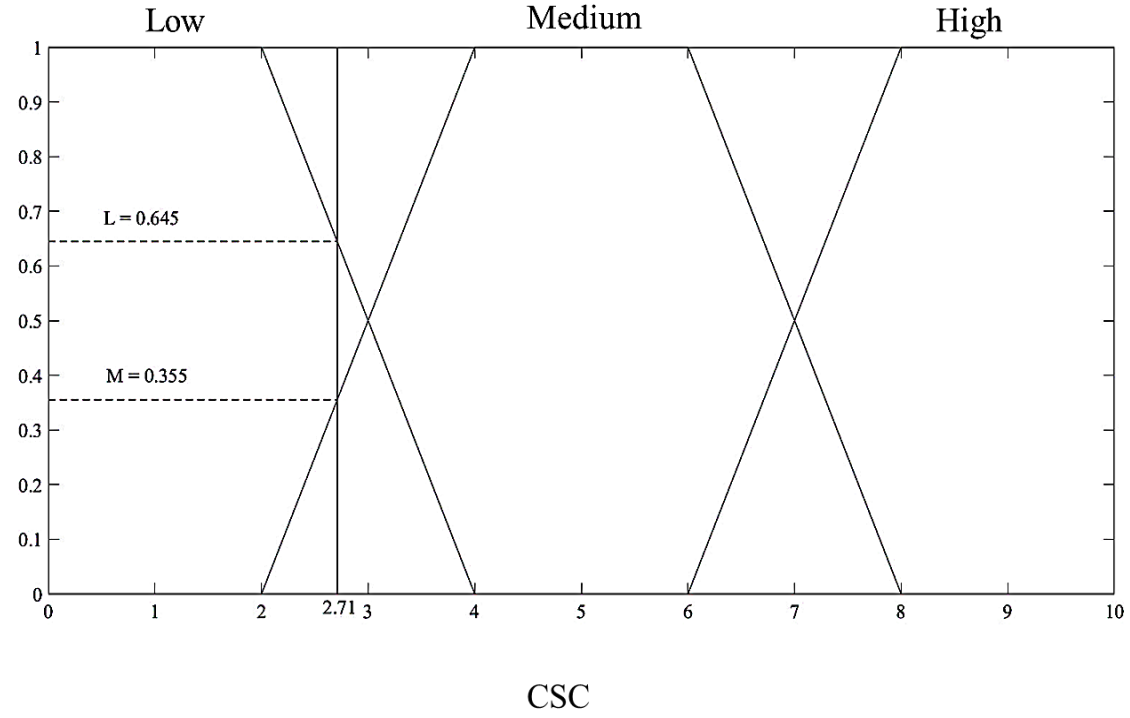


Figure 5.7: CSC for Case Study 2

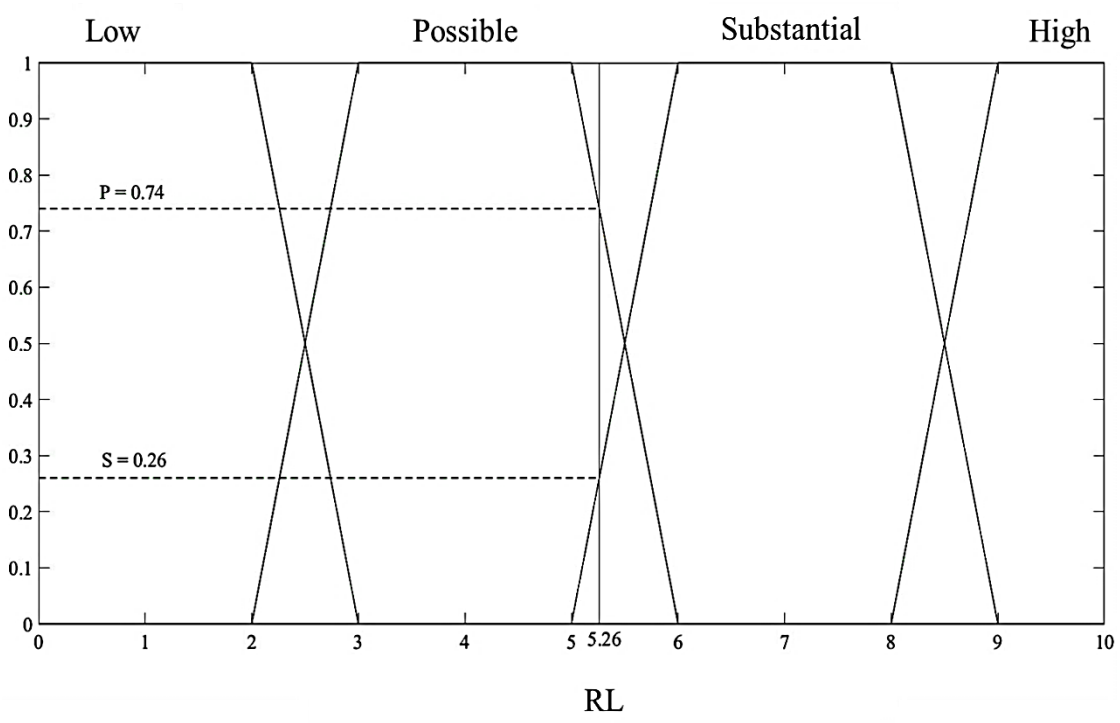


Figure 5.8: RL for Case Study 2

5.4 Case Study 3

The risk assessment case study presented in this section addresses the needs of three adjacent structures. A strategic route with greater than £500,000 is carried by this project.

This case study addresses the needs for concrete repair on three adjacent structures. These structures are crossing a regional route. However, the structures are deteriorating due to chloride-induced corrosion, which is occurring in the reinforcements. This corrosion is visible only on the abutments/piers, which are positioned well behind the carriageway. In the short run, it is expected that the deterioration will not have any negative effects on the capacity of the structure. To deal with this issue, the proposed method involves studying maintenance options and identifying options for the repairs of the concrete. In addition to this, in an "Asset Management Plan" on the structure, a

preventive maintenance need is identified. This would involve repainting the structures with a new protective system. Such a project would require some areas of the structure to be blast cleaned back to the bare metal. It was also recognised that the current protective system is time-expired. Therefore, there is an urgent need for intervention based on an initial inspection. To proceed with this project at this point, a complete replacement of the protective system is needed. This would assist in delivering the minimum whole life cost maintenance. Furthermore, the use of a suitable protective system, which offers a life expectancy of about 20 years from its application, is identified by "Value engineering".

Overall, in terms of the risk event, it is expected that there will be a continued deterioration in the structures due to chloride-induced corrosion of the reinforcements. Inspecting the structures has shown that spalling, as well as rust staining, appears on the surfaces of all three structures. In fact, a high risk of active corrosion was identified in two of the structures tested. The third structure showed a medium risk. It is worth mentioning that de-icing salts, which occur due to spraying from passing traffic results in the deterioration of such structures. Therefore, there is an absolute certainty that the structures will continue to deteriorate. Nevertheless, assessing the structures has shown that, at present, the structural capacity is not affected by spalling and it is unlikely that spalling will have an influence in the short term of about three to four years. In addition, restricting the regional routes due to deterioration/spalling is not needed. However, the overall appearance of the structures is adversely affected by deterioration.

Along with deterioration of the structures, the protective coating may fail as well, as detailed earlier. Investigators investigating the structures have reported that there is enough evidence to conclude that the protective coating is failing. This is mainly due to

the expiration of this coating, which results in the exposing of bare metals in some areas. Although there is a certainty that the structures are deteriorating, the structure's overall integrity is not in doubt. Thus, there appear no safety consequences. Additionally, since there is no need for restricting network usage, there are no functionality consequences. However, with an asset management plan, it has been identified that there is a need for intervention to replace the protective coating system. It has also been concluded that if work is not undertaken immediately, there will be a significant increase in costs in the future. As far as environmental consequences are concerned, these are known to be low, due to the absence of any harmful contaminants in the current protective system, which could pollute watercourses.

5.4.1 Risk assessment

Step 1: Input FF and CSC.

Data available is taken from experts and defines as a numerical number. The range and linguistics variables are shown in Table 4.1.

Step 2: Creating UFNs by converting inputs.

The crisp numbers have been converted to UFNs according to Table 4.1. The numbers of FF and CSC of the elements are then aggregated.

$A_{FF(safety)}$=(1,2,2,3),(3,3,3,3)

$A_{CSC(safety)}$=(5,5,5,5),(9,9,9,9)

Step 3: Aggregating UFNs.

Equations 4-2, 4-3,4-4 and 4-5 are used for transferring to fuzzy sets UFNs as follows:

$$A_{FL}^{s} = \left\{\left(k, \mu_{A_{FL}^{s}}(k)\right) \mid k \in K = [0,10], \mu_{A_{FL}^{s}}(k) = \begin{cases} 1 & k = 1.81 \\ 0 & otherwise \end{cases}\right\}$$

$$A_{cs}^{s} = \left\{\left(q, \mu_{A_{cs}^{s}}(q)\right) \mid q \in Q = [0,10], \mu_{A_{cs}^{s}}(q) = \begin{cases} 1 & q = 6.4 \\ 0 & otherwise \end{cases}\right\}$$

Step 4: Transferring the UFNs into fuzzy sets.

FF_{safety}= (1.70, 2.35, 3.05,3.65)

CSC_{safety}= (6.40, 6.40, 6.40, 6.40)

Step 5: Fuzzy inference process

The experiences and engineering judgments are used to produce 120 rules. The fire strength of every rule can be calculated by equation 4-7 for the input fuzzy sets, which is then moved to conclude the fuzzy sets of rule firing. The truncated MF can then be used by equation 4-8 for the conclusion of fuzzy sets of every rule. After aggregating the conclusion, equation 4-9 can be utilized using the fuzzy output of RL represented to form a single fuzzy set to a failure mode. For example, the fuzzy set of Vs_{FF}, Vs_{CSC} are the input fuzzy sets and are found using the entire rules. In this example the four rules used are:

- Rule# IF $Deterioration, safety_{FF}$ is very low and $Deterioration, safety_{CSC}$ is high then RL is possible.
- Rule# IF $Deterioration, safety_{FF}$ is very low and $Deterioration, safety_{CSC}$ is medium then RL is possible.
- Rule# IF $Deterioration, safety_{FF}$ is low and $Deterioration, safety_{CSC}$ is high then RL is substantial.
- Rule# IF $Deterioration, safety_{FF}$ is low and $Deterioration, safety_{CSC}$ is medium then RL is substantial.

The firing strength is calculated by equation 4-7:

$\alpha_s = \min\left[max\left(\mu_{A_{FF}^s}(k) \wedge \mu_{T_{FF}^s}(k)\right), max\left(\mu_{A_{CSC}^s}(q) \wedge \mu_{T_{csc}^s}(q)\right)\right]$

$\alpha_i = \min[((0.19) \wedge (0.81)), ((0.80) \wedge (0.20))]$

Max = (~~L~~), (2P), (2S), (~~H~~)

Step 6: Defuzzification.

Crisp number of fuzzy set output can be defuzzified by the equation 4-10, through which the RL of vandalism is obtained.

$RL_{Deterioration,safety} = \frac{\sum_{q=1}^{n-1} z_q \mu(Z_q)}{\sum_{q=1}^{n-1} \mu(Z_q)} = \left(\frac{(0.19\times6)+(0.19\times6)+(0.80\times9)+(0.20\times9)}{0.19+0.19+0.80+0.20} = 8.17\right)$

$(RL_{Deterioration,value\ for\ money} = 5.96)$

$(RL_{Deterioration,enviroment} = 6.29)$

$(RL_{Deterioration,time} = 6.67)$

$(RL_{Deterioration,trafic\ delay} = 8.27)$

$(RL_{Deterioration,Reputational_damage} = 8.43)$

$(RL_{Deterioration,SocioEconomic} = 5.43)$

In the same way, every RLs of elements can use the same equation to get the result as shown in Table 5.33.

Table 5.33: Results of risk assessment

Structure	RL Substructure	Elements	FF(MF)	CS (MF)	Risk Score	Risk percentage
Bridge RL(7.23)	Deterioration RL(7.12)	Safety	(VL0.19,L.81)	(M0.80,H0.20)	8.17	83%Substantial 17% High
		Value for money	(VL0.19,L.81)	(L0.825,M0.175)	5.96	4% Possible 96%Substantial
		Environment	(VL0.19,L.81)	(L0.675,M0.325)	6.29	100%Substantial

		Time	(VL0.19,L.81)	(L0.50,M0.50)	6.67	100% Substantial
		Traffic delay	(VL0.19,L.81)	(M0.40,H0.60)	8.27	73%Substantial 27% High
		Reputational damage	(VL0.19,L.81)	(M1)	8.43	57%Substantial 43% High
		Socio-Economic	(VL0.19,L.81)	(L1)	5.43	57% Possible 43% Substantial
	Protective Coating RL(7.50)	Value for money	(L0.95,M0.05)	(L0.28,M0.72)	8.23	77%Substantial 23% High
		Environment	(L0.95,M0.05)	(L0.87,M0.13)	6.62	100% Substantial
		Time	(L0.95,M0.05)	(L0.90,M0.10)	6.54	100%Substantial
		Reputational damage	(L0.95,M0.05)	(L0.30,M0.70)	8.18	82%Substantial 18% High
		Socio-Economic	(L0.95,M0.05)	(L0.65,M0.35)	7.22	100% Substantial

5.4.2 Risk Assessment of all Structure Levels

In this case, the fuzzy–AHP (FAHP) is used to achieve the element level and substructure level to find the WFs of each of them. According to the estimation scheme in Table 4.2, every expert judgment has to produce pairwise comparisons from the element level to the substructure level. The following process is carried out to obtain the WFs of the elements level and the substructure level. The calculation process is as follows:

Step 1: Establishing an estimation scheme.

The estimation scheme is made using the judgments recorded which were agreed upon by the experts. The estimation scheme can be used as shown in Table 4.2.

Step 2: In a risk tree, constructing Pair-wise comparison factors.

The relative differences between substructures and elements produced from expert judgments are shown in Table 5.38 and Table 5.39. Four comparisons have been taken from each expert and are free to use any of the tables (numerical numbers, linguistic terms or fuzzy numbers).

Step 3: Creating UFNs by converting inputs.

The expert or engineering judgements used to make the decisions are shown in Table 4.1, which are then converted to UFN as shown in Table 5.38 and Table 5.39.

Step 4: Aggregate UFNs.

UFN numbers are aggregated in Table 5.39 alongside the respective expert opinion in the Expert index. By using equation 4.3, Table 5.38 shows the comparison of each substructure level.

$$M_1 = \{a_1, b_1, c_1, d_1\} = \left\{\frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}, \frac{\sum_{l=1}^{5} a_t EI_t}{\sum_{l=1}^{5} EI_t}\right\}$$

$$= \left\{\frac{(1\times0.65)+(1\times0.35)}{(0.65+0.35)}\right\} = (1.70, 2.70, 2.70, 3.70)$$

Step 5: Using the comparison matrix to calculate fuzzy WFs.

An overall comparison matrix can be developed for the hazard group after performing steps 1 to 4. With the use of aggregated UNFs, detailed by equation 4.11, it is possible to establish the comparison matrix, *P*.

$$P = \tilde{A} = \begin{bmatrix} \tilde{a}_{1,1} & \tilde{a}_{1,2} & \cdots & \tilde{a}_{1,n} \\ \vdots & & \ddots & \vdots \\ \tilde{a}_{n,1} & \tilde{a}_{n,2} & \cdots & \tilde{a}_{n,n} \end{bmatrix}$$

As shown in Table 5.35 and Table 5.36, the overall comparison matrix can be achieved.

$$S(x_a) = x_a^{1/log9}$$

Table 5.41 shows that converted entries are completed in the comparison matrix, *P*.

UFN geometric is U_a of the *a*-th row in the comparison matrix and is calculated by equation 4.12, as shown in Table 5.34.

$$U_a = \{a_a, b_a, c_a, d_a\} = \left\{ \sqrt[2]{\prod_{j=1}^{2} a_{1,j}}, \sqrt[2]{\prod_{j=1}^{2} b_{1,j}}, \sqrt[2]{\prod_{j=1}^{2} c_{1,j}}, \sqrt[2]{\prod_{j=1}^{2} d_{1,j}} \right\} =$$

$W_{\text{Deterioration}} = (1.07, 1.80, 1.80, 3.07)$

$W_{\text{Protective coating}} = (0.89, 1.21, 1.21, 1.75)$

Table 5.34: Comparison matrix of a-th row

	A	**B**	**C**	**D**
Deterioration	1.30384	1.643168	1.643168	1.923538
Protective coating	0.519875	0.608581	0.608581	0.766965

Following on, the hazard fuzzy WF will be achieved using equation 4.13, as presented in Table 5.35.

$$W_A = \{a_a, b_a, c_a, d_a\} = \left\{ \frac{a_a}{\sum_{j=1}^{n} d_j}, \frac{b_a}{\sum_{j=1}^{n} c_j}, \frac{c_a}{\sum_{j=1}^{n} b_j}, \frac{d_a}{\sum_{j=1}^{n} a_j} \right\}$$

$$W_{\text{Deterioration}} = \{a_a, b_a, c_a, d_a\} = \left\{ \frac{1.03}{2.69}, \frac{1.64}{2.25}, \frac{1.64}{2.25}, \frac{1.92}{1.82} \right\} =$$

$W_{\text{Deterioration}} = (0.48, 0.72, 0.72, 1.05)$

$W_{\text{Protective coating}} = (0.19, 0.27, 0.27, 0.42)$

Table 5.35: WF of hazard fuzzy

Fuzzy WFs				
Deterioration	0.484608	0.72973	0.72973	1.054736
Protective coating	0.193226	0.27027	0.27027	0.420551

Step 6: Defuzzification as well as normalisation.

Crisp number of fuzzy WF can be easily obtained using equation 4.14, as shown further in Table 5.36.

$(W_{\text{Deterioration}} = \frac{0.48+2(0.72+0.72)+1.05}{6} = 0.74)$

$(W_{\text{Protective coating}} = 0.28)$

Table 5.36: Crisp number of fuzzy WF

Defuzzification and Normalization	
Deterioration	0.743044
Protective coating	0.282476
SUM	1.02552

The hazardous WF's final WFs can be found by equation 4.15, as Table 5.37 shows.

$WF_{\text{Deterioration}} = \frac{w_c}{\sum_{i=1}^{4} w} = \frac{0.74}{(0.74+0.28)} = 0.72$

$(WF_{\text{Protective coating}} = 0.27)$

Table 5.37: Final WFs of hazardous

FINAL WF	
Deterioration	0.724553
Protective coating	0.275447

Step7: Risk Level and Weight Factors.

Once the WFs of elements are obtained, the RL of the "bridge element" substructure RL can be found from the synthesis of element WFs by using equation 4.18.

$$RL_{structure} = \sum_{j=1}^{2} RL_j WF_j = RL_D \times W_D + RL_P \times W_P$$

$$= \sum_{j=1}^{2} RL_j WF_j = 7.12 \times 0.72 + 7.50 \times 0.27 = 7.23$$

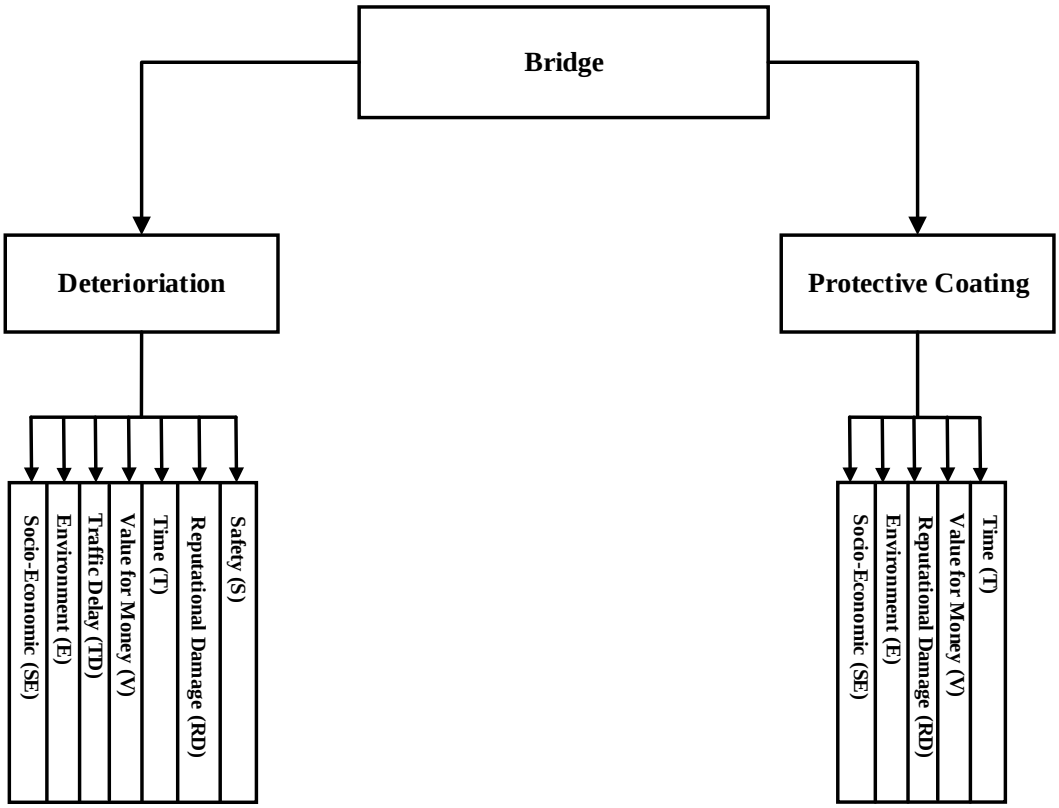


Figure 5.9: Risk tree for bridge risk analysis

Converting and Aggregate UFNs

Table 5.38: Expert judgements for substructure of bridge structure.

	Expert 1				**Expert 2**			
Comparison	0.65				0.35			
Deterioration vs Protective coating	1	2	2	3	3	4	4	5

Table 5.39: Aggregation of Expert judgements.

Aggregate				
Deterioration vs Protective coating	1.70	2.70	2.70	3.70

Table 5.40: Pairwise comparison matrix *P* established for bridge elements

	Deterioration				**Protective coating**			
Deterioration	1	1	1	1	1.7	2.7	2.7	3.7
Protective coating	0.27027	0.37037	0.37037	0.588235	1	1	1	1

5.4.3 Maintenance Decision Making Option:

The input of FF and CS of every failure mode can be measured by FRA to obtain the RL of every failure. The RL of the substructures is the result of the product of RL and WF of the elements. Finally, the RL of the structure is obtained by the substructure. The element, substructure and structure of the bridge is shown in Table 5.33.

Table 5.41: Risk assessment results.

Structure	**RL Substructure**	**RC**	**Elements**	**PC**	**Risk Score**	**Risk percentage**
Bridge RL(7.23)	Deterioration RL(7.12)	72%	Safety	32%	8.17	83%Substantial 17% High
			Value for money	20%	5.96	4% Possible 96%Substantial
			Environment	15%	6.29	100%Substantial
			Time	11%	6.67	100% Substantial
			Traffic delay	8%	8.27	73%Substantial 27% High
			Reputational damage	7%	8.43	57%Substantial 43% High
			Socio-Economic	7%	5.43	57% Possible 43% Substantial
	Protective Coating RL(7.50)	28%	Value for money	43%	8.23	77%Substantial 23% High
			Environment	23%	6.62	100% Substantial
			Time	16%	6.54	100%Substantial
			Reputational damage	11%	8.18	82%Substantial 18% High
			Socio-Economic	8%	7.22	100% Substantial

As the RL of the structure of the bridge is 7.23, it is labelled as Substantial. This reduces the risk in the transition region "As Low As Reasonably Practicable" (ALARP). It can be assumed that the requirement for safety corresponds to the system's overall RL, which should not be greater than 5. In terms of the overall maintenance budget, this is £600,000. In addition, Table 5.42, Table 5.43 and Table 5.44 show the detailed costs that include costs for parts, materials, equipment, labour as well as any relevant costs. Four maintenance options can be supposed. Maintenance should reduce the RL of the Bridge structure, provided that either of the four maintenance options mentioned below is used. These are:

Option 1: maintain all Deterioration types.

Option 2: maintain the safety of deterioration and all Protective Coating types.

The RL of all of the structures is estimated after the implementation of matching optional maintenance.

Table 5.43 shows the cost and RL of every option, and the best option can be identified using a decision making model.

Table 5.42: Maintenance costs

Structure	**Substructure**	**Risk Score**	**Final Cost with 10%**
Bridge	Deterioration	7.12	(420,000+42,000) 462.000
	Protective Coating	7.50	(240,000+24,000) 264.000

Table 5.43: Maintenance options costs along with corresponding RLs.

Options	Cost	RL
Option 1	462.000	5.12
Option 2	514.000	4.71

Normalised cost is recommended, where there are three options attached from the cost and risk model.

$$x_{cost}=\frac{cost_1}{\sqrt{\sum_{i=1}^{m} {cost_1}^2}} = \frac{462.000}{\sqrt{(462.000)^2+(514.000)^2}} = 0.47$$

And normalised RL of structure for option 1 is:

$$x_{RL}=\frac{RL_1}{\sqrt{\sum_{i=1}^{m} {RL_1}^2}} = \frac{5.12}{\sqrt{(5.12)^2+(4.71)^2}} = 0.52$$

The weighted cost is normalised for option 1. The cost and risks are equally significant and are calculated as:

$z_{1\,cost} = w_{cost} \times x_{cost}$ = 0.5× 0.47 = 0.236

The weighted RL structure is normalised for option 1 and can be calculated as follows:

$z_{1\,RL} = w_{RL} \times x_{RL}$ = 0.5× 0.52 = 0.26

Also, Table 5.44 shows the calculation of the next options of the weighted RL and cost normalization. Thus, the best option can be calculated as:

$O^+ = \{0.236, 0.235\}$

$O^- = \{0.245, 0.26\}$

The option 1 degree of preference can be perceived as:

$D_1^+ =$

$\sqrt{(z_{1\,cost} - {z_{1\,cost}}^+)^2 + (z_{1\,RL} - {z_{1\,RL}}^+)^2} = \sqrt{(0.236-0.236)^2 + (0.26-0.235)^2}$ = 0.025

$D_1^- =$

$\sqrt{(z_{1\,cost} - z_{1\,cost}{}^-)^2 + (z_{1\,RL} - z_{1\,RL}{}^-)^2} = \sqrt{(0.236 - 0.245)^2 + (0.26 - 0.26)^2} =$

0.009

$P_1 = \frac{D_1^-}{D_1^+ + D_1^-} = \frac{0.025}{0.025 + 0.009} = 0.26471$

Table 5.44: The outcome of preference evolution at every option

Options	x_{cost}	z_{cost}	x_{RL}	z_{RL}	D^+	D^-	P	**Rank**
Option 1	0.47	0.236	0.52	0.26	0.025	0.009	0.26471	2
Option 2	0.49	0.245	0.47	0.235	0.009	0.025	0.73529	1

5.4.4 Results

This case study shows the successful use of the three fuzzy models, FRA, FAHP and TOPSIS in a step by step manner. A risk assessment is carried out and the outcomes are calculated. Evidently, option 2 is the most suitable maintenance option due to its highest preference degree of 0.7930%. Additionally, option 2 also appears to be the best maintenance option.

The ideal option appears to be the one with the highest preference degree, based on the proposed risk-cost model. In fact, the overall bridge system RL can be decreased from 7.23 (Substantial 100%) to 4.71 (Possible 100%) if option 2 is used for carrying out maintenance work. Also, the associated costs of £514,000 will be within the budget. Thus, the best maintenance option is proposed, which highlights a suitable option for reducing the RL. As the RL of the structure of the bridge is 7.23, it is labelled as "Substantial".

Figure 5.10, Figure 5.11 and Figure 5.12 show the FF, CSC and RL of Case Study 3.

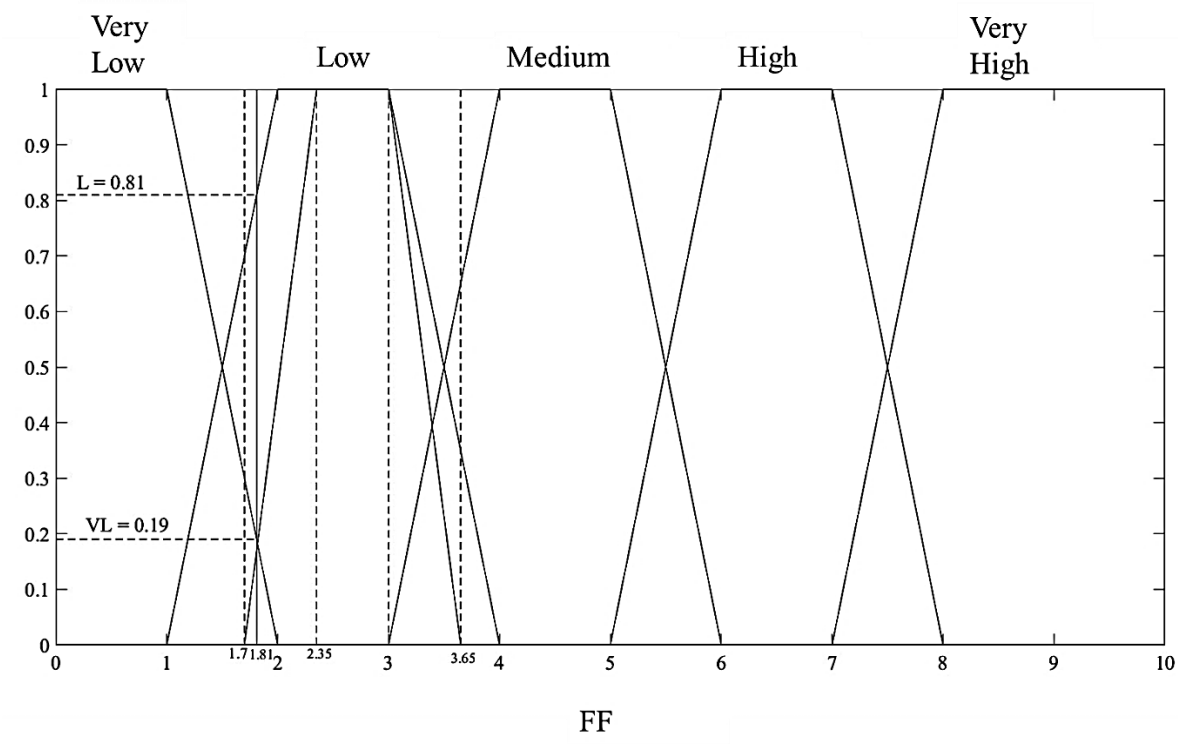


Figure 5.10: FF for Case Study 3

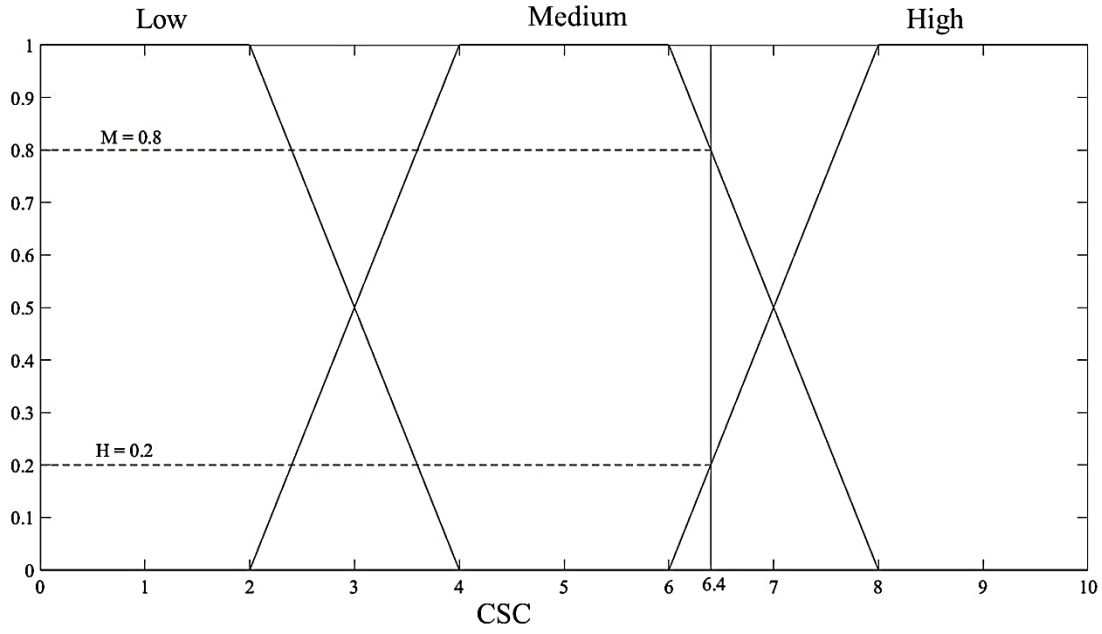


Figure 5.11: CSC for Case Study 3

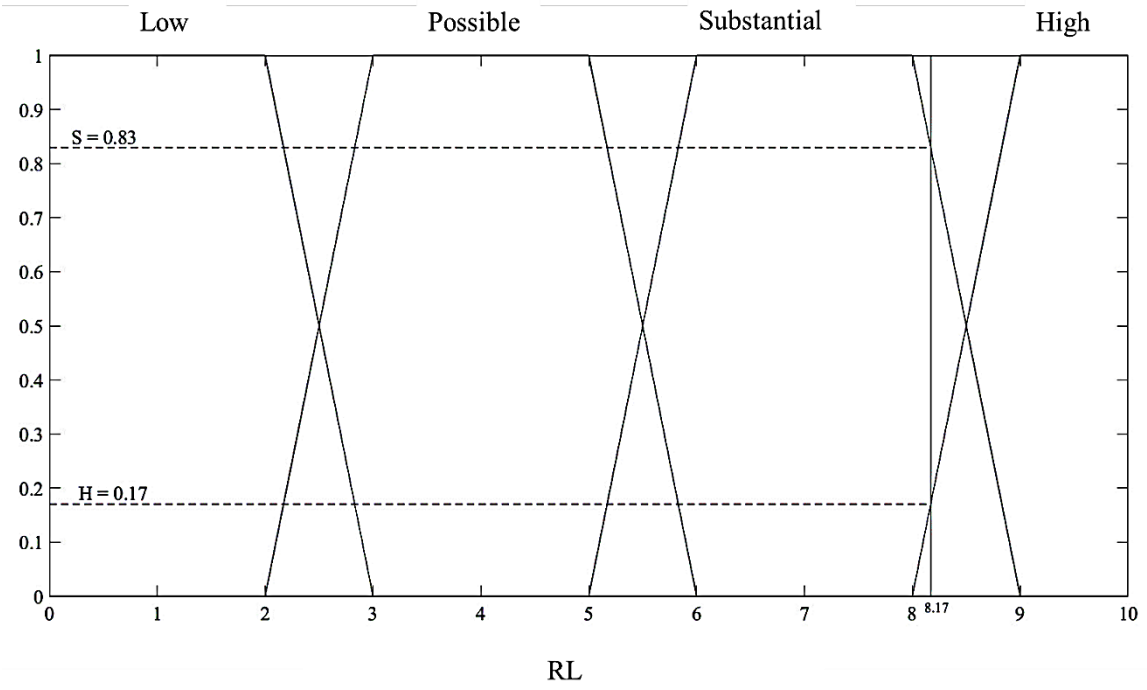


Figure 5.12: RL for Case Study 3

5.5 Conclusion

This chapter focuses on the presentation of three case studies for the risk assessment of highway bridges. Three case studies were used to validate and verify the reliability of the risk assessment and safety management model. The three case studies utilized in this study are relevant to the safety aspects of bridges. The chapter provides in detail the corresponding risk responses for each case study. The case studies were collected from literature reviews of relevant sources.

Risk assessment was performed on these three case studies for different bridge structures to evaluate all the associated risks. The case studies use two primary parameters, which are: Failure Frequency (FF) and Consequence Severity Criteria. It is worth mentioning that conventionally, bridge risk assessment techniques have relied upon probabilistic approaches, where decisions are formed using incomplete information from estimated data sources. A challenge in this context is to get valid and

accurate data which can be difficult to obtain. Nevertheless, by using FRA, FAHP and TOPSIS, the bridge risk assessment can be developed in a systematic way that equips specific procedures. This model allows the processing of both quantitative and qualitative risk information and data. Further, it allows establishing a new risk parameter known as CSC to ensure reliable results. The hazards with a higher CSC are suitably identified, assessed and managed. It recognises and processes expert knowledge, engineering judgments, and historical risk data. It can also process imprecise, ambiguous and uncertain information to inform a workable result.

The risks can be evaluated using linguistic expressions or knowledge transformed from various sources, and it gives increased flexibility to analyse FF and CSC. The results from the risk assessment process of the bridge using the proposed framework suggests that the approach can proactively identify the critical components of the bridge to accelerate maintenance, safety management and set safety standards.

CHAPTER 6: EVALUATION MODEL - DISCUSSION

6.1 Introduction

This chapter presents a discussion on the evaluation model by discussing the results from the three case studies used in Chapter 5. In addition, the chapter also discusses the advantages and disadvantages of the application of the developed model. The advantages, as well as disadvantages, of using FRA, FAHP and FTOPSIS are also discussed. Further possible improvements to the model are also suggested.

6.2 Discussion of key findings from case studies

Three case studies were presented in Chapter 5, which were used in the risk assessment of typical highway bridges. Such studies assisted in the validation as well as verification of the reliability of the proposed risk and safety assessment model. The three case studies utilized in this study are relevant to the safety aspects of bridges. Corresponding risk responses for each case study were calculated. Such a procedure assists in evaluating all associated risks.

For case study 1, the use of FRA, FAHP and TOPSIS deemed successful. It was evident from the results that maintaining the joints and waterproofing system in the structure can result in the best maintenance possible for the bridge. In addition, this option had the highest preference degree. Therefore, keeping into consideration the suggested risk-cost model, such an option appears to be ideal. The study outcomes also suggested that possible reductions in RL of the entire system are achievable with the use of such an option where the risk levels can be changed from high to low. In terms of cost calculations, the results showed that the associated costs of the project do not exceed the

budget limit, which is a favourable point. Also, the results reveal that with the implementation of such a maintenance option, a noteworthy reduction in the associated costs of the project is expected. The decrease in costs could be up to £104,000.

For case study 2, the use of FRA, FAHP and TOPSIS deemed successful. According to the results, maintaining the overweight vehicle option can result in the best maintenance possible for the bridge. This option also had the highest preference degree and thus, considering the suggested risk-cost model, such an option appears to be ideal. The study outcomes also suggested that possible reductions in RL of the entire system are achievable with the use of such an option where the risk levels can be changed from substantial to low. In terms of cost calculations, the results showed that implementing this option can potentially show a favourable decrease in the associated costs of the project, which will not exceed the budget limit. The decrease in costs could be up to around £100,000.

For case study 3, the use of FRA, FAHP and TOPSIS deemed successful once again. The results showed that if the option of maintaining the safety of deterioration as well as maintaining the protective coating types is considered, then this would be the ideal option for the bridge. This option also had the highest preference degree and thus, considering the suggested risk-cost model, such an option appears to be ideal. The study outcomes also suggested that possible reductions in RL of the entire system are achievable with the use of such an option where the risk levels can be changed from substantial to possible. In terms of cost calculations, the results showed that implementing this option can potentially show a favourable decrease in the associated costs of the project of up to £86,000.

Overall, all three case studies showed that implementing the ideal options could result in a potential decrease in the overall costs. This is indeed a favourable point while attaining high safety standards. Also, from the findings of these studies, it can be concluded that the proposed risk model and the cost model are both significant in terms of their contribution to the overall decision making process, as expected of any TOPSIS method. Also, the results show that the recommended risk-based decision-making model would be viable for the engineers as well as asset management teams for better comprehending the issue. In addition, it will help the relevant bodies in making accurate decisions in terms of potential risk eliminating schemes.

Finally, the main key finding from these three case studies is that FRA, FAHP and TOPSIS can be successfully used in the bridge risk assessment. In addition, the resulting model, which is proposed, allows the processing of both quantitative and qualitative risk information and data. Reliable results are expected due to the establishment of a risk parameter known as CSC. Since CSC inclusion can recognise and process expert knowledge as well as engineering judgements, it is able to process the imprecise, ambiguous and uncertain information to inform a workable result.

6.2.1 Validation of numerical outputs from the developed model

The numerical outputs from the model were assessed in terms of their accuracy, in order to examine the precision of the model. To do so, the approach adopted to develop the model was compared with the methodology used to produce models presented in the literature that have also used Fuzzy logic approaches for similar projects (An et al., 2011; Sansakorn and An, 2015). In addition, the model existing in the literature have also made use of a mix of three fuzzy logic techniques. This helps validate the methodology adopted in the current work.

Further, numerical outputs of the current study were also verified by comparing the data with results presented in the literature and the results presented in the Highways Agency's Asset Renewal Scheme Justification and Appraisal report, on Structures (Brown, 2014). This report presents classic recent case study examples, against which, the numerical outputs in this thesis were validated. The report presented results in the form of Risk Levels. A good agreement was observed between the Risk Level results of this study and the report, which further confirms the verification and the validation of the mathematical model adopted in this study.

6.3 Advantages and disadvantages of the application of the developed model with fuzzy methods

Fuzzy logic techniques have several advantages associated with their use. For solving ill-defined, nonlinear and complex problems, these techniques are known to perform well when compared to the conventional approaches. This is because of the ability of fuzzy techniques to make use of the theory of fuzzy sets. Fuzzy techniques are capable of integrating deductive and empirical information along with expertise regarding system dynamics and behavior. As a result, such abilities of these techniques lead to the rendering of the fuzzy logic system making it essential in achieving increasingly tactile as well as transparent qualitative insight for those systems which are represented by inadequate and poor mathematical models. Furthermore, as discussed previously in the literature review, fuzzy techniques can be used as either self-reliant methods or as integrated schemes with other approaches. Hence, they provide a profusion of alternative schemes and structures (Pappis and Siettos, 2005). However, in terms of each technique, while there are major advantages present, there are also some

disadvantages associated with the use of fuzzy techniques such as FRA, FAHP and FTOPSIS. The following sections discuss the potential advantages as well as the disadvantages of these methods in detail.

6.3.1 Application of FRA

6.3.1.1 Advantages

The advantages of adopting FRA are numerous and have been reported in several studies. In fact, there exists a great amount of literature which has appeared in the last few decades on the introduction of fuzzy logic. FRA has commonly been implemented for various safety-related studies and its applications have many robustness features (Chan et al., 2009). These include:

- Enhanced handling of uncertainties
- Reduced model complexities
- Competencies for multiple experts' modelling
- Enhanced cognitive modelling of expert judgements
- Excellent for numerically solving complex, non-linear problems
- Ability to model increasingly complex situations
- More prototypical than traditional methods
- Easier to design, comparatively

6.3.1.2 Disadvantages

While the advantages of a typical FRA application are several, there are also some disadvantages associated with this technique (Abdelgawad and Fayek, 2010). These are listed below:

- Biasness amongst fundamentalists in terms of the crisp logic-based systems
- Needs additional tuning before being operated, comparatively
- Requires the determination and tuning MFs

6.3.2 Application of FAHP

6.3.2.1 Advantages

The use of FAHP is very popular for bridge-related issues concerning the repair and maintenance works (Selih et al., 2008; Pan, 2008; Jakiel and Fabianowski, 2015; Cheng et al., 2019). As Javanbarget et al. (2012) mentioned, FAHP is an excellent technique which has superiority over other multicriteria techniques due to its competency in detecting inconsistencies, flexibility for use by decision-makers and its intuitive appeal. Generally, this technique is found to be convenient as well as straightforward to use by users due to its pairwise comparison form of data input. Moreover, this method is distinctively advantageous for use as compared to any other method because it allows the problem under investigation to be broken down into parts which can be useful for decision-makers. The resulting parts, as well as built hierarchies for criteria, assist decision-makers with capturing subjective as well as objective evaluation measures. In addition, it is able to reduce biasness in any decision made along with offering a strong mode for checking consistencies in the evaluation measures (Torfi et al., 2010; Mahmoodzadehet et al., 2007).

6.3.2.2 Disadvantages

While FAHP has gained an increasing amount of popularity, there are still some limitations of this technique based on the arising issues in this method. Basically, as

discussed earlier, the method of decision making in this technique requires splitting the problem into various subsystems. Adequate number of pairwise comparisons are needed to be completed within and between these subsystems. As a result, the number of pairwise comparisons might increase to an extent where the overall process becomes an extensive drawn-out one. In addition, the use of the 9-point scale poses as another limitation to this method. This is because of the resulting complexities and confusion in the system for distinguishing by decision makers (Macharis et al., 2004; Zeng et al., 2007).

6.3.3 Application of FTOPSIS

6.3.3.1 Advantages

In the risk assessment of bridges, FTOPSIS has been used (Wang and Elhag, 2006) and was found to function better as compared to other fuzzy versions of TOPSIS. In the classification of reversal issues, FTOPSIS has been recognized due to its potential strengths. In fact, this technique is known to function well when compared to FAHP (Mousavi et al., 2015). In terms of the precise advantages of FTOPSIS, these are listed below (Dantsoho, 2015):

- Simplified computational processing
- Enhanced flexibility in terms of the choice sets
- Easy and reasonably comprehensive concept
- Ability for measuring each alternative's relative performances in simplified mathematical forms
- Advanced computing performance

6.3.3.2 Disadvantages

Although FTOPSIS is known to be a widely applied technique in MCDM, it is unable to rank in cases with substantial number of criteria. In fact, the technique has a major limitation due to its inability for computing weight of indices. However, as Jato-Espino et. (2014) and Haghshenas et al. (2016) mentioned, such a weakness of this method can be eliminated with the use of a FAHP method for the calculation of the criteria as well as weighing for sub-criteria.

6.4 Improvement to the model

Typical of any research work, this current study also has some weaknesses and limitations. Therefore, based on this current research, some improvements to the proposed model can be made.

In terms of the CSC parameter, this study has successfully established this parameter as a multi-consequences parameter, which takes into consideration eight factors. Since each factor has its own associated ranking system for RLs in linguistic terms, the model's overall rulebase becomes complex. In fact, if more linguistic terms are used to describe RLs, it is expected that the rulebase will become bigger. This would make the designing of an appropriate rulebase very difficult. Also, this would result in increased difficulties for experts who would then be required to design and input several rules, probably in hundreds. Therefore, in order to take tackle this issue, the design of the rulebase must be facilitated. To do so, a software can be developed which can perform calculations easily. This is needed because determining the RL of different parameters in the maintenance of highway bridges is very important. Thus, developing and utilising a software appears to be an effective solution. This would be an additional feature to an

overall developed software, which would be developed on the current model proposed. Additionally, while such a solution would be able to deal with complex problems in an easy and quick manner, the software could be further enhanced by collecting useful feedback from industrial users. This would assist in the facilitation of the assessment process. Moreover, if a software is developed, the risk-based decision-making feature of the model can also be integrated in the software. Finally, the development of an appropriate software would allow for the consideration of even more case studies.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Bridges are crucial structures in today's transportation industry and are vital for land transportation. They are known to have direct impacts on economic as well as social developments. Based on the literature review provided in this work, it can be established that bridges require a great deal of maintenance throughout their service life. This is mainly because bridges are subjected to multiple loadings along with several risks. In fact, various statistical investigations have reported bridge failures that occur around the world. Usually, issues such as corrosion, traffic accidents, vehicle collisions, fire, structural instability, safety issues and overall poor risk management are the main reasons for most bridge failures.

This research study was aimed at the development of a model for the safety risk analysis of bridge structures. The work was based on the use of FRA, FAHP and TOPSIS methodologies. The proposed model presented in this research can assist civil engineers, safety officers, health and safety advisors, designers, operators as well as project managers with adequate decision making tasks. This would further allow them to improve the safety risk management by manipulating and controlling safety risks.

Overall, this research study has been able to successfully achieve its targeted aim of enhancing the safety of bridge structures by the development of a safety risk model. The objectives which have been achieved by this research can be summarised as:

- **Objective 1**: To study and examine the current safety-related issues and investigate the types of risk present in the bridge industry.

This objective was achieved by first motivating performing this study. Next, a detailed research methodology to be adopted in this study was planned and discussed. The significance of known important steps in performing the current research and describing research methods applied in this study was highlighted. In addition, the collection of data on bridge failures in terms of industrial reports as well as journal articles helped achieve this objective. Consequently, this allowed for the identification of the major types of bridge failures. In addition, statistical information on such failures was found and summarized.

- **Objectives 2 and 3**: To undertake an extensive literature review in order to form a deeper understanding of the current safety issues, which exist along with the corresponding types of risks in the bridge safety industry and to identify the most critical elements of the chosen type of the bridge.

A review of the relevant literature was performed by first providing detailed background on bridges. Case studies concerning bridge accidents were discussed in order to understand the reasons behind such accidents. In addition, the problem of corrosion in highway bridges was also discussed in detail along with providing the description of risk analysis and possible solutions to bridge failures. Furthermore, a review of fuzzy reasoning techniques, FRA, FAHP and FTOPSIS was provided followed by the application of these techniques to bridge structures.

- **Objectives 4, 5 and 6**: To develop a risk model to assess the failure modes of the bridge structures based on the collected outcome of studies. To develop a cost estimate model for maintenance cost analysis of the bridges. To develop an overall risk-cost model to optimise the risk reduction and

maintenance costs for the best maintenance solution based on the collected outcome of studies.

The new safety risk model applicable mainly to bridges was developed and presented. Three input parameters, CS, FF and WF are introduced and then used for assessing the risks from components levels all the way to system level. The CSC parameter is introduced as the multi-consequences parameter, which takes into consideration eight factors that are considered significant for the risk analysis of bridges. The eight factors, which are, functionality, safety, value for money, environment, traffic delay, time, reputational damage and socio-economic consequences are discussed in detail. Also, the fuzzy techniques, FRA, FAHP and FTOPSIS are discussed in detail along with explaining their contribution to the current study and the proposed safety model.

The numerical outputs from the model were assessed in terms of their accuracy, in order to examine the precision of the model. To do so, the approach adopted to develop the model was compared with the methodology used to produce models presented in the literature that have also used Fuzzy logic approaches for similar projects. In addition, the model existing in the literature have also made use of a mix of three fuzzy logic techniques. This helps validate the methodology adopted in the current work. Further, numerical outputs of the current study were also verified by comparing the data with results presented in the literature and the results presented in the Highways Agency's Asset Renewal Scheme Justification and Appraisal report, on Structures.

- **Objective 7**: To validate and verify the reliability of the risk assessment and safety management model with the assistance of case studies.

Case studies were used to assist in illustrating the implementation of the suggested safety risk management model. Thus, the three case studies utilized in this study, which

are relevant to the safety aspects of bridges were discussed. This included discussing and providing in detail the corresponding risk responses for each case study.

- **Objectives 8 and 9**: To produce an overall efficient and effective safety risk assessment and management framework, applicable to the highway bridges. To provide recommendations for improvement of the bridge maintenance strategy

This objective was achieved after the development and verification of the model. This stage included a thorough discussion of the evaluation model by interpreting the results from the three case studies used. These case studies were obtained by the Highways Agency's publication and were focused on highway bridge structures. Verification and validation of the numerical outputs of the model confirmed the development of an overall efficient and effective safety risk assessment and management framework, which is applicable to highway bridges. In addition, the advantages and disadvantages of the application of the developed model were discussed in terms of using FRA, FAHP and TOPSIS. Next, any limitations or weaknesses in the model were identified. Further possible improvements to the model were then suggested by making recommendations for future studies.

7.2 Research Novelties

For the first time, this work has carried out research as well as propose a safety model for risk assessment of highway bridges. Precisely, the research novelties can be summarised as:

1) The bridge safety risk model was proposed based on the use of fuzzy reasoning approaches along with FAHP and TOPSIS. 3 input parameters, i.e. FF, CS and WF were used for assessing the potential risks on the operation of bridges. In

this process, a modified Consequence Severity Criteria (CSC) parameter was developed and introduced. For the first time, this multi-consequences parameter, referred to as the CSC, is introduced in the risk assessment of bridges. It takes into consideration eight factors that are considered significant for the risk analysis of bridges. These are functionality, safety, value for money, environment, traffic delay, time, reputational damage and socio-economic consequences. The use of this multi-consequences parameter can aid risk analysts in risk control measures.

2) In the case of no available information or risk data, it is possible to use subjective estimations with the proposed risk model. This is because the model permits the use of imprecise as well as vague descriptors for directly capturing experts' judgements. For instance, descriptors such as "impossible" or "likely" can be used. In addition, the flexibility of this method is evident in its process which includes the ability to combine expert opinions with several different background experiences.

3) There are certain complexities associated with the application of FAHP in general. However, the proposed risk assessment model uses an enhanced version of FAHP, which needs only a few expert judgements. In addition, this FAHP application does not require any consistency test.

4) The developed model is based specifically on highway bridges. Hence, the benefits of the model can be summarised in its ability to combine engineering judgements as well as expert knowledge with various risk information for the assessment of highway bridges in a reliable approach. In addition, the model can deal with uncertain, incomplete, ambiguous and imprecise data along with

directly applying the linguistic terms in a flexible manner for the risk assessment.

5) The application of this risk-cost model allows the determination of "preference degrees of maintenance options". This involved taking into consideration the cost and risk reduction. Therefore, the outcomes of this model allow the determination of the highest preference degree in a maintenance option. This can decrease the system RL to the lowest possible.
6) The model is validated with the use of three unique case studies. These are relevant to the safety aspects of bridges. In addition, the corresponding risk responses for each case study are discussed. Such a procedure allows for the validation as well as verification of the proposed risk model. Also, the model appears to be successfully working and can thus be used for assessing risk levels for any type of bridge structures in the UK.

7.3 Recommendations for future work

Further work is recommended in this section based on the work presented in this thesis. Future work can be carried on the key issues perceived in this study in order to improve the model further. To elaborate, this research makes use of FRA, FAHP and TOPSIS in combination, for developing the model. However, the outcomes and key findings from this work indicate that with the use of FAHP, an increase in the total hazard groups results in an increase in the complexity as well as difficulty for making calculations for pairwise comparison matrices. Moreover, with the introduction of a CSC parameter, which involves taking 8 factors into consideration, the rule base becomes bigger. Designing rulebases then becomes a difficult task due to the several associated

linguistic terms. Hence, as suggested in Section 6.4, the development of a software is an appropriate decision for facilitating the application of this proposed model. It will also allow for reducing the time requirements. Thus, the development of a reliable software would appear to be an ideal and effective solution.

Furthermore, it is worth mentioning that while the current model is designed specifically for highway bridges, the utilised methodologies make it applicable for use in several safety considerations. In addition, once the software is prepared, useful feedback from industrial users can assist in its further improvement.

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