THE UNIVERSITY OF ZAMBIA

SCHOOL OF ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

OPTIMIZATION IN THE STRUCTURAL DESIGN OF COMPOSITE DECK BRIDGES

By

CHIKUMBUSO LUNGU

"A Dissertation submitted to The University of Zambia in partial fulfilment of the requirements for the degree of Master of Engineering in Structural Engineering,"

2022

Copyright Declaration

Declaration

I, **Chikumbuso Lungu**, declares that this dissertation is entirely my own work as specified in acknowledgements and that neither the dissertation nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Author

CHIKUMBUSO LUNGU	Signature: ________________	Date: ___/___/2022

Supervisor

DR MICHAEL N. MULENGA	Signature: ________________	Date: ___/___/2022

Certificate of Approval

This dissertation of **Chikumbuso Lungu** is approved as fulfilling the requirements for the award of the **Masters of Engineering** in **Structural Engineering** at the University of Zambia.

Examiner - 1

Name: ________________________ Signature: ____________________ Date: ___/___/2022

Examiner - 2

Name: ________________________ Signature: ____________________ Date: ___/___/2022

Examiner - 3

Name: ________________________ Signature: ____________________ Date: ___/___/2022

Chairperson of Board of Examination

Name: ________________________ Signature: ____________________ Date: ___/___/2022

Dedication

In memory of my late grandmothers Elina Zimba Banda and Lucy Zulu Lungu.

To my beloved wife Bwalya M. Lungu, for giving me all forms of support during my studies.

To my parents Gertrude Banda Lungu and Peter Lungu, for the continuous encouragement during the course of my studies

My son Chawanzi Lungu, as my core source of motivation.

To myself, a rare recognition.

I dedicate this work.

Chikumbuso Lungu

Acknowledgements

Without the following people, this dissertation would have not been possible:

- First and foremost, gratitude goes to the Almighty God for giving me the breath of life and light to comprehend and contribute to the body of knowledge in bridge engineering. Psalm 36:9
- I would also like to thank my parents and siblings for being such a blessing to me. Their great support in my academic journey cannot be ignored.
- My great appreciation goes to my supervisor Dr. Michael N. Mulenga, mentored me through this program. I would like to appreciate him for giving me his time to guide me and encourage me to push on even when it seemed hopeless at times. I would be too proud to forget to mention his efforts in making me realize my academic career.
- The following people played an important role in offering help through my work, especially when developing the app in C#: Kennedy Kangwa, Francis Nyongani and Ngoyi Lungu.

ABSTRACT

The study aimed at demonstrating the positive outcome of incorporating optimization techniques in the design procedure for designing steel-concrete composite bridges was conducted. Optimization algorithms have the capability of finding optimal or near optimal solutions in complex problems. In order to accomplish this task, a software known as COMPOPT, was developed in C# programming language to optimize composite bridge designs based on a classical method of optimization known as 'direct search'. The software output was then compared to structural designs that would be obtained through the typical 'traditional' design procedure. Traditional design procedure is a term in this study that alludes to normal procedure of design that practicing structural engineers follow in the design process, including use of design aids such as structural analysis and design software like Prokon and Robot. In summary, the output structural designs from the developed C# application were compared to typical structural designs from selected practicing structural engineers in Zambia. The results showed that the design output from COMPOPT performed better than the typical designs on several key parameters.

Keywords: *Optimization Techniques; Direct search method; Steel-Concrete Composite Bridges; Bridge Optimization; COMPOPT;*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

COMPOPT	Composite Bridge Design and Optimization Software
LM1	Load Model 1
GUI	Graphic user interface

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Optimization is the process of finding the best or most effective use of a situation ‘optimal solution’ with a given a set of limitation. The mathematical tools and concepts used to arrive at this ‘optimal solution’ are termed as optimization techniques. This has been a growing area of interest to civil engineers because of its applicability (Himani & Monisha, 2015).

Optimization can be applied to various types of structures in civil engineering design. Pedro, et al (2017) noted that structural optimization is a very relevant field and has been a growing focus on research. Initial emphasis had been given to truss structures and some important advances were carried out. However, it is essential to note that the main focus of these studies was the implementation and development of different optimization procedures applied to academic examples (Pedro, et al., 2017).

There is a general sense that this field hasn’t received adequate attention. The slow progress in this field is largely attributed to tedious procedures involved in the calculation. But the emergence of computers has brought some significant interest in application of these techniques to structural engineering problems (Numan, 2012).

However, this research focused on the application of optimization techniques to Structural Design of Concrete-Steel Composite Bridges. This type of bridge is mainly composed of a reinforced concrete decking supported on steel girders. Standard rolled section steel beams are rarely used as main girders, instead plate girders are usually used and have proven to be more economical since the plate size and thickness chosen for efficiency.

In the design of multi-girder composite bridges, a number of similarly sized longitudinal plate girders are arranged at uniform spacing across the width of the bridge, as shown in the typical cross section in Figure 1.1. The deck slab spans transversely between the longitudinal girders and cantilevers transversely outside the outer girders. The girders are braced together at supports and at some intermediate positions. Composite action between the reinforced concrete deck slab and the longitudinal girders is achieved by means of shear connectors welded on the top flanges of the steel girders. Figures 1.1 and 1.2 show a typical cross section and a longitudinal profile of a composite bridge.

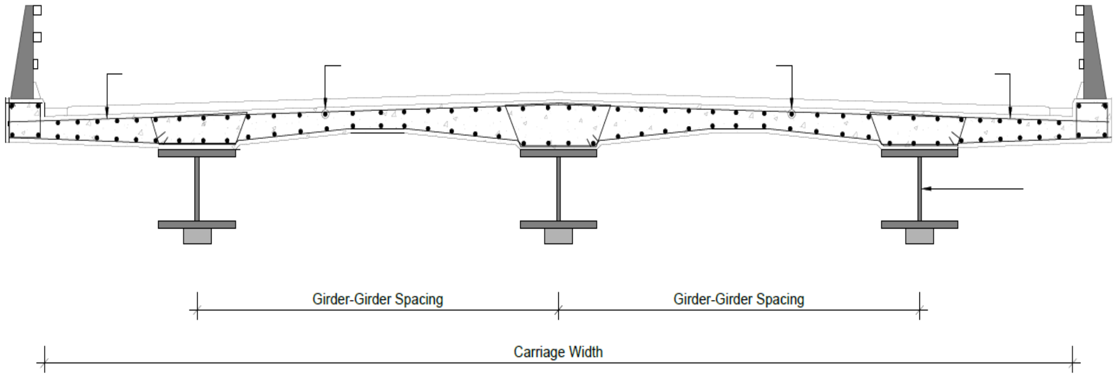


Figure 1.1: Cross Section View

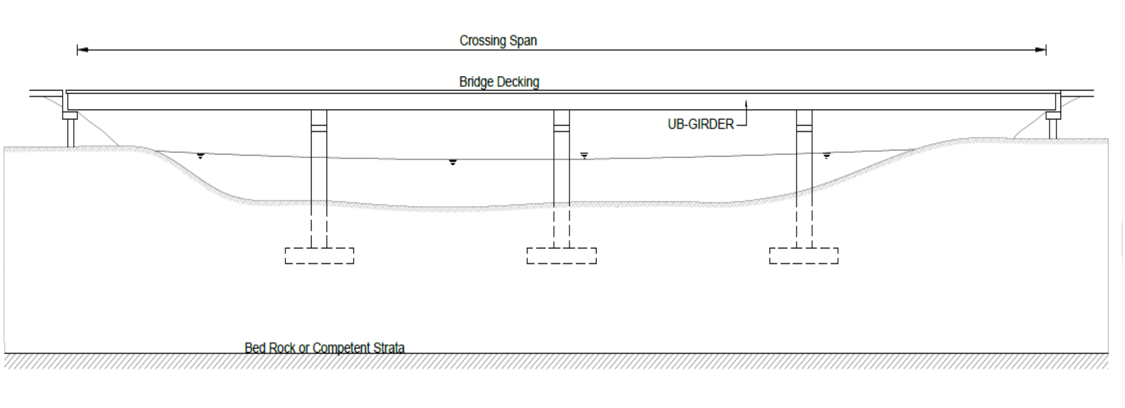


Figure 1.2: Longitudinal Section

Therefore, this study developed an optimization software tool that: (1) optimizes the selection of girders and reinforced concrete decking, (2) Optimizes the topology of the bridge spatial parameters such as the spacing in between piers, and (3) compares output design from the software to typical design that would be produced by a practicing structural engineer.

1.2 PROBLEM STATEMENT

In conventional design procedures, the initial or preliminary design is usually done by 'rule of thumb'. A rule of thumb is a rule or principle that one follows, which is not based on exact calculations, but rather on experience. This means that there is a vast array of possible designs that will fit requirements from design codes depending of the experience and background of the designer. It is a well-known fact that given any given design assignment, there's a cluster possible designs that will all pass the codes requirements as demonstrated in Figure 1.2. Considering the Concrete-Steel Composite Deck Bridge in this study, the following variable combined differently produce different designs:

- Girder spacing
- Plate girder sizing
- Pier to Pier spacing

Therefore, the problem or function objective is to find the combination of these variable that produce the least cost or volume of material.

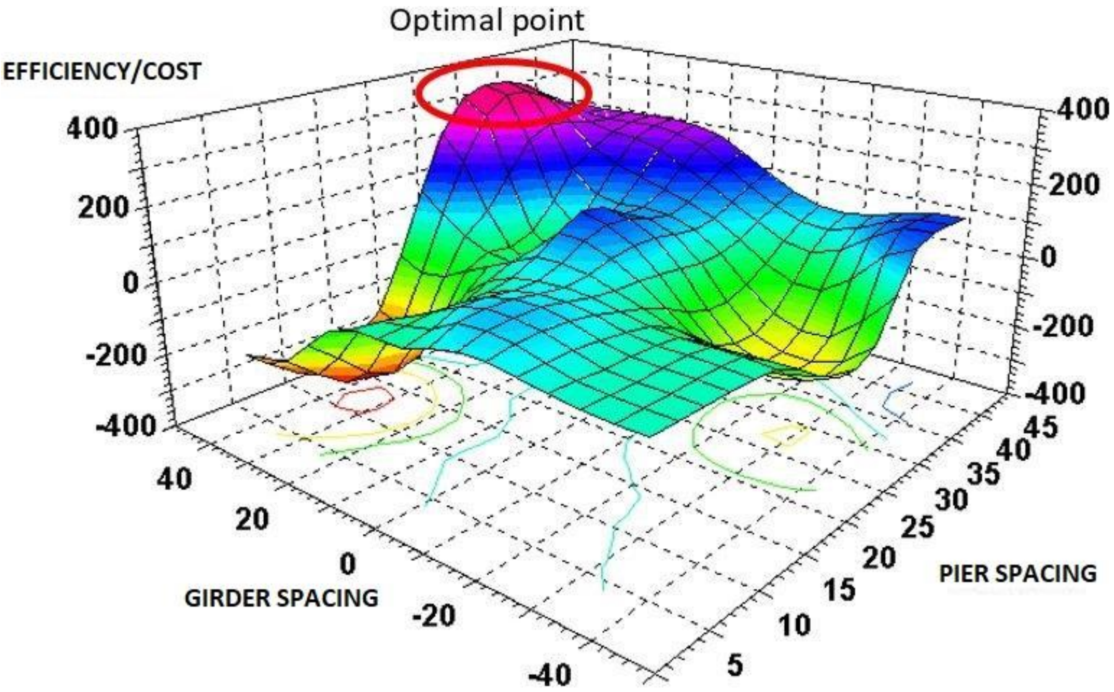


Figure 1.3: Graph of Topology parameters to Cost

Source: (Deore, 2018)

1.3 OBJECTIVES

The objectives of the research are follows:

1.3.1 Main objective

To develop an optimization software tool to be used as an accessory to composite bridge design.

1.3.2 Specific objectives

The specific objects of this project are as follows:

- Identify the design criteria used for concrete-steel composite bridges.
- Identify optimization techniques and algorithms that are useful in composite bridge design.
- Develop a software tool for optimizing the sizing of girders and topology of the composite bridge design.
- Ascertain the suitability of incorporating the optimization techniques in structural design of bridges.

1.4 RESEARCH HYPOTHESIS

In order to address the problem statement, this research was designed to test hypothesis that for each bridge design problem, there exist an optimal design solution. Further, incorporating optimization techniques to the design process would produce more cost-effective designs than the designs obtained by using conventional methods of design. Before the advent of computers, finding the optimal design was a daunting task, considering the number of iterations one has to take to find the optimal design. It seems that this impediment has been removed by the development of computers, therefore this research tested this hypothesis by comparing the structural design that 'optimization techniques' produce to the designs produced using conventional methods.

By varying topological parameters and cross section parameters with a goal of finding the optimal solution, the research aimed to develop a tool that would generate the most cost-effective multi-girder steel-concrete composite bridge designs. This was done by using a classical method of optimization which compares all the available set of solutions and picks the optimal solution with the least weight.

As previously discussed in the introduction, research should focus on cost optimization of large and realistic structures to facilitate the usage of optimization methods in structural design practice. Composite multi-girder bridges have desirable elements to demonstrate this since it is common practice to utilize plate girders. Optimization should be carried out for real-world projects to close the gap between theory and practice. Therefore, this research seeks to contribute to closing of this gap by implementing cost optimization in practice.

To address the third specific objective, a software application has been developed to make the optimization generalized and reusable. Though this application is limited to composite multi-girder bridges, this research foresees that its implementation should demonstrate how incorporating optimization into design can minimize material use, cost of projects and how this approach would be better than the conventional approach.

1.5 RATIONALE OF STUDY

Recent advances in the field of computational intelligence have led to a number of promising optimization algorithms. These algorithms have the potential to find optimal or near-optimal solutions to complex problems within a reasonable time frame. Although a significant amount of research has been published in the field of structural optimization since the 1960s, little of the research effort has been utilized in structural design practice. One reason for this is that only a small portion of the research targets real-world applications. Therefore, there is a need to conduct research on cost optimization of realistic structures, particularly large structures where significant cost savings may be possible. To address this need, a software application for cost optimization of composite steel multi-girder bridges.

1.6 SCOPE OF STUDY

In order to enhance the practicability of the study, a scope on the following section of the study was imposed.

1.6.1 Optimization techniques

There are a number of optimizations techniques that have been proposed for use in this field of study. They can broadly be grouped into two types, (1) Classical methods and (2) Advanced Optimization techniques. The solution produced by advanced techniques have been generally been found to approximate the actual optimal solution and convergence isn't always assured (Shodhganha, 2000).

Since the study was only attempting to demonstrate the usefulness of incorporating optimization techniques in structural design, the author decided to use a classical method, known as direct search. The software tool is developed is limited in scope to use direct search method. Classical methods have a disadvantage. When implemented into a computer program, the program tends to fail when the problem they're solving becomes too complex. For this reason, parameters chosen for optimization on the composite bridge where limited to:

- Slab decking thickness
- Universal Beam Selection
- Girder to Girder distance
- Pier to Pier Spacing

1.6.2 Software Tool for Optimization

The scope on the software tool were also limited to certain functions. For instance, the computer program was written to design the slab decking assuming that the sections are simply supported. This was done to create uniformity with the design problem given to the practicing engineers.

The computer program was also written to design certain key structural members on a composite bridge. These include:

- Structural design of the concrete decking

- Structural design of girders, and
- Positioning of the piers

The program is limited in scope in that it doesn’t design other elements of bridge such as the bearings, foundations and other pertinent elements of the bridge.

The selection of beams is also limited to Universal Sections as opposed to plate girders. This was done to reduce complexity of the parameters to optimize. As a consequence of using universal beams, the program was further limited to design spans not longer than 15m. This is supported by a study done by Momtahan and Hicks where they presented a graph showing the effective spans that go along with Universal Sections (Momtahan & Hicks, 2013).

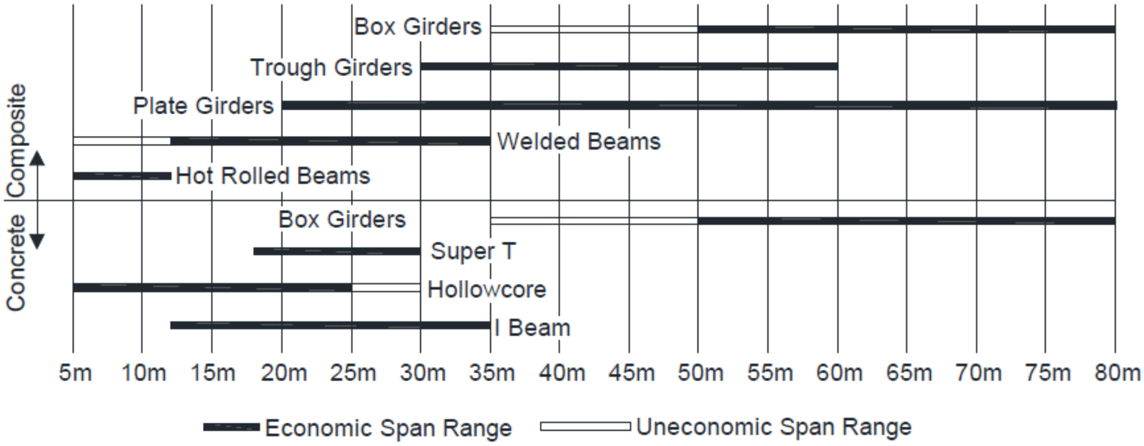


Figure 1.4: Graph of Topology parameters to Cost

Source: (Momtahan & Hicks, 2013)

1.7 ORGANISATION OF THE DISSERTATION

Chapter 1 introduces the background of the study. It gives details to the identified problem which gave rise to the need for the research. Aims, objectives, and research questions are articulated in this chapter. The significance of the study and the scope are also underscored in detail. Other aspects of the dissertation comprehensively covered in later chapters are also briefly indicated. Chapter 2 presents the literature review based scholarly articles by other researchers and identifies the knowledge gaps for this research. Chapter 3 presents the Methodology employed in this research. The Research design, comprising of Research Philosophy, Research Methodology (Strategies of Enquiry), Methods (Tools & Techniques), and Sources are outlined. Data collection methods, instruments used, and the data analysis method are described. Chapter 4 presents the *Results and Analysis of all* data gathered for the research. Data obtained from the software tool has been documented and analysed as well. The findings of this research are presented and critiqued in reference to results obtained from the practicing structural engineers. *Chapter Five presents the Discussion of the Results whilst Chapter Six gives the Conclusions, Study Limitations, and Recommendations*

Each chapter has an introduction briefly describing what the previous chapter covered to provide continuity (ramping) as described by Banda (2019) and what the reader is to expect in the chapter at hand. The main body of the chapter is then given in detail and a chapter summary that summarizes the contents of the chapter.

1.8 SUMMARY

The chapter presents the background to ‘Optimization Techniques’ as a field applicable in the structural engineering field and specifically applicable to Design of Steel-Concrete Composite Bridges. It briefly outlines the necessity to incorporate Optimization techniques in the Design process and how this study demonstrates this by making a tool that uses a classical method of optimization in Bridge Design. The chapter describes the aims, objectives, and questions answered by the research. The significance of the study, challenges faced and how the overall dissertation is organized. The chapter also summarises the contents of each chapter in the Dissertation

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Literature Review allows the researcher to check publications of studies conducted on the same topic or similar topics by other researchers so as to familiarize with what other researchers have found on the same topic under investigation. A review on literature also identifies the gaps in former researches. The review acquaints the researcher with the methodologies that other researchers employed in carrying out the research.

Therefore, this chapter presents the literature reviewed. Firstly, publications on optimizations were reviewed and objective function defined. Secondly, literature on design criteria was reviewed to design the constraints of the objective function.

2.2 OPTIMIZATION IN GENERAL

2.2.1 Definition of Optimization

From all the literature reviewed, the definition of optimization can be summarized as a procedure used to make a design or system as effective as possible using mathematical techniques. An optimization problem is there defined by an objective function, design variables and constraints

2.2.2 Formulation of the Optimization Problem

Perhaps the optimization problem of composite bridges was best described best by Pedro, et al (2017) as follows: *"To find the optimum design of the bridge, the cost of structure, represented by equation 1 has to be minimised while satisfying the constraints in equation 2."* (Pedro, et al., 2017)

$$C = f(x_1, x_2, \dots \dots, x_n) \qquad \text{.... } \textit{Equation 2.1}$$

$$g_j(x_1, x_2, \dots \dots, x_n) \leq 0, j = 1, \dots, m \qquad \text{.... } \textit{Equation 2.2}$$

Where C is the cost function; g_i are the constraints of the problem; x_j are the discrete variables.

In the late 1900s, Richard H Gallagher (1973) wrote that any structural optimization problems constitute of three basic features which include: Design variables, Objective function and Constraints. Each of these aspects of the problem is discussed in turn. (Gallagher & Zienkiewicz, 1973)

2.2.3 Design Variables for the composite steel bridge

The design variables of an optimum composite bridge design problem may consist parameters that describe the structural configuration of member sizes, orientation of plate girders, girder to girder spacing, pier to pier spacing and overall topology. The topology is the geometric and spatial arrangement of the structure and remains unaffected by smooth changes in shape and configuration of members (Dowling, et al., 1982).

A paper written by Petr, et al (2010) argued that there exist a natural hierarchy, or order of complexity, among the different classes of design variables. The simplest design variable is the size of a member. The majority of papers published on optimal design deal exclusively with the selection of member sizes because of relative simplicity of the problem. However, if practical application of numerical optimization was to be implemented, complex variables involved in bridge design have to be considered (Petr, et al., 2010).

2.2.4 Objective function

Majid (1994) defined the ‘Objective Function’ as the function whose least (or greatest value) is sought in an optimisation procedure, and constitutes basis for the selection of one several alternative acceptable designs. The objective function is in actual sense, a scalar function of the design variables. It represents the most important single property of design, such as cost or weight. The cost function may be written as follows (Majid, 1994).

$$W = \sum_{i=1}^{m} \rho_i L_i A_i \qquad \text{.... Equation 2.3}$$

Where ρ density of the material is, L represents the length of the member, A is the cross section of the member and m represents the number of members in the frame.

An important concept, used in optimisation problems is that of the gradient of the objective function. That is, finding the maximum or minimum of the objective function

2.2.5 Constraints

Shodhganha (2000) describe a constraint, in an optimization problem as a restriction to be satisfied in order for the design to be acceptable. Constraints may take form of a limitations imposed directly on a variable or a group of variables (known as explicit constraint), or may represent a limitation on quantities whose dependence on the design variables cannot be stated directly (implicit constraint). (Shodhganha, 2000).

There are two types of constraints namely: equality and inequality constraints. An equality constraint is expressed in equation 2.4 for E such constraints. Theoretically, each constraint may represent an opportunity to remove a design variable from the optimisation process, hence reducing the magnitude of the search space. An inequality constraint is expressed in the form given in equation 2.5, where a total of I constraints conditions exists.

$$\boldsymbol{g(x) = 0, \quad i = 1, \dots, E} \qquad \text{.... } \textit{Equation 2.4}$$

$$\boldsymbol{g(x)_i \leq 0 \;\; i = 1, \dots, I} \qquad \text{.... } \textit{Equation 2.5}$$

2.2.6 Search space

The search space is characterised by the number of design variable in the optimization problem. The number of design variables determines the dimensionality of the optimization problem, where n variables correspond to an n-dimensional problem. A simple problem with only two design variables can be visualized in a comprehensible manner with a surface plot as shown in Figure 2.1, usually called a cost surface or landscape. In such a plot, each pair of x- and y-coordinates represents a point in the search space, and the corresponding z-coordinate represents the value of the objective function at that particular point. Typically, objective functions have several local optima, but only one global optimum. What is referred to as optimum depends on whether we are seeking a minimum or a maximum of the function. By convention, it is assumed that the objective function should be minimized. If the objective function should be maximized instead, we can simply invert the sign of the function and minimize (Mourabit, 2016).

2.3 NUMERICAL OPTIMIZATION METHODS

Types of Numerical Optimization Methods can be broadly divided into two. Shodhganha (2000) classified optimization techniques into two broad categories, namely: Classical optimization techniques and advanced optimization techniques. The research endeavoured to take a more practical approach by using a classical method, namely direct linear programming. Advanced Techniques generally give an approximate optimum and finding the exact optimum solution isn’t assured in this approach.

Therefore, the current trend in optimization is to use so-called metaheuristic algorithms. These algorithms are stochastic as they use randomization, and they are often inspired from phenomena in nature. The most famous example is probably the genetic algorithm that simulates evolution in a population over several generations to reach a solution. Other popular examples include swarm-behaviour of ants or bees, cooling of metals, or pollination of flowers.

2.3.1 Classical Optimization techniques

Classical Optimization techniques are usually used when the objective function is continuous and differentiable. These methods are analytical and employ techniques of calculus to locate the optima. Some of the classical methods include: Direct methods, Gradient methods, Linear programming methods and interior point methods.

Most classical optimization algorithms are deterministic, and some of them calculate the gradient of the objective function to guide the next step. Such algorithms are called gradient-based, and a typical example is the well-known Newton-Raphson algorithm.

2.3.2 Advanced Optimization Techniques

Most real-world optimization problems are too complex to find the global optimum with these classical optimization techniques. Therefore, the current trend in optimization is to use so-called metaheuristic algorithms which fall under advanced optimization techniques. These algorithms are stochastic as they use randomization, and they are often inspired from phenomena in nature. The most famous example is probably the genetic algorithm that simulates evolution in a population over several generations to reach a solution. Other popular examples include swarm-behaviour of ants or bees, cooling of metals, or pollination of flowers.

There are many advanced methods that have been developed in the recent years. This may be attributed to the advancement in computing power of computers which has made implementation of these methods possible. These methods include: Simulated annealing, Particle swarm methods and Evolutionary optimization methods. Most of the research done by other authors on design optimization of steel portal frames was with the use of evolutionary methods, specifically the genetic algorithm.

Evolutionary algorithms (EAs) are usually used to solve large complex optimization problem. That is, problem having very large number of decision variables and non-linear objective functions are often solved by EAs. EAs are designed to mimic the metaphor of natural biological evolution or social behaviour. For example, like how ants find the shortest route to a source of food and how birds find their destination during migration. The behaviour of such species is guided by learning and adaptation (Shodhganha, 2000).

The most widely used evolutionary-based optimization technique is the genetic algorithm (GA). Genetic algorithms are developed based on the Darwinian principle of the survival of the fittest and the natural process of evolution through reproduction (Shodhganha, 2000).

2.4 EXISTING APPROACHES TO OPTIMIZATION OF COMPOSITE BRIDGES

There have been significant strides in researching optimization techniques and their application. Most research has been attempting to demonstrate how advanced optimization techniques could be used on various engineering structures. It is important to note that recent technological revolution has enabled the use of optimization techniques. Before the advent of computers, the tedious iterative nature of calculations involved in optimization hindered engineers to adopt optimization techniques. But with the increase in computing power brought in by the electronic era, using these techniques has made possible and easy (Himani & Monisha, 2015) and (Numan, 2012).

Among the most recent published papers, Fabeane et al (2017), probably defined the optimization problem very well in terms of composite bridges. They presented the problem as follows: Finding $X = \{X_1, X_2, \dots, X_n\}^T$ that minimizes (or maximizes) the function $f(X)$ under the following constraints (Equations 2.6, 2.7 and 2.8):

$$g_j(X) \le 0, \quad where\ j = 1,2,\dots.,m \quad Equation\ 2.6$$
$$l_j(X) \le 0, \quad where\ j = 1,2,\dots.,p \quad Equation\ 2.7$$
$$X_i^l \le X_i \le X_i^u \text{ ………………………… Equation 2.8}$$

$f(X)$ represents the objective function of the problem which could be, for instance 'least weight of the bridge' or the 'most economical bridge design'. Equations 2.1 and 2.2 represents the constraints on the problem that should be respected so that the obtained solution falls in between these specified bounds. An example of a constraint in bridge design would be deflection. The optimum design needs to have a deflection that falls within the bounds of the permissible deflection allowed by standard codes. Equation 2.3 is called lateral restriction (Fabeane, et al., 2017).

Now, the current tradition approach to optimization in the structural design industry is limited to the experience and knowledge of the designer. In their paper, Kazakis, et al., noted that what practicing structural engineers deem as an "optimal design" is their choice among rather limited set of design alternatives, dictated by their experience and intuition (Kazakis, et al., 2017).

Optimization techniques nested in numerical mathematics however a plethora of alternative designs than what the traditional approach presents. Traditional optimization is limited to the designer's knowledge and experience but advanced optimization techniques can analyse over a thousand alternative design in a second (this is made possible with advanced computing power).

2.4.1 Metaheuristics approach vs Classical approach

There are two (2) main categories of optimization techniques in numerical computation namely: Classical optimization techniques and advanced optimization techniques. Classical optimization techniques use techniques of differential calculus in locating optimum solutions. These methods are relatively old, and could be dated as far back as the Newtonian era. Metaheuristics optimization techniques on the other hand, were developed quite recently. They're based on certain characteristics and behaviour of biological, molecular, swarm and neurobiological systems (Singiresu, 2019).

Examples of metaheuristic algorithms include: genetic algorithms, simulated annealing, particle swarm optimization, ant colony optimization and neural network methods of optimization. Metaheuristics optimization methods mimic the way nature approaches optimization in these systems. This has allowed researchers in this field to benefit from the billions of years' nature has had experimenting on this problem and finding a workable solution to it. For instance, the Ant colony optimization is based on the behaviour of real ant colonies, which are able to find the optimal path from their nest to a food source.

Natures problems are riddled with a multitude of variables and constraints which make the optimization problem very complex. But nature has found a way around this and this makes the algorithms based on nature very powerful and useful in engineering problems. Metaheuristic algorithms have been popular due to their ability to provide solution to complex engineering problem. A lot research recently conducted in the study of optimization has been mostly exploring the use of application of metaheuristics optimization techniques. However, these algorithms have limitations on applications. Despite been able to handle a lot of variables, convergence to an optimum solution isn't always assured and there is no guarantee that the solution will be found globally. (Chopard & Tomassini, 2018)

In comparison to metaheuristic algorithms, classical optimization techniques have an advantage in that convergence is always assured, given that the problem isn't too complex and objective function is 'continuous and differentiable'. The methodology of this study led to use of this type of algorithm given the nature of the problem. A classical method known as direct search method was adopted.

2.4.2 Direct methods

Singiresu (2019), posits that a function of one variable $f(x)$ is said to have a local minimum at $x = x^*$ if $f(x^*) \leq f(x^* + h)$ for all positive and negative values of h. Similarly, $f(x)$ is said to have a local maximum at $x = x^*$ if $f(x^*) \geq f(x^* + h)$ for all values of h significantly close to zero. By Singireu's definitions, it follows that, a function $f(x)$ has an absolute global optimum at $x = x^*$ if $f(x^*) \geq f(x)$ or $f(x^*) \leq f(x)$ in the domain over which $f(x)$ is defined. This is the mathematical basis upon which all optimization methods are based on including the direct search methods (Singiresu, 2019).

Direct search methods are applicable to multi-dimensional unconstrained optimization problems. Given that these methods also don’t require gradient function, direct search methods could be used in problems where the data set is scattered and there’s no easily identifiable function. Example of direct methods include: Random search method and ‘univariate and pattern searches’ (Chapra & Canale, 2015).

This study endeavoured to use a derivation of this method through a C# program. C# programming language is an object-oriented language. Object oriented programming is a paradigm based on the concept of ‘objects’ which can contain data and code. With this capability, the direct search method was implemented on the C# platform (Hanson, 2004).

2.4.3 Composite Bridge optimization

A number of research has been done on application of optimization techniques applied to composite bridges. Most of it actually attempts to use metaheuristic optimization techniques, comparing the rates of convergence or simply testing them on a design parameter. Another criterion by which the research on this topic can be categorized is by observing which variables are of interest. There are studies investigating the optimization of topological parameters and those optimizing cross section parameters.

Kazakis, et al. (2017), defined structural topology optimization as a procedure of rearranging of structural elements and material into a design domain, thereby eliminating unnecessary material volume. In a composite bridge, this means the spatial arrangement of piers and positioning of girders (Kazakis, et al., 2017).

A study conducted by Lythell & Sternberg (2020) on cost optimization of composite bridges noted that most design offices adopt a trial-and-error based approach when designing composite bridges. They hypothesised that implementing this iteration in a computer software with an optimization algorithm would produce more cost-effective preliminary designs. When tested, their results showed that the software was a viable tool for preliminary designs (Lythell & Stenberg, 2020).

In summary, a recurring theme was observed in the literature reviewed which is: Optimization techniques ultimately improve design results. Additionally, all the papers reviewed posited that introduction of an optimization improved the design results. The only disadvantage is that redundancy on the resulting solution is reduced.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

The previous chapter reviewed literature related to the research topic. A detailed description of the optimization problem was defined, design process of multi girder bridge was outlined and an overview of C# programming and its application to the problem was noted down. This Chapter presents the methodology used to acquire data and carry out the research. It outlines and discusses the methods employed to address the specific objectives of the research.

3.2 RESEARCH TYPE

Leedy and Ormrod (2016) defined research as a systematic process of collecting, analysing, and interpreting information (or data) in order to increase our understanding of a phenomenon about which we are interested or concerned. They also described it as a process that produces new knowledge through direct engagement with social practice and problems (Leedy & Ormrod, 2016).

In his book, Research Design, Creswell (2009) wrote about the three main approaches types of research including descriptive, analytical, applied, fundamental, quantitative qualitative, conceptual, and imperial research types. He however highlighted that qualitative and quantitative research types are the main categories that the other fall in. This research employed both qualitative and quantitative techniques as described in the following sections.

3.3 RESEARCH DESIGN

Research design encompasses decisions regarding what, where, when, how much, by what means concerning an inquiry or a research study constitute a research design. Kothani (2004) further explained that a research design is the arrangement of conditions for collection and analysis of data in a manner that aims to combine relevance to the research purpose with economy in procedure. In a nutshell, the research design is the conceptual structure within which research is conducted, constituting a plan for the collection, measurement and analysis of data collected (Kothani, 2004).

Creswell (2009) mentions three types of research designs in his book namely Qualitative, Quantitative and Mixed Method.

3.4 METHODOLOGY APPROACH OF THE STUDY

A mixed method approach was adopted to meet the main objective, since the specific objectives contain both elements of Qualitative and Quantitative analysis. Content analysis approach was used to address the first and second objective. This included a review of literature to identify design criteria in concrete-steel composite bridges and optimization techniques applicable to this study.

The third objective was addressed using experimental design. This included a study of the correlation between varying certain topology parameters and cost of construction for the bridge. Optimization techniques were used to identify a combination of topology variables that produce the most cost-effective design. This was demonstrated by developing an ‘Optimization Software Tool’. The fourth specific objective was addressed by conducting a comparative study where the Design Output from the software tool developed was compared to the Designs Produced by practicing structural engineers.

3.5 DATA COLLECTION

3.5.1 Primary Data Collection

This included acquiring knowledge on C# programming methods & syntax, review of project case studies of multi girder bridge design and construction.

3.5.2 Secondary Data Collection

Secondary data was collected by going through and comprehensively examining various credible literature on structural design of multi-girder composite bridges.

The collection of primary data along with secondary data was done so that the two data sets complimented each other.

3.6 RESEARCH PHILOSOPHY

Grinx (2020) described research philosophy as the orientation that guides the research process and emphasises that philosophical factors that guide research need to be understood to ensure that the product of the research is acceptable. Philosophical factors emanate from the researcher’s general orientation about the world which is usually shaped or influenced by his or her past experiences, area of specialization, and or the beliefs or traditions of those who trained the researcher.

In their book, Management and Business Research, Easterby-Smith et.al. (2015) stated four main reasons why a clear understanding of the philosophical issues is important, namely:

a) First is that the researcher has an obligation to understand the basic issues of epistemology
in order to have a clear sense of her/his reflexive role in research methods. This brings clarity to the theory of knowledge that the researcher will contribute to the body of knowledge.
b) Secondly, it also brings the researcher clarify the research designs. This will aid the researcher to consider what kind of evidence is required and how it should be gathered & interpreted. Clarity on the research design makes the research know how the evidence gathered will provide good answers to the basic questions being investigated in the research.
c) Thirdly, it helps the researcher recognise the designs that will work and those that won’t. It will also help to identify the inherent limitations with each particular approach; and
d) And lastly, it helps the researcher identify and even create designs that may be outside the researcher's experience and also suggest how to adapt research designs according to the constraints of different subject areas.

They further mentioned that a research process, therefore, demands that the following key questions be answered: (Easterby-Smith, et al., 2015)

1) Which methodologies and methods ought to be adopted and utilized?
2) How will the choice of the methodology and its attendant methods be justified?

As discussed in his book, Foundations of Research, Grix (2004) wrote that the justification of the choices of the particular methodology and methods is drawn from the philosophical stance of the researcher which are the assumptions made in the research (Grix, 2004).

This research thus took a subjective ontological approach and had a highly constructivist epistemological approach. The research, therefore, was predominantly qualitative. However, to a lesser extent, quantitative methods were also employed making the overall study a mixed-methods approach with the qualitative approach taking dominance.

This according to Mills et.al, (2009), is described as mixed-method research which is based on a methodological research strategy that includes more than one method of collecting data and or more than one method of analysing the data. The methods may be based on qualitative techniques, quantitative techniques, or a mix of both (Ibid).

3.6.1 Research Methodology

Upon describing what's out there to know and what and how can we know about it, through defining ontology and epistemology, the research dwelt on how it may be done to acquire the required knowledge.

3.6.2 Methods

Establishing how to go about acquiring the required knowledge led to the precise selection of tools and techniques to be employed in this data acquisition.

3.6.3 Sources

This was a roundup of the structure of the research approach for this dissertation and dwelt on where the data was to be collected from.

Primary data collection involved conducting interviews with structural engineers. Secondary data was collected by going through and comprehensively examining various credible literature on the management of construction claims and disputes.

The collection of primary data along with secondary data was done so as not to over-depend on primary data but also serves to validate and complement primary data findings.

3.7 RESEARCH METHODOLOGIES (Strategies of Inquiry)

The research used mainly the following instruments:

a) Content Analysis
b) Optimization Tool Development
c) Experimental Design

3.7.1 Content Analysis

Content Analysis is described by Luo (2019), as a research method used to identify patterns in recorded communication through systematically collecting data from a set of texts, which can be written, oral, or visual. Sources vary from books, newspapers, magazines, recorded speeches, and interviews, web content, social media posts, photographs, and films.

3.7.1.1 Objectives of Content Analysis

The goals of content analysis include, but are not limited to:

- To find correlations and patterns in how concepts are communicated.
- Understanding the intentions of an individual, group, or institution.
- Identifying propaganda and bias in communication.
- Revealing differences in communication in different contexts.
- Analysing the consequences of communication content, such as the flow of information or audience responses

This research focused mainly on bullet one and two, which dwelt on finding the optimization techniques applicable to structural engineering problems specifically in bridge design. This aided in meeting the first objective.

3.7.1.2 Advantages of content analysis

Content analysis has the following advantages

- Easier data collection
- No direct interaction with participants, the researcher's presence doesn't influence the results.
- Transparent and replicable - It follows a systematic procedure that can easily be replicated by other researchers, yielding results with high reliability.
- Highly flexible – can be done at any time, in any location, and at low cost, the researcher just needs to assess the applicable, verifiable sources.

3.7.1.3 Disadvantages of content analysis

Content analysis has the following disadvantages

- Reductive – it tends to present a subject or problem in a simplified form, disregarding context, the degree, and unclear meanings.
- Subjective – It almost always involves some level of subjective interpretation, which can affect the reliability and validity of the results and conclusions.
- Time intensive - Manually coding large volumes of text is extremely time-consuming, and it can be difficult to automate effectively.

The research however exploited the pros of content analysis and approach the method with the cons in mind so as not to fall short of its weaknesses.

3.7.1.4 Conducting the Content analysis

Here are the guidelines followed when conducting a Content Analysis Study.

- Define clear and direct research question(s).

This conformed to the four research questions that had been established for this research.

- Select the content to be analysed

This includes books, published articles, journals, and conference papers that are related to claims and dispute, management. More than twenty (20) sources have been put in place for this purpose.

Parameter for inclusion was published articles and in the case of online sources, the sources were evaluated on how consistent they have been providing articles and constant check of whether the articles remain available at the time of writing of this write-up.

The author also put into consideration, how recent the articles are. Sources in the last 10 years taking precedence, and some, though to a lesser extent, within the last 20years were considered to widen the resource base.

- Define the units and categories of analysis

Similarly, as discussed during multiple case studies, the research predefined units and categories of analysis based on whether the content in question was gathered for an individual, a group, an organization, an event, or a process.

- Code the text according to the rules

A set of rules was to be developed to create a uniform manner of evaluating the content at hand. Since it was coming from different backgrounds need was there, to bring it into a form that comparisons between the data sets were to be achieved. This was achieved by the use of the Google forms platform, which generated pie chats as soon as respondents completed the online questionnaire.

- Analyse the results and draw conclusions.

Aided by the Google forms platform used, the analysis had partially been conducted by the platform and the charts produced were then used to run some conclusions. Collected data was therefore scrutinized to find patterns and deduce conclusions in response to the dissertations' research questions. Correlations and trends were sought as a way of analysis.

Interpretations of what the results meant were discussed.

3.7.2 Optimization Tool Development – COMPOPT

In order to meet the third objective, the researcher needed to develop an optimization software tool (from here now, will be referred to as 'COMPOPT') based on a classical method of optimization known as direct search. COMPOPT was designed in such a way that it utilized an algorithm based on direct search method to design selected structural element of a composite bridge. The output structural design from this tool was then compared to the designs that would typically be produced by a practicing structural engineer.

A number of factors had to be considered when undertaking this task. The following steps were taken when developing the optimization program.

1. First the author drew out an algorithm that the program was to follow.
2. Secondly, the author had to choose which programming language the 'optimization program' had to written in.
3. Using the appropriate syntax, the author wrote code for each block on instructions following the order of the algorithm developed in step one (1).
4. The program was compiled and packaged. The errors noticed were corrected until the program ran smoothly.

3.7.2.1 Optimization Algorithm for a Steel Composite Bridge

An algorithm, as defined by Skiena (2020) is a procedural sequence of steps laid out to perform a specific function. An optimization algorithm therefore is a sequence of steps that outlines a procedure which when followed, seeks to find the optimal solution according to the objective function. (Skiena, 2020)

The general optimization algorithm generally takes the form:

$$\text{Objective function: } C = f(x_1, x_2, \dots \dots, x_n) \qquad \text{.... } \textit{Equation 3.1}$$

$$\text{Constraint function:} g_j(x_1, x_2, \dots \dots, x_n) \leq 0, j = 1, \dots, m \; where \; x_i \; are \; the \; variables \qquad \text{.... } \textit{Equation 3.2}$$

In this research, the authors goal was to make a computer program that uses an optimization technique in the design process for structural design of bridges. The logic steps that the program followed are outlined in figure 3.1.

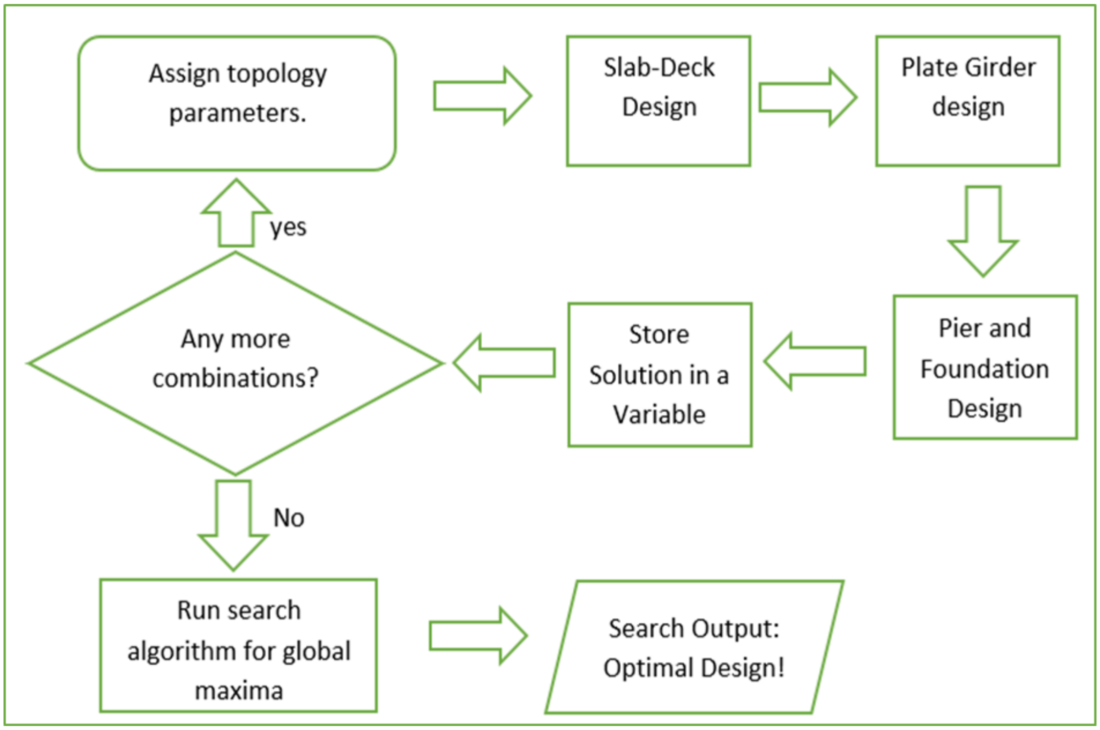


Figure 3.1. Logic Steps

The logic steps in figure 3.1 were implemented in a computer program. The algorithm is design in a loop. With each loop, a solution is stored and after all possible designs (combinations) have been exhausted, the program runs an optimization function through the data set of all feasible designs and finds the most economical design. The objective function in this program, sought the design that had the least weight.

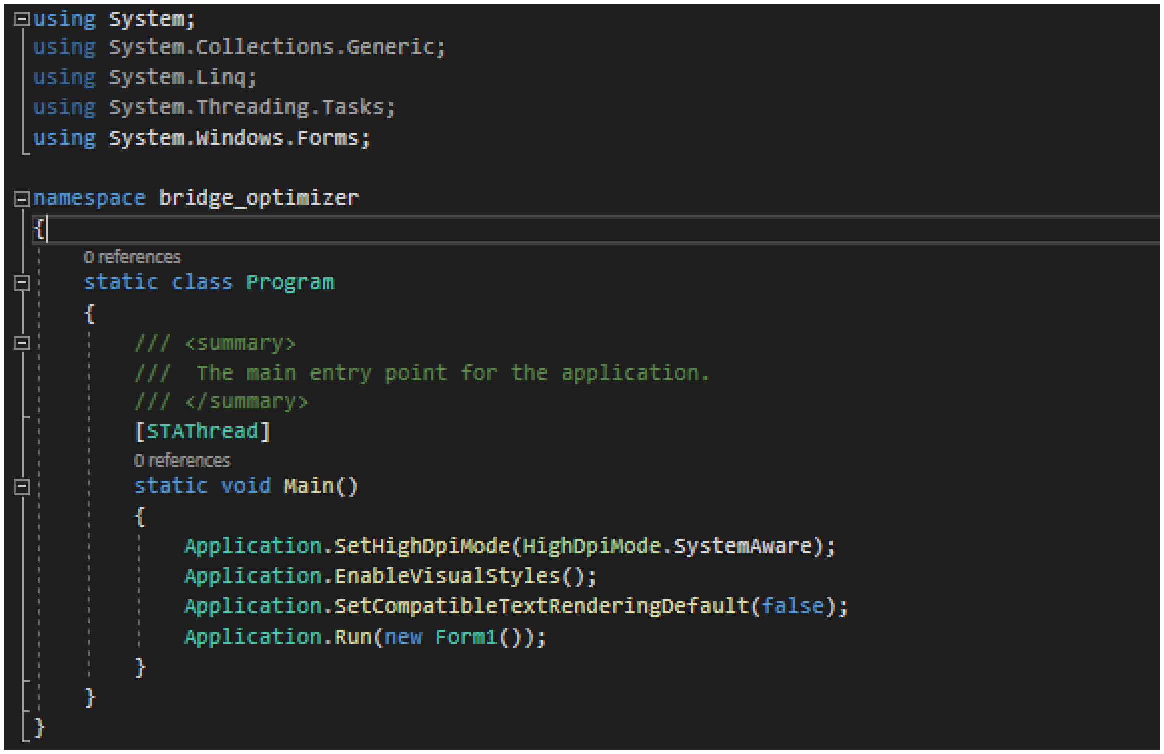
Least weight criteria was used because of it direct correlation to economy of the design. The relationship is presented as follows:

$$\text{Weight of bridge design (accumulative weight of individual elements)} \quad \alpha \quad \text{Cost of Design}$$………*Equation 3.3*

COMPOPT has 7 forms in total. Six of these forms have been devoted to prompting the user to enter certain bridge parameters required for the program to execute the functions. The description of each step is as follows:

Step 1: Start

The ‘Static Void Main ()’ functions initiates the program as shown in figure 3.2.



```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace bridge_optimizer
{
    0 references
    static class Program
    {
        /// <summary>
        ///  The main entry point for the application.
        /// </summary>
        [STAThread]
        0 references
        static void Main()
        {
            Application.SetHighDpiMode(HighDpiMode.SystemAware);
            Application.EnableVisualStyles();
            Application.SetCompatibleTextRenderingDefault(false);
            Application.Run(new Form1());
        }
    }
}
```

Figure 3.2: Program.cs_Program Initializer

Step 2: Assignment of Parameters

Six (6) forms have been dedicated to prompt the ‘User’ to enter the topology, material and cross-sectional parameters required for structural design calculations. Topology variables are variables that define the special layout of solid structure. Material parameters define material properties for use in the program (Kazakis, et al., 2017),

The topology parameters of a composite bridge would include:

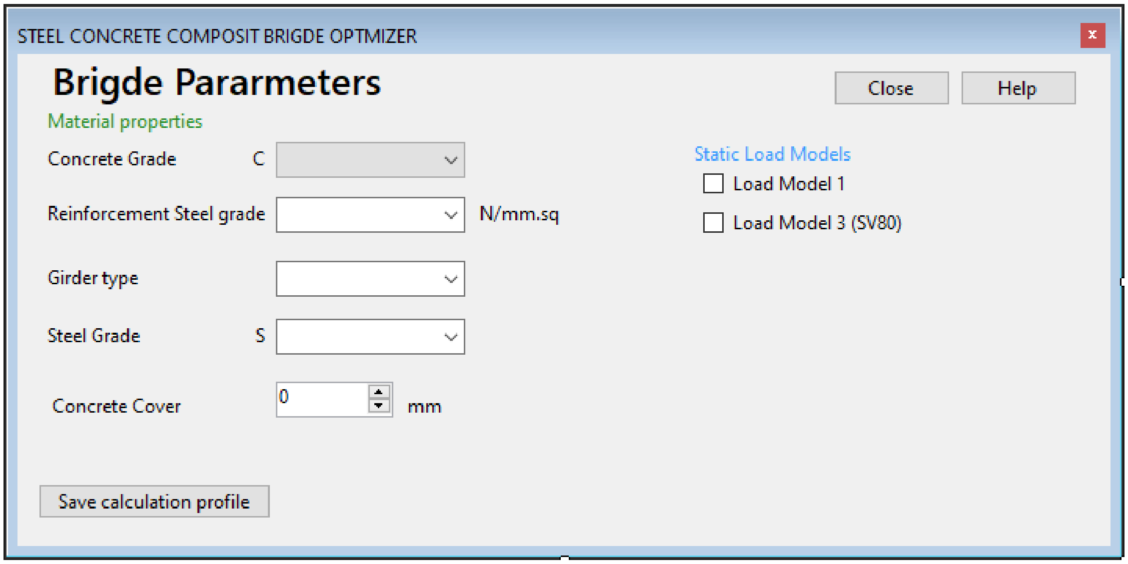
- Distance between Piers,
- Carriage way width,
- Positioning and orientation of girders,

- Thickness of the decking and
- Head clearance.

Examples of material properties include:

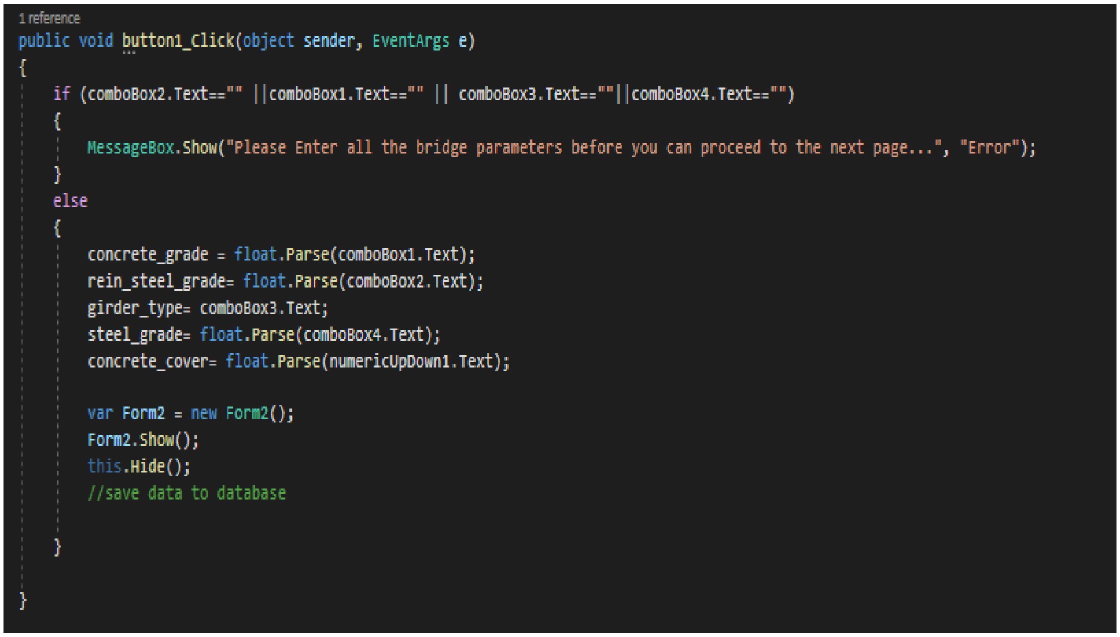
- Concrete strength class (C15, C20, C25, C30 and so on),
- Steel grade
- Reinforcement grade

Implementing the instruction in C# required both Back-End and Front-End programming. Front end constituted ‘user interface’ graphics design and arrangement of items on the forms. Back end programming constituted coding the ‘engine’ running calculations logics steps as shown in figures 3.2 and 3.3.



Concrete Cover 0 mm

Figure 3.3: Form 1 showing Front End programming (User Interface Design)



```
1 reference
public void button1_Click(object sender, EventArgs e)
{
    if (comboBox2.Text=="" ||comboBox1.Text=="" || comboBox3.Text==""||comboBox4.Text=="")
    {
        MessageBox.Show("Please Enter all the bridge parameters before you can proceed to the next page...", "Error");
    }
    else
    {
        concrete_grade = float.Parse(comboBox1.Text);
        rein_steel_grade= float.Parse(comboBox2.Text);
        girder_type= comboBox3.Text;
        steel_grade= float.Parse(comboBox4.Text);
        concrete_cover= float.Parse(numericUpDown1.Text);

        var Form2 = new Form2();
        Form2.Show();
        this.Hide();
        //save data to database

    }

}
```

Figure 3.4: Illustration of Back end programming (Event handler for the ‘Next Button’)

Figure 3.4 shows a snippet of the back-end programming for Form 1. Back-end programming consist of blocks of code (instructions) that define the functionality of the GUI (graphic user interface).

Step 3: Slab Decking Design

Slab decking design comes after the topology parameters are assigned by the user. Both live loads and dead loads are considered in this step. The bridge decking is the structural component that receives the live loading first. Therefore, logic entails that it be design first.

Live load models outlined in the Eurocode are considered and the slab deck is designed using unit strip method accounting for the dead loading as well.

Design of the slab decking serves as a constraint function in the optimization general function. The following check had to be satisfied for a design the program could to the next step.

1. Check for the cover

The program checked if the entered value for the cover was greater or equal to the cover derived from provisions given in BS EN 1992-1-1:2004 Equation 3.4 (British Standards Institute, 2004)

$$C_{nom} = C_{min} + \Delta C_{dev} \; \ldots.Equation\ 3.4$$

where values for $C_{min,dur}$ were taken obtained from BS 8500-1 (British Standard Institute, 2006).

2. Actions on the Bridge Decking

Permanent actions considered in the design include:

- Reinforced concrete slab with unit weight of 25kN/m^3
- Surfacing with a unit weight of 24kN/m^3

Variable action considered in the include

- Traffic Load Model 1 following the provisions shown in BS EN 1991-2 2003 (British Standards Institute, 2003).

3. Flexural Design Checks

The program also checked if the slab deck section had adequate moment by use of Equation 3.5.

$$M_c \geq M_{ult} \; \ldots.Equation\ 3.5$$

where M_c is the flexural strength of the section and M_{ult} is the ultimate moment imposed in the slab decking.

4. Shear Checks

Similarly, the program checked for shear capacity of the section by use of Equation 3.6.

$$V_c \geq v \;\; \ldots.Equation\ 3.6$$

where V_c is the shear capacity of the section and v is the applied shear force.

5. Deflection checks

   The program lastly, checked if the maximum deflection was less than the permissible deflection.

Step 4: Plate Girder/Universal Beam Design

The structural design of the steel girders came after the ‘slab decking design’ step. This is because the girders receive the loads from the slab decking and are obviously the next structural element in the load path.

Standard sections were used instead of plate girders to limit the scope and to increase variations in options. The methodology approach assumed that the beams are fully retrained due to the shear studs in composite bridges. The following checks were made in each iteration:

1. Resistance of cross section to bending ULS

The program made the following check:

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0 \;\; \ldots.Equation\ 3.7$$

where M_{Ed} is the design value of the bending moment and M_{cRd} is the design resistance for bending about one principal axis which takes different forms depending on the classification of the section.

2. Resistance to shear forces and buckling ULS

Equation 3.8 below checked for section resistance to shear loading.

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0 \; \ldots.Equation\ 3.8$$

where V_{Ed} is the design shear force imposed on the member and $V_{c,Rd}$ is taken as the design shear resistance of the section.

The shear buckling check utilized Equation 3.9. (clause 5.1, EC 3-5)

$$\frac{h_w}{t_w} > 72\frac{\varepsilon}{\eta} \; \ldots.Equation\ 3.9$$

3. Resistance to flange induced buckling ULS

For flange induced buckling check, Eurocode 3-5 requires that the ratio h_w/t_s should satisfy Equation 3.10:

$$\frac{h_w}{t_w} > k\frac{E}{f_{yf}}\sqrt{\frac{A_w}{A_{fc}}} \; \ldots\ldots.Equation\ 3.10$$

where A_w is the area of the web, A_{fc} is the area of the compression flange, and f_{yf} is the yield strength of the compression flange.

4. Resistance of the web to transverse forces ULS

Design resistance of webs of standards sections was checked according to Clause 6 of Euro Code 3-5. Equation 3.11 is the expression for local buckling.

$$F_{Rd} = \frac{f_{yw} L_{eff} t_w}{\gamma_{M1}} \quad \ldots . Equation\ 3.11$$

where F_{Rd} is the design resistance of webs to local buckling, t_w is the thickness of the web, γ_{M1} is the partial safety factor = 1.0 and L_{eff} is the effective length of the web.

5. Defection SLS

Permissible deflection was as per Equation 3.12.

$$Permissible\ deflection \leq \frac{Span}{360} \quad \ldots . Equation\ 3.12$$

Step 5: Pier and Foundation Design

Girders in composite bridges are supported by Piers and abutments. The fourth logic step involves design of these structures.

Step 6: Storage of Solution in variable

In the context of research, the solution consists of: bridge decking design, Girder design, Pier design and foundation design. This logic steps involves storage of this solution onto a declared variable.

Step 7: 'Do While Loop' condition statement

This step in the folk in the algorithm where the program is made to repeat previous set of steps if a set condition has not been met or end the iteration if the said condition has been met. The condition in this case is used to gather all solutions available per given topology parameters and store them in an array.

Step 8: Run a Search for Global Maxima/Minimum

This step is executed after the set of solutions have been stored in the array. This step involves running a search for a solution that has least accumulative mass or cost. This research assumed that accumulative mass is directly proportional to cost.

Step 9 Present Optimal Solution and Structural Detail

This step presents the solution that is deemed Optimal. The optimal solution is presented in form of a structural detail.

Step 10: End

The program is terminated on this step.

3.7.3 Experimental Design

Djuris et al defined experimental design is a concept used to organize, conduct and interpret results of experiments in an efficient way, making sure that as much useful information as possible is obtained by performing a small number of trials (Djuris, et al., 2013).

This study intended to use an experimental design to compare the results that the software produced to the results obtained from practicing structural engineers in Zambia. It was hypothesised that the results from the software will produced more optimized bridge designs than the conventional methods of design of Composite Bridges.

3.7.3.1 Dependent and Independent Variables

Independent variables in an experimental design approach are those variables that the researcher studies to have a possible effect on one or more variables of interest. In contrast, dependant variables are those that are potentially influenced by another variable (Leedy & Ormrod, 2016).

Table 3.1 tabulates the classes of independent and dependent variables used by the author in the experimental design. The hypothesized relationship is as follows:

Independent Variables ⟶ Dependent Variables

Table 3.1: Class of Variables used in this research

Independent Variables		Dependent Variables
Method of approach used when designing the Composite Bridge. That is: Classical approach used by practicing structural engineers, or Use of an Optimization Tool	→	Bridge topology variables that define the spatial arrangement of the bridge such as: Thickness of slab decking Size of piers Discrete variables such as size of girders. Weight of the designed bridge that will also affect the geotechnical design

3.7.3.2 Control of Confounding Variables

In order to maximize internal reliability of the established cause and effect relationship between the two variables been investigated in this study, the author had to employ the following strategies to control the influence of confounding variables:

1. Keeping input parameters and standard codes of practice constant. For instance, the standard code of practice used was limited to the Eurocode. The software tool was programmed using standards stipulated in the Eurocode. The question given to the test participants was also the same to keep the input parameters constant.
2. Randomization: The test subjects used were picked at random and from variety of sectors within the structural engineering practice.
3. All participants were exposed to the same conditions and given the same amount of time.

3.7.3.3 Static Group Comparison ('Design 3'')

In their book titled 'Practical Research', Leedy and Ormorod described a variety of research designs that have emerged out of Experimental Design methods. These designs differ in the extent to which the researcher manipulates the independent variable and controls for confounding variables. They presented a number of designs which were generally categorised into: *pre-experimental designs, true experimental designs, quasi-experimental designs, ex post facto designs,* and *factorial designs* (Leedy & Ormrod, 2016)

The design that was appropriate for this research is classified under ‘pre-experimental design’, known as ‘Static Group Comparison’. It was the third design on the list. The static group comparison design involves both the experimental group and the control. Its design can be represented in the form shown in table 3.2 (Leedy & Ormrod, 2016).

Table 3.2: Representation of Activities that happen in a ‘Static Group Comparison Design’

GROUP	TIME ⟶	
Control Group. (Practicing Structural Engineers)	Activity: Use of Conventional structural design approach	Observation of resulting design
Experimental Group. (Optimization Software Tool)	Activity: Use of the Optimization Tool in the structural design	Observation of resulting design

In this static group comparison design, the practicing engineers (the control group) were allowed conduct the structural design using the approach they normally use then the results were observed. The experimental group in this design consisted of the author using the optimization tool to compare the software’s output to the practicing engineers’ output. The resulting designs were then compared across the following parameters:

1. Weight of concrete for the decking,
2. Area of tension reinforcement per unit width,
3. Total weight of girders required, and
4. Number of piers required.

The advantage of this design is that is reliable to draw conclusions from the findings. If the optimization tool influences the designs procedure in a positive manner as hypothesised, then the findings on the experimental trial will show.

3.7.4 Experimental Design Example

In order to test the Output Solution obtained from the Software, a comparative study was done. COMPOPT solution were compared with a typical design that would be obtained using the conventional method. Design Solutions obtained using the conventional method, five (5) practicing structural engineers were asked to design a Composite bridge, given the same conditions. Their results were then compared to the output from the software, for the design problem described below.

Design Problem: Design a simply supported Concrete-steel composite bridge. The deck carries a 100mm thick surfacing, together with traffic load (LM1) udl with 5.5 kN/m^2 and tandem axle load of 100 kN (300 kN/3m lane width). You may use any number of Piers you deem necessary for the crossing and also any number girders supporting the slab decking, for the design problem described below.

Design Problem: Design a simply supported Concrete-steel composite bridge. The deck carries a 100mm thick surfacing, together with traffic load (LM1) udl with 5.5 kN/m^2 and tandem axle load of 100 kN (300 kN/3m lane width). You may use any number of Piers you deem necessary for the crossing and also any number girders supporting the slab decking, given the following parameters for the crossing:

- Crossing span: 20m
- Carriage way width: 10m
- Use Universal Beams as Girders

For the purposes of comparison, the engineer’s solutions were then summarised and presented in table. The comparison was based on the following:

- Weight of concrete for the decking,
- Area of tension reinforcement per unit width,
- Total weight of girders required, and
- Number of piers required

3.8 SCOPE OF STUDY

The scope study is limited to the application of optimization to the design of composite multi girder bridges. It doesn’t cover other types of bridges even though this would be good use. In proceeding studies, inclusion of other types of bridges into the software application would make it more useful.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 INTRODUCTION

Chapter 3 described the methodology used to address the specific objectives and methods used in this research. It gave a clear outline of what this research was pursuing, methods used to gather data and tools and techniques to analyse data. This chapter presents the analysis and discussion of the findings obtained from data gathered. It therefore provide a basis from which conclusion and recommendations can be made.

From the content analysis made, an optimization algorithm was developed, from which the programming of the tool was based. Then using methods outlined in Experimental Design, the Output from the Software Tool Developed was compared to the results obtained from practicing structural engineers.

4.2 OPTIMIZATION ALGORITHM

From the knowledge acquired through content analysis, the following logic steps were considered to give the most logical path that the program must follow to reach a desired solution. The desired solution in this context is the combination of Slab-Decking Design, Selected Plate Girder/Universal Beam and, Pier and Pad Foundation Design. This includes eight steps.

Step 1: Start

This step starts the program. The ‘Static Void Main ()’ functions initiates the program.

Step 2: Assignment of Topological Parameters

As defined in in the first Chapter, Topology Parameters are variables that define the special layout of solid structure. (Kazakis, et al., 2017) In this case, the topology parameters of a composite bridge would include: Distance between Piers, Carriage way width, Positioning and orientation of girders, thickness of the decking and head clearance.

Therefore, the first step in the algorithm is to assign topology parameters. In the programming, this step involves prompting the user to input variables that define the specific layout of the bridge such as the crossing span, carriage-way width and head clearance required.

Step 3: Slab Decking Design

This step comes after the topology parameters are assigned. Both live and dead loading are considered in this step. The bridge decking is the structural component that receives the live loading first. Therefore, logic entails that it be design first.

Live load models outlined in the Eurocode are considered and the slab deck is designed using unit strip method accounting for the dead loading as well.

Step 4: Plate Girder/Universal Beam Design

In composite bridges, the decking is supported by structural steel beams which could either be plate girders or universal beam. Design of the girders is the third action block

Step 5: Pier and Foundation Design

Girders in composite bridges are supported by Piers and abutments. The fourth logic step involves design of these structures.

Step 6: Storage of Solution in variable

In the context of research, the solution consists of: bridge decking design, Girder design, Pier design and foundation design. This logic steps involves storage of this solution onto a declared variable.

Step 7: 'Do While Loop' condition statement

This step in the folk in the algorithm where the program is made to repeat previous set of steps if a set condition has not been met or end the iteration if the said condition has been met. The condition in this case is used to gather all solutions available per given topology parameters and store them in an array.

Step 8: Run a Search for Global Maxima/Minimum

This step is executed after the set of solutions have been stored in the array. This step involves running a search for a solution that has least accumulative mass or cost. This research assumed that accumulative mass is directly proportional to cost.

Step 9 Present Optimal Solution and Structural Detail

This step presents the solution that is deemed Optimal. The optimal solution is presented in form of a structural detail.

Figure 4.1 is a flow chart showing the logic steps in the optimization tool.

Step 10: End

The program is terminated on this step.

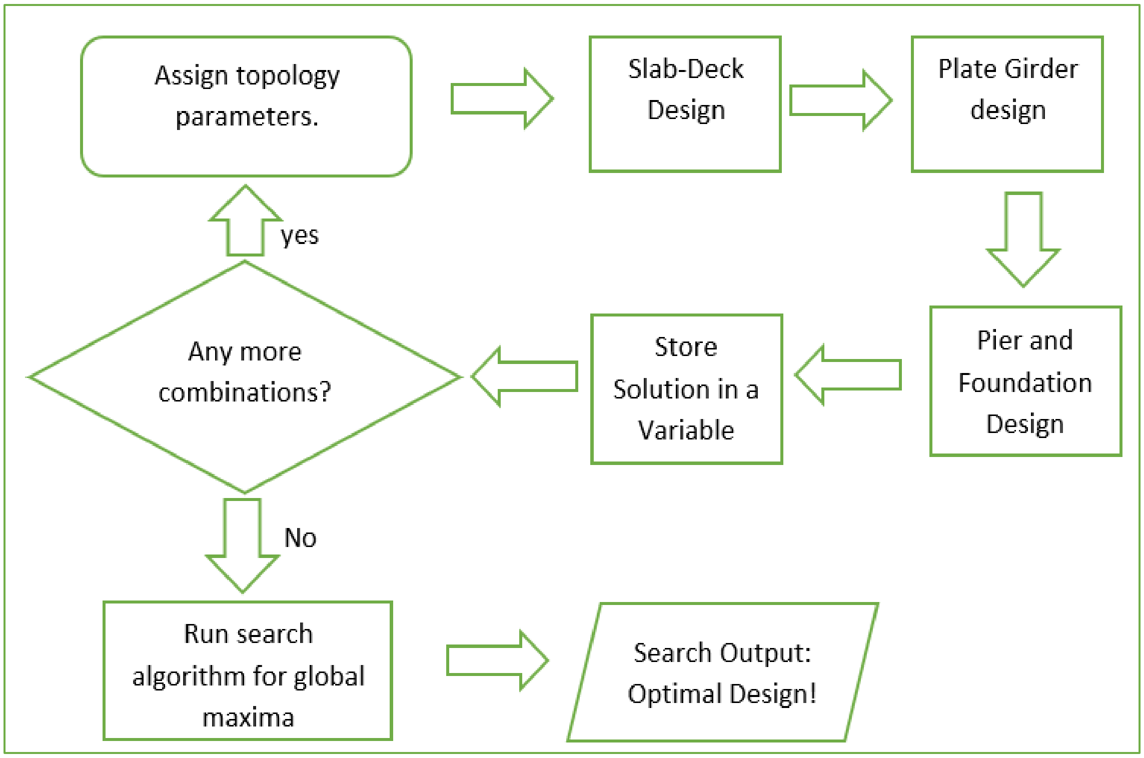


Figure 4.1: Sequential Logic Steps

4.3 EXPERIMENTAL DESIGN: DEVELOPMENT OF AN OPTIMIZATION TOOL USING C#

This section outlines briefly the process of the software development and the output of the application processes.

For interface and application coding, C# was used as the programming language. The interface was required to perform the following functions

- Prompt the user to enter the material properties of concrete and structural steel

- Prompt the user to enter the constraints on the bridge topology. These include: The required width of the bridge (Carriage way), bridge span (crossing length) and to impose limitations on where the piers can be placed.

- Allow the user to input the hydrological and geotechnical data of the crossing.

From the user data input, the program executed the following functions blocks:

1) Initial assignment of Topology parameters such as: Girder to girder spacing, Number of longitudinal and cross girders and pier to pier spacing.
2) Slab deck design using unit strip method.
3) Plate girder design
4) Pier and foundation design.
5) Store solution (feasible design) in a variable.

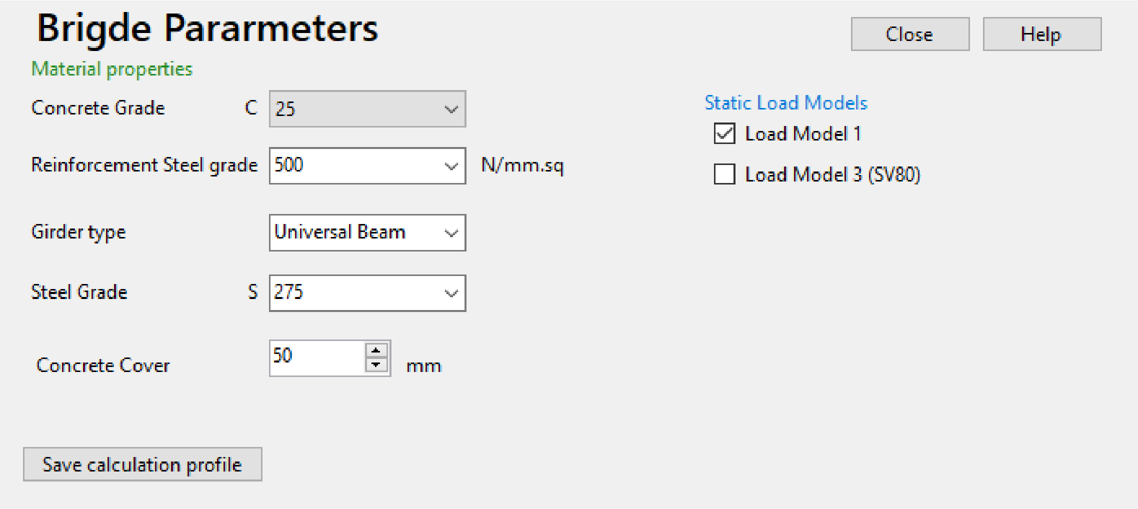
The iterations are repeated until all possible topology arrangements have been exhausted. Forms 1 to 8 indicate data capture and output.

4.3.1 Form 1: Bridge Parameters

This is the first form that was built on to prompt the user to input material properties for both the steel and concrete that would later be used in the design calculations. On this form, the user is prompted to choose which static load models are to use in the calculations. As shown in figure 4.2, the application prompts the user to enter the following properties:

1. Concrete Grade: The application gives the user the following concrete grades to choose from: C20, C25, C30 and C35. In this example given, C25 was used.
2. Reinforcement steel grade: The reinforcement grades presented here include: 250 N/mm^2, 450 N/mm^2 and 500N/mm^2. 500N/mm^2 was chosen for the example as per Code …
3. Girder Type: An option is presented to either use the standard Universal beam sections or the plate girder type. The universal section was selected for the example given.
4. Steel grade: Structural steel grades presented here S275, S355 and S450. S275 was selected, as per Code ….

5. Concrete Cover: The user is allowed to enter the cover in millimetres. 50mm was entered for illustration as shown in figure 4.2



Brigde Pararmeters

Material properties

Concrete Grade C 25

Reinforcement Steel grade 500 N/mm.sq

Girder type Universal Beam

Steel Grade S 275

Concrete Cover 50 mm

Static Load Models

☑ Load Model 1

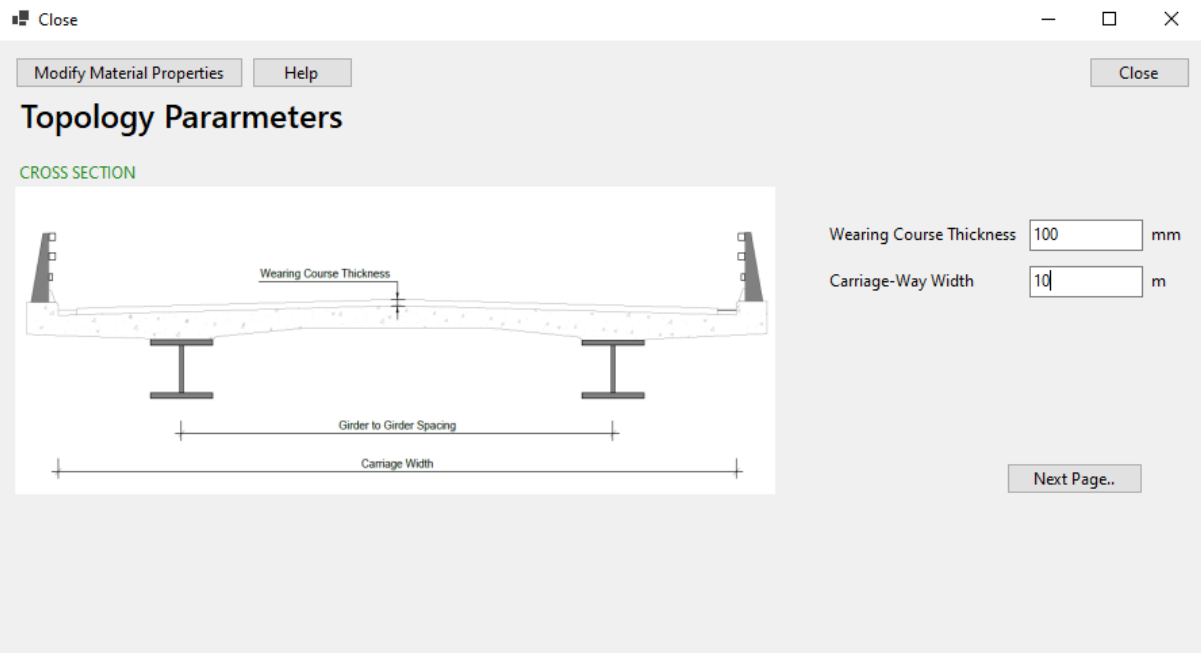
☐ Load Model 3 (SV80)

Figure 4.2: Form 1 – Bridge Parameters

4.3.2 Form II: Topology Parameters - Cross Section

The ‘save calculation’ button in Form I directs the user to Form II. The second form allows the user to input constant topological parameters that define the cross section. These include wearing course thickness and the carriage way width. Other parameters such as ‘slab deck thickness’ and ‘reinforcement’ was determined by the program.

In example considered, wearing course thickness was taken as 100mm and carriage way thickness was 10m as shown in figure 4.3.



Topology Pararmeters

Wearing Course Thickness 100 mm

Carriage-Way Width 10 m

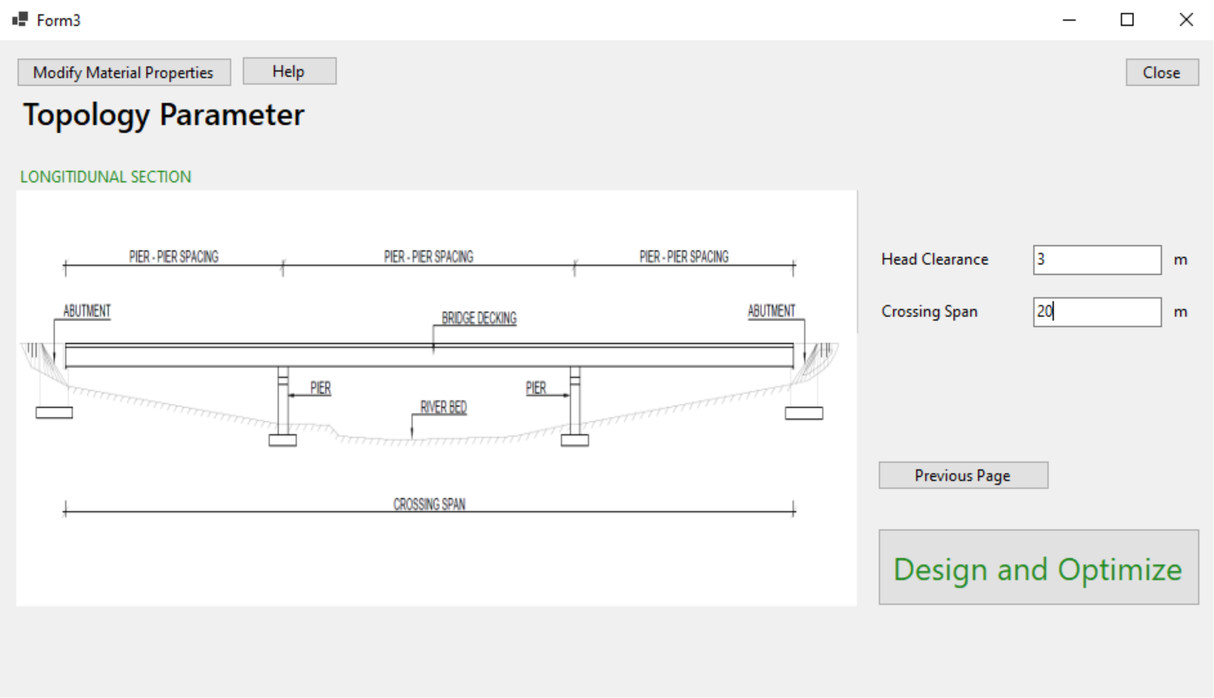
Figure 4.3. Form II- Cross Section Parameters

4.3.3 Form III: Topology Parameter – Longitudinal Section

The ‘Next Page’ Button’ on form two directs the user to Form III. This form allows the user to input Longitudinal section parameters. These include:

- Head Clearance and,
- Crossing span.

In the example considered, head clearance was 3m and crossing span was 20m as shown in figure 4.4. Other parameters such as pier positioning was computed by the program.


Form3

Topology Parameter

LONGITIDUNAL SECTION

Head Clearance 3 m

Crossing Span 20 m

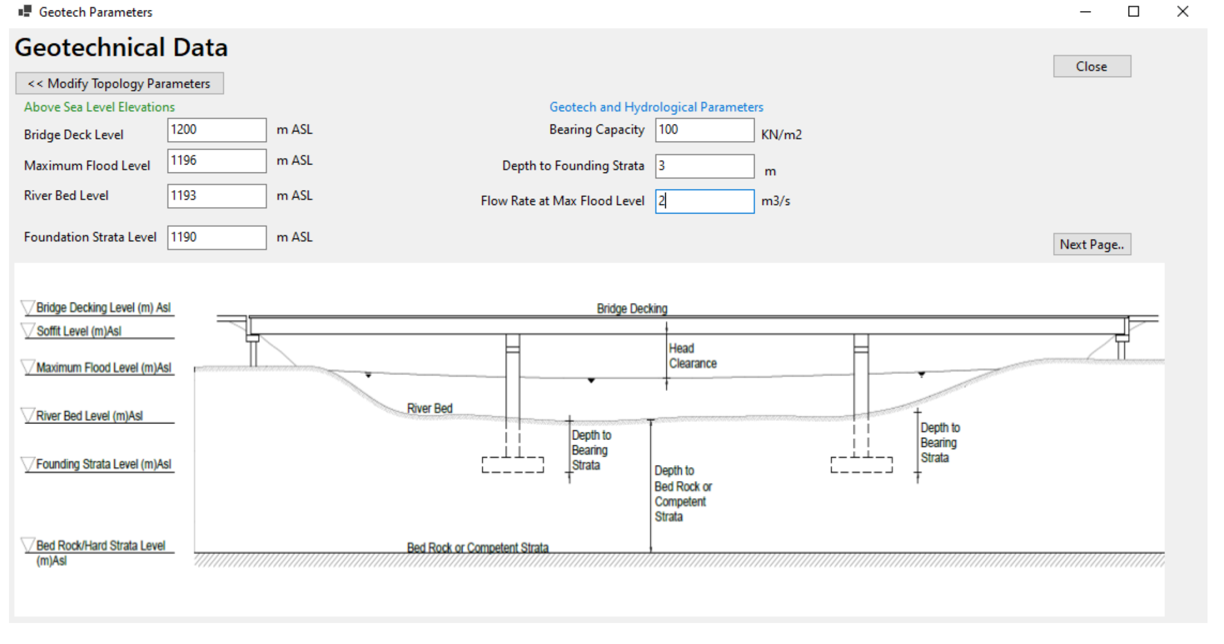
Figure 4.4. Form III –Longitudinal Section

4.3.4 Form IV: Geotechnical Data

The ‘Next Page’ Button’ on form three directs the user to Form IV. This form allows the user to input geotechnical data, levels of pertinent elements and hydraulics of the river. This data enables the program to determine the suitable depth to competent founding soils and sizing of the footing and piers. These parameters include:

- Depth to founding strata (Competent soil)
- Bearing capacity of founding strata
- Flow rate of the river peak floods
- Bridge deck level
- Maximum Flood level
- River Bed level
- Founding strata level

In the example considered, each parameter was assigned a value as shown in figure 4.5.



Geotechnical Data

Above Sea Level Elevations

Bridge Deck Level: 1200 m ASL
Maximum Flood Level: 1196 m ASL
River Bed Level: 1193 m ASL
Foundation Strata Level: 1190 m ASL

Geotech and Hydrological Parameters

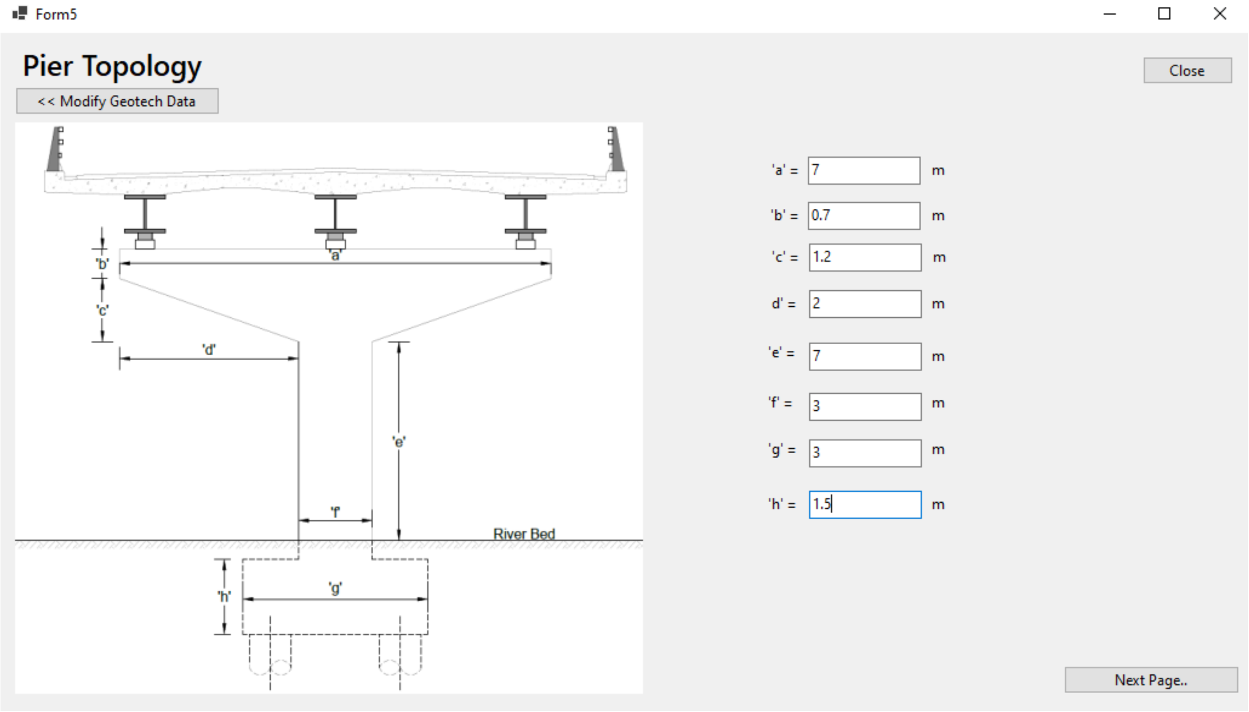
Bearing Capacity: 100 KN/m2
Depth to Founding Strata: 3 m
Flow Rate at Max Flood Level: 2 m3/s

Figure 4.5. Form IV – Geotechnical Data

4.3.5 Form V: Pier Topology

The ‘Next Page’ Button’ on form four directs the user to Form V. This form allows the user to input default dimensions of the pier. The program checks if these dimensions are reasonable considering the superstructure dimensions. For instance, the ‘Pier Head Width’ should be long enough to accommodate girders holding the decking.

In the example considered, each parameter was assigned a value as shown in figure 4.6.



'a' = 7 m
'b' = 0.7 m
'c' = 1.2 m
d' = 2 m
'e' = 7 m
'f' = 3 m
'g' = 3 m
'h' = 1.5 m

Figure 4.6. Form V Pier Topology

4.3.6 Form VI: SOLUTION_ Structural Detail of the Pier, Footing and Decking

The ‘Design and Optimize’ Button on Form V initiates the computation process. The program computes all feasible bridge designs and select the *optimal design* based on weight. The solution (*optimal design)* is then presented in forms VI and VII. Form VI presents the structural detail of the Pier and the pad footing.

The solution to the example is presented in figure 4.7 and Figure 4.8.

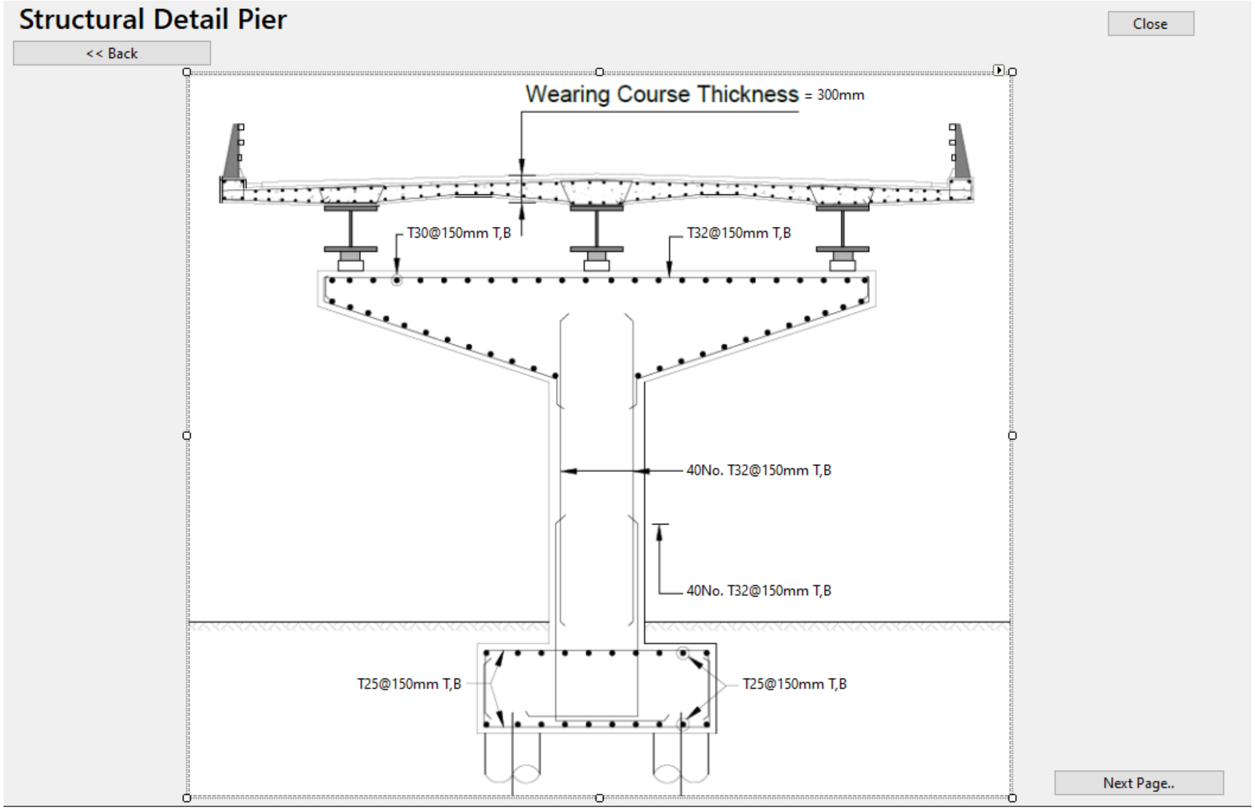


Figure 4.7. Form VI- Structural Detail of Pier and Footing

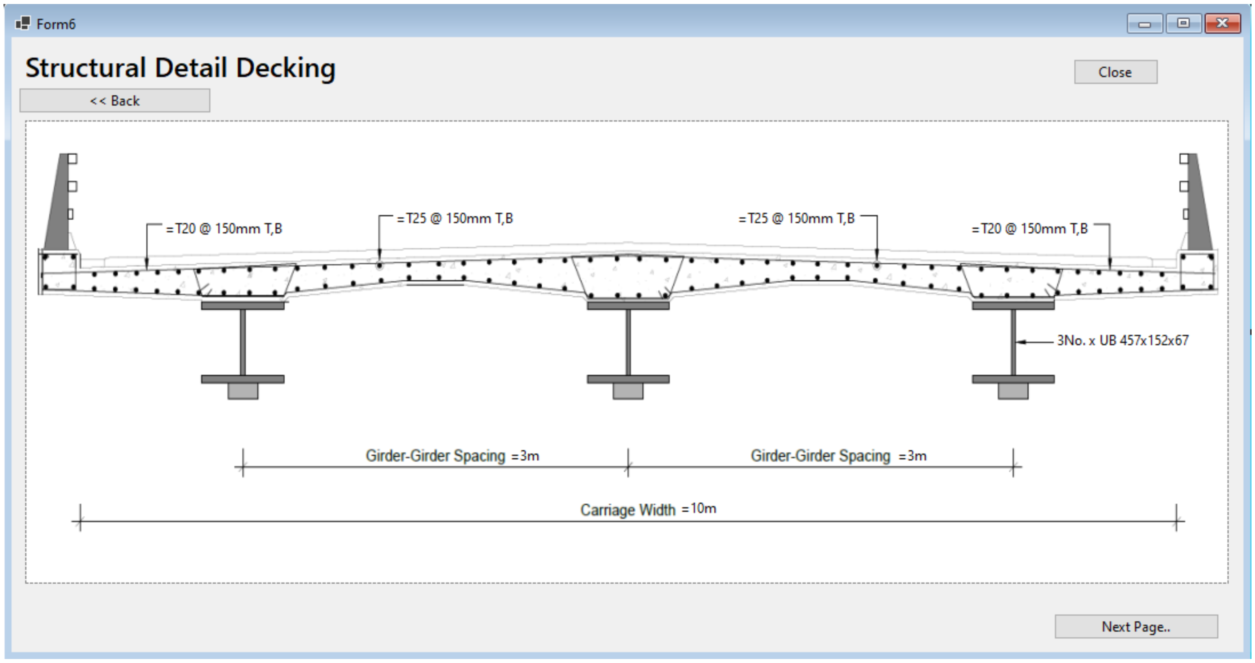


Figure 4.8. Form VII – Cross Section Structural Detail of Decking

4.3.7 Experimental Design Example

In order to test the Output Solution obtained from the Software, a comparative study was done. This was to compare the Design Solution from the software and a typical design that would be obtained using the conventional method. In order to get a good representation, the Design Solution obtained using the conventional method, five (5) practicing structural engineers were asked to design a Composite bridge, given the same conditions. Their results were then compared to the output from the software, given the design problem with same conditions described below.

Problem: Design a simply supported Concrete-steel composite bridge. The deck carries a 100mm depth of surfacing, together traffic load (LM1) udl with 5.5 kN/m^2 and tandem axle load of 100 kN (300 kN/3m lane width). You are free to use any number of Piers you deem necessary for the crossing and also any number girders supporting the slab decking. The parameters for the crossing and beam type are as follows;

- Crossing span: 20m
- Carriage way width: 10m
- Use Universal Beams as Girders

4.4 DESIGN OUTPUT RESULTS

This section presents the results obtained from the survey on design conducted. As stated in the methodology, a comparative study was required to compare the software output (COMPOPT) to the solutions that practicing structural engineers would come up given the same design problem. The survey was included giving practicing engineers a bridge design problem and compiling their results.

Five structural engineers were selected for the study using purposive selection techniques and were all given the same design problem. For the purposes of comparison, each engineer's solution was condensed into a table for a given bridge. Selected key parameters were tabulated in Tables 4.1 to 4.5. This was done to compare the following:

a) Weight of concrete for the decking,
b) Area of tension reinforcement per unit width,

c) Total weight of girders required, and

d) Number of piers required.

4.4.1 Design Output from COMPOPT

The results from COMPOPT were summarised in Table 4.1.

Table 4.1. Summary of Design Solution from COMPOPT

Parameters	**Results**
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	5m c/c
Main Girder-Girder Spacing	2.5m
Slab Decking	
Slab thickness	233.57mm
Tension Main Reinforcement	T32@250mm
Tension Reinforcement Area	3220mm^2/m run
Girder System	
Main Girder Section	4No. 356x171x67UB
Main Girder Spacing	2.5m
Piers	
Pier-Pier Spacing	3No. Pier @ 5m

From the above results, calculations were made to determine the following:

1) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete$$
$$= 24(Crossing\ Span\ \times\ Carriage\ way\ width\ \times slab\ thickness)$$

$$Weight\ of\ Concrete = 24KN/m^3\ \times\ 20m\ \times 10m\ \times 0.25m$$

$$Weight\ of\ Concrete = \mathbf{1200\ kN}$$

2) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{3220mm^2/m\ run}$$

3) Total weight of girders required

-Girder Selected: 4No. 356x171x67UB

-Unit weight: 67.1kg/m

$$Total\ weight\ of of\ girders = Unit\ weight\ \times crossing\ span\ \times No. \times 10m/s^2$$

$$Total\ weight\ of of\ girders = 67.1Kg/m\ \times 20m\ \times 4No. \times 10m/s^2$$

$$Total\ weight\ of of\ girders = \mathbf{53.68\ kN}$$

4) Numbers of Piers

$$Number\ of\ Piers = \mathbf{3No.}$$

4.4.2 Structural Engineer ’A’

Table 4.2 summarise the results from Engineer 'A’

Table 4. 2. Summary of Results from Engineer ‘A’

Parameters	Results
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	10m c/c
Main Girder-Girder Spacing	2.8m
Slab Decking	
Slab thickness	400mm

Tension Main Reinforcement	T32@175mm
Tension Reinforcement Area	4600mm^2/m run
Girder System	
Main Girder Section	4No. 533x210x109UB
Main Girder Spacing	2.5m
Piers	
Pier-Pier Spacing	1No. Pier @ 10m

From these results, calculations were made as follows:

5) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete = 24(Crossing\ Span\ \times\ Carriage\ way\ width\ \times slab\ thickness)$$

$$Weight\ of\ Concrete = 24KN/m^3\ \times\ 20m\ \times 10m\ \times 0.4m$$

$$Weight\ of\ Concrete = \mathbf{1920\ kN}$$

6) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{4600mm^2/m\ run}$$

7) Total weight of girders required

-Girder Selected: 4No. 533x210x109UB

-Unit weight: 109Kg/m

$$Total\ weight\ of of\ girders = Unit\ weight\ \times crossing\ span\ \times No.\times 10m/s^2$$

$$Total\ weight\ of of\ girders = 109Kg/m\ \times 20m\ \times 4No.\times 10m/s^2$$

$$Total\ weight\ of of\ girders = \mathbf{87.2KN}$$

8) Numbers of Piers

$$Number\ of\ Piers = \mathbf{1No.}$$

4.4.3 Structural Engineer ’B’

Table 4.3 summarises the results from Engineer 'B’

Table 4.3. Summary of Results from Engineer ‘B’

Parameters	Results
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	6m c/c
Main Girder-Girder Spacing	2.5m
Slab Decking	
Slab thickness	300mm
Tension Main Reinforcement	T25@125mm
Tension Reinforcement Area	3930mm^2/m run
Girder System	
Main Girder Section	5No. 406x178x74UB
Main Girder Spacing	2.5m
Piers	
Pier-Pier Spacing	2No. Pier @ 6m

From these results, calculations were made as follows:

1) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete = 24(Crossing\ Span \times Carriage\ way\ width \times slab\ thickness)$$

$$Weight\ of\ Concrete = 24KN/m^3 \times 20m \times 10m \times 0.3m$$

$$Weight\ of\ Concrete = \mathbf{1440\ kN}$$

2) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{3930mm^2/m\ run}$$

3) Total weight of girders required

-Girder Selected: 5No. 406x178x74UB

-Unit weight: 74.2Kg/m

$$Total\ weight\ of of\ girders = Unit\ weight\ \times crossing\ span\ \times No. \times 10m/s^2$$

$$Total\ weight\ of of\ girders = 74.2Kg/m\ \times 20m\ \times 5No. \times 10m/s^2$$

$$Total\ weight\ of of\ girders = \mathbf{74.2\ kN}$$

4) Numbers of Piers

$$Number\ of\ Piers = \mathbf{2No.}$$

4.4.4 Structural Engineer ’C’

Table 4.4 summarises the results from Engineer 'C’

Table 4.4. Summary of Results from Engineer ‘C’

Parameters	Results
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	5m c/c
Main Girder-Girder Spacing	5m
Slab Decking	

Slab thickness	300mm
Tension Main Reinforcement	T32@150mm
Tension Reinforcement Area	5360mm^2/m run
Girder System	
Main Girder Section	3No. 457x152x67UB
Main Girder Spacing	5m
Piers	
Pier-Pier Spacing	3No. Pier @ 5m

From these results, calculations were made as follows:

1) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete$$
$$= 24(Crossing\ Span\ \times\ Carriage\ way\ width\ \times slab\ thickness)$$

$$Weight\ of\ Concrete = 24KN/m^3\ \times\ 20m\ \times 10m\ \times 0.3m$$

$$Weight\ of\ Concrete = \mathbf{1440\ kN}$$

2) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{5360mm^2/m\ run}$$

3) Total weight of girders required

-Girder Selected: 5No. 457x152x67UB

-Unit weight: 67.2 kg/m

$$Total\ weight\ ofof\ girders = Unit\ weight\ \times crossing\ span\ \times No.\times 10m/s^2$$

$$Total\ weight\ ofof\ girders = 67.2Kg/m\ \times 20m\ \times 5No.\times 10m/s^2$$

$$Total\ weight\ ofof\ girders = \mathbf{67.2\ kN}$$

4) Numbers of Piers

$$Number\ of\ Piers = \mathbf{3No.}$$

4.4.5 Structural Engineer ’D’

Table 4.5 summarises the results from Engineer 'D’

Table 4.5. Summary of Results from Engineer ‘D’

Parameters	Results
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	5m c/c
Main Girder-Girder Spacing	2.8m
Slab Decking	
Slab thickness	250mm
Tension Main Reinforcement	T32@175mm
Tension Reinforcement Area	4600mm^2/m run
Girder System	
Main Girder Section	4No. 406x178x67UB
Main Girder Spacing	2.8m
Piers	
Pier-Pier Spacing	3No. Pier @ 5m

From these results, calculations were made as follows:

1) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete = 24(Crossing\ Span\ \times\ Carriage\ way\ width\ \times slab\ thickness)$$

$$Weight\ of\ Concrete = 24KN/m^3\ \times\ 20m\ \times 10m\ \times 0.25m$$

$$Weight\ of\ Concrete = \mathbf{1200\ kN}$$

2) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{4600mm^2/m\ run}$$

3) Total weight of girders required

-Girder Selected: 4No. 406x178x67UB

-Unit weight: 67.1 kg/m

$$Total\ weight\ of of\ girders = Unit\ weight\ \times crossing\ span\ \times No. \times 10m/s^2$$

$$Total\ weight\ of of\ girders = 67.1Kg/m\ \times 20m\ \times 4No. \times 10m/s^2$$

$$Total\ weight\ of of\ girders = \mathbf{63.68\ kN}$$

4) Numbers of Piers

$$Number\ of\ Piers = \mathbf{3No.}$$

4.4.6 Structural Engineer 'E'

Table 4.6 summarises the results from Engineer 'E'

Table 4.6 Summary of Results from Engineer 'E'

Parameters	Results
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	5m c/c
Main Girder-Girder Spacing	2.5m
Slab Decking	

Slab thickness	300mm
Tension Main Reinforcement	T32@150mm
Tension Reinforcement Area	5360mm^2/m run
Girder System	
Main Girder Section	4No. 533x210x82UB
Main Girder Spacing	2.5m
Piers	
Pier-Pier Spacing	3No. Pier @ 5m

From these results, calculations were made as follows:

1) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete = 24(Crossing\ Span\ \times\ Carriage\ way\ width\ \times slab\ thickness)$$

$$Weight\ of\ Concrete = 24KN/m^3\ \times\ 20m\ \times 10m\ \times 0.3m$$

$$Weight\ of\ Concrete = \mathbf{1440\ kN}$$

2) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{5360mm^2/m\ run}$$

3) Total weight of girders required

-Girder Selected: 4No. 533x210x82UB

-Unit weight: 82.2Kg/m

$$Total\ weight\ ofof\ girders = Unit\ weight\ \times crossing\ span\ \times No.\times 10m/s^2$$

$$Total\ weight\ ofof\ girders = 82.2Kg/m\ \times 20m\ \times 4No.\times 10m/s^2$$

$$Total\ weight\ ofof\ girders = \mathbf{65.76\ kN}$$

4) Numbers of Piers

$$Number\ of\ Piers = \mathbf{3No.}$$

CHAPTER 5: DISCUSSION AND ANALYSIS OF RESULTS

5.1 INTRODUCTION

The output from the structural Engineers were all compared with the solution obtained from the optimizing tool (COMPOPT) in form of graphs. This section presents the comparisons made in form of bar charts. Table 5.1 summarises the results from which the bar charts were derived from.

Table 5.1. Summary of Results

SUMMARY OF RESULTS						
	Optimization Tool (COMPOPT)	**Engineer 'A'**	**Engineer 'B'**	**Engineer 'C'**	**Engineer 'D'**	**Engineer 'E'**
Deck Slab Thickness	250mm	400mm	300mm	300mm	250mm	300mm
Weight of Decking (kN)	1200	1920	1440	1440	1200	1440
Area of Tension Rebar Required (mm^2/m run)	3220	4600	3930	5360	4600	5360
Girder Section Chosen	356x171x67 UB	533x210x109 UB	406x178x74 UB	457x152x67 UB	406x178x67 UB	533x210x82 UB
No. of Girders (No.)	4	4	5	3	4	4
Total Girders Weight (kN)	53.67	87.2	74.2	67.2	62.68	65.76
No. of Piers Required (No.)	3	1	2	3	3	3

5.2 COMPARISION OF THE OPTIMIZED SOLUTION TO THE SOLUTIONS PRODUCED BY PRACTICING ENGINEERS

In order to test the output from the optimizing software, a comparison study had to be made. Five practicing structural engineers were asked to design a composite bridge given the same input parameters used by the optimizing tool. The solutions were compared on parameters that contribute to the cost of construction of bridges. The following parameters were chosen:

1. Weight of concrete deck.
2. Area of Tension Reinforcement
3. Weight of Girders in the solution
4. Number of Piers in the solution

5.2.1 Weight of Concrete Deck Comparison

A comparison of the weight of the decking from each solution is shown in Figure 5.1. it is observed that the solution from 'Engineer A' had the heaviest bridge decking with a weight of 1920 kN. This decking had the highest depth of 400mm. The solutions from 'Engineer D' and the 'COMPOPT' had the least weight of 1200 kN for a deck depth of 250mm. It was also clear that the depth of the bridge deck slab was found to be the highest contributing factor to the overall weight of the deck.

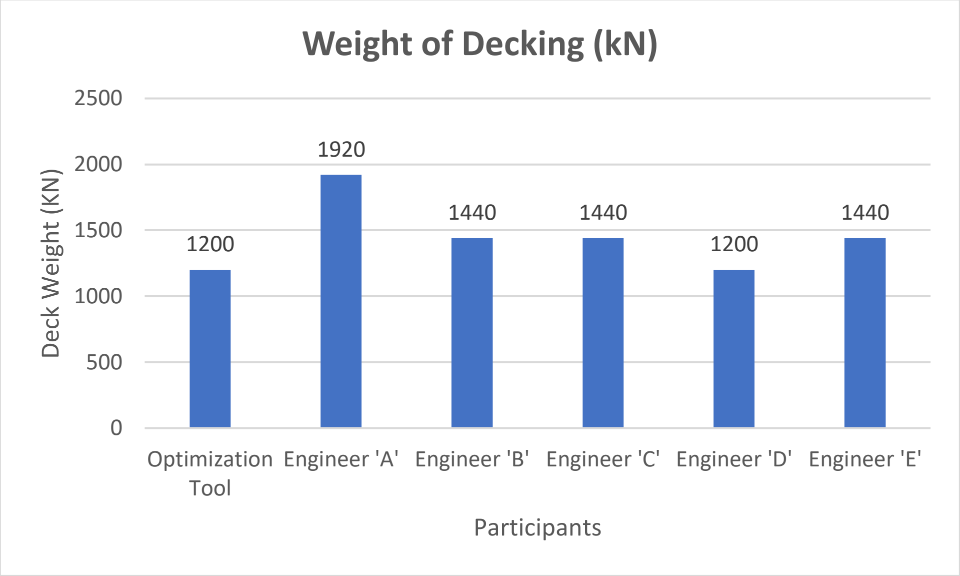


Figure 5.1. Weight of Bridge Decking

5.2.2 Comparison of Area of Tension Reinforcement Required

Figure 5.2 is a bar chart comparing the area of reinforcement required on each solution.

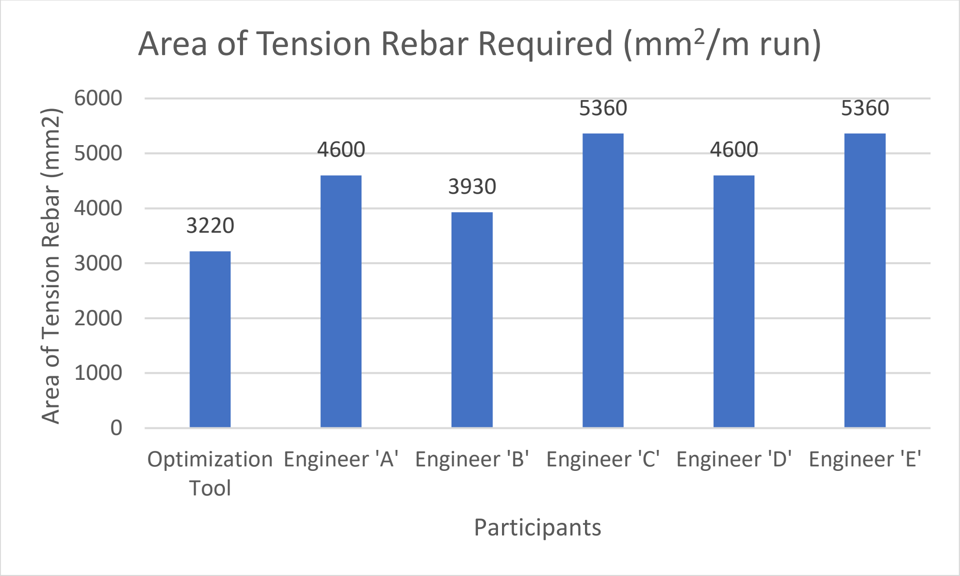


Figure 5.2. Area of Tension Rebar Required for each solution

Engineers ‘E’ and ‘C’ obtained the highest amount of Tension reinforcement per unit strip of the bridge decking. The solution from COMPTOPT gave the least required area of Tension Rebar.

5.2.3 Comparison of Total Weight of Girders Required

Figure 5.3 shows a comparison of the girder sizes obtained in each solution. COMPOPT gave the least weight of girders whilst Engineer A obtained the heaviest girders.

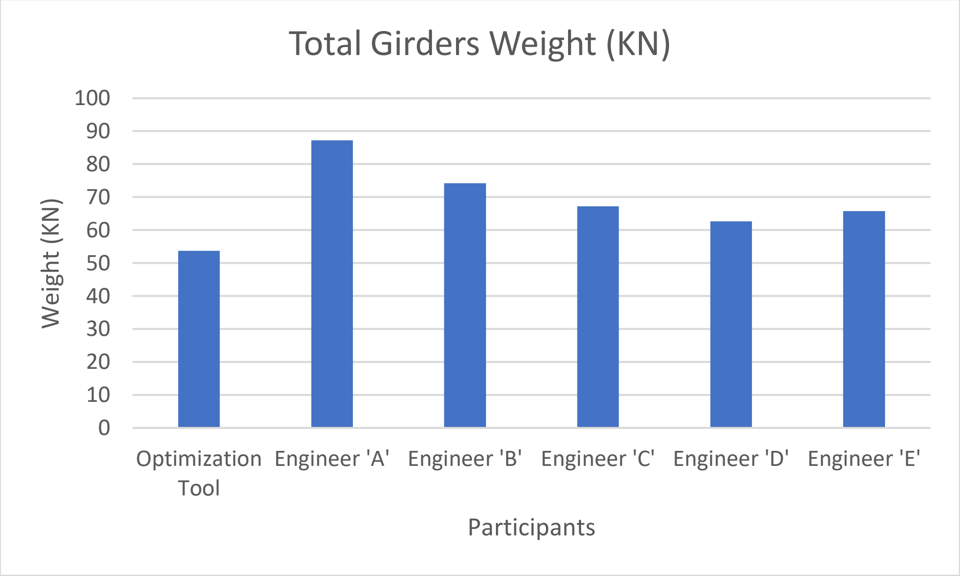


Figure 5.3. Comparison of Total Girder Weight in each solution

5.2.4 Comparison of the Total Number Piers Required

Figure 5.4 compares the number of piers used per each design output. It is clear that the solution from the optimization tool agrees with most of the solutions from the practicing Engineers.

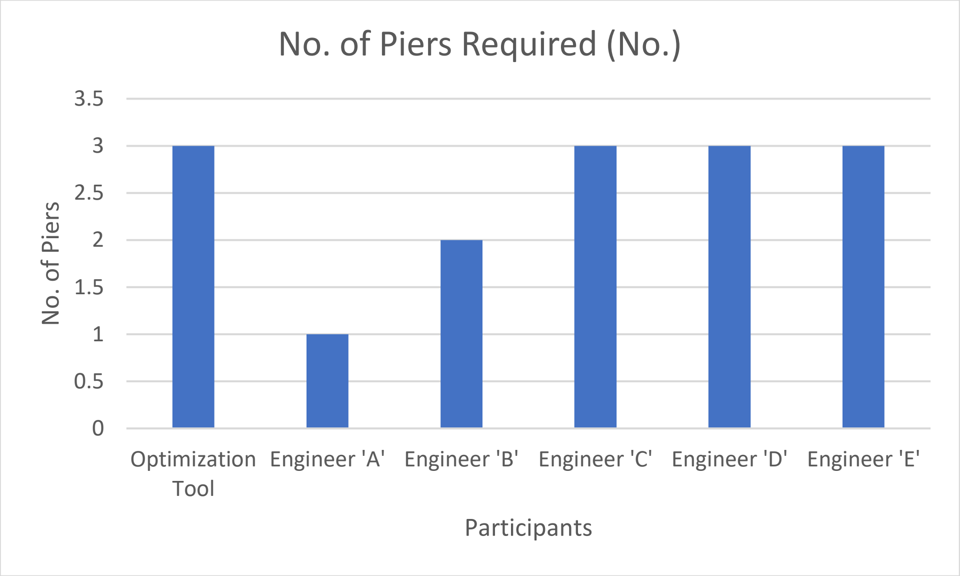


Figure 5.4. Comparison of Number of piers Used

CHAPTER 6: CONCLUSIONS, RECOMMENDATIONS AND STUDY LIMITATIONS

6.1 INTRODUCTION

The previous chapter basically discussed the results obtained from the study. A summary of results on selected key parameters was outlined and analysed which laid a basis for the comparative study. The aim of the comparative study was to test the output from the optimization tool (COMPOPT) against conventional designs. As anticipated, the output from the optimization tool performed well on a number of parameters as discussed in the previous chapter. This chapter outlines the conclusions, recommendations and limitations of the study.

6.2 CONCLUSION

This section gives conclusions based on each objective of this study.

6.2.1 Identify the design criteria used for concrete-steel composite bridges.

This was done mainly through a desk study. Literature was reviewed on the methods used to design concrete –steel composite bridges. As discussed in the literature review, the methods used here in Zambia conform to the Eurocode and the British standard, BS 5400.

For the bridge decking, the unit strip method was used by all 5 practicing engineers. Even though two of them used Prokon and Robot as design aids, their main design approach for deck design is the Unit Strip method. The girders were all designed using the checks outlined in the codes

6.2.2 Identify optimization techniques and algorithms that are useful in composite bridge design.

From the desk study conducted, the research revealed that there are broadly two categories of Optimization Techniques namely, Advanced Optimization techniques and Classical Optimization techniques. The study focused on the latter due to practicality of the solutions (Design Output). The study also showed that most of classical methods are more useful and practical of the two categories. These are able to reach optimum solutions deterministically given that the problem isn’t too complex. Advanced methods are more applicable to complex problems where an optimum solution can’t be found analytically. Moreover, advanced techniques only guarantee a near optimum solution.

To demonstrate the use and practicality of classical methods, the author developed a software tool to optimize topology parameters in the mentioned bridge. The tool is based on the direct search method using nested for-loops in C-Sharp programming language.

6.2.3 Develop a software tool for optimizing the sizing of girders and topology of the composite bridge design.

This specific objective was met by developing the optimizing software tool described in Chapter Four. The program is able to optimize the bridge deck slab, Universal Beam selection and, pier and footing design. The solutions from this tool were compared to various design solutions obtained from practicing structural engineers in the industry. The software was able to produce thousands of feasible solutions (Designs) with each given solution. From these solutions, the software was able to pick the optimal design based on ‘least weight’ criteria for the objective function.

6.2.4 Compare the resulting design with that obtained from the conventional design, by use of a case study.

A comparative study was done to compare the output from the software to the solutions produced by practicing structural engineers in the construction industry. The comparison was done based on four (4) parameters as described in Section 5.2. The parameters included:

1. Weight of concrete deck.
2. Area of Tension Reinforcement
3. Weight of Girders in the solution
4. Number of Piers in the solution

The comparative study showed that the software output compared favourably on all four parameters. The study also showed that the concrete decking contributes most significantly to the overall weight of the bridge.

6.3 RECOMMENDATIONS

6.3.1 Adoption of Optimization Techniques in the Design Process

Various studies have shown that the major limiting factor that has been hindering the adoption of Optimization techniques in the conventional design procedures has been the tedious nature of the calculations involved when optimizing. However, the advent of computers and programming has made optimization easy. It is recommended that practicing Structural Engineers use this tool for design of concrete bridges.

6.3.2 Further Areas of Study

Further research should be done in this area to assess the viability of incorporating optimization techniques in structural design for Composite Bridges in particular. This may also be done through existing Structural Design Software. Structural Engineers and Software Engineers should work together to incorporate optimization techniques in structural design software preferably now, that we have the computers fast enough to run these programs.

Structural Engineers in Zambia with interest in computer programming should also conduct studies to explore using Advanced Optimization techniques in a more practical manner, especially where the number of variables is considerably many. Cost optimization of bridge designs for conditions in Zambia should be considered.

6.3.3 Further work to be done in COMPOPT

The comparative study showed that COMPOPT scored favourably on all four parameters. The study also showed that the concrete decking contributes most significantly to the overall weight of the bridge and that the software is useful for preliminary design stage. For further studies, more features can be added to COMPOPT to include optimal preliminary design of piers and foundations

6.4 LIMITATIONS

6.4.1 Limitation of Study

The study was limited to design checks (and methods) stipulated in the Eurocode and BS5400. It didn’t make a comparison to other codes of design to establish which code produced the best optimized solutions.

6.4.2 Limitation in the Optimizing Software Tool (COMPOPT)

The software tool is designed to only optimize certain selected topology parameters. The third objective of this study was to demonstrate the use and incorporation of optimization techniques in structural design. The software tool was developed just to do just that. However not all viable parameters for optimizations were considered. This is partly due to fact that they are infinite variables on a composite bridge to optimize. This study considered mostly parameters that define the topology of the bridge.

6.4.3 Limitations on the Collection of Data

Several other limitations posed a constraint to the smooth flow of the research process. Amongst the limitations includes:

- Most consulting companies have restrictions on data release, even for research purposes. Because of these policies, the researcher faced the prohibition of accessing data for the intended research purpose.
- Published literature specific to Zambia. Globally, various literature linked to the research is available. However, literature specifically about Zambia was limited and hard to access.
- Limitations of Purposive Sampling Technique – This technique is convenient, economic, and targets the perceived resourceful subjects. However, its limitations include higher subjectivity and bias as compared to probability sampling techniques.

6.5 SUMMARY

In summary, the research was conducted successfully, with each specific objective being met. The specific objectives in-turn helped to accomplish the main objective which was to develop an optimization software tool to be used as an accessory to composite bridge design. The tool was successfully developed and demonstrated the advantages of incorporating Optimization Techniques in structural design (more specifically, Concrete-Steel Composite Bridges).

REFERENCES

AASHTO, 2002. *Standard Specification for Highway Bridges*, s.l.: American Association of State Highway and Transportation Officials.

British Standard Institute, 2006. *BS8500-1: Concrete-Complementary British Standard to BS EN 206-1: Method of Specifying and guidance to the Specifier*, London: BSI.

British Standards Institute, 2003. *Eurocode 1: Actions on structures- Part 1.2: Actions on structures. Traffic Loads on Bridges*, London: BSI. Print.

British Standards Institute, 2004. *Eurocode 2: Design of Concrete Structures- Part 1-1: General rules and rules for buildings*, Londoon: BSI. Print.

BS 5950, 2000. *Structural use of steelwork in buildings; Part 1: Code of practice for design – rolled and welded sections.* s.l.:s.n.

Chanakya, A., 2009. *Design of Structural Elements: Concrete, Steelwork, Masonry and Timber Designs to British Standards and Eurocodes.* 3rd ed. New York: Spon Press.

Chapra, S. C. & Canale, R. P., 2015. *Numeral Methods for Engineers.* 7th ed. New York: Mcgraw-Hill Education.

Chopard, B. & Tomassini, M., 2018. *An Introduction to Metaheuristics for Optimization.* 1st ed. Cham: Springer.

Creswell, J. W., 2009. *Research Design: Quantitative, Qualitative and Mixed Methods Approach.* 3rd ed. Los Angeles: SAGE.

Deore, M., 2018. *Medium.Com.* [Online]
Available at: https://medium.com//@tomdeore/deep-learning-in-decent-style-part-1-ed747e7cc2a3
[Accessed 28 October 2019].

Djuris, J., Ibric, S. & Djuric, Z., 2013. Experimental design application and interpretation in pharmaceutical technology. *Woodhead Publishing Series in Biomedicine,* III(1), pp. 31-56.

Dowling, P., Mears, T., Owens, G. & Raven, K., 1982. A development in the automated design and fabrication of portal framed industrial buildings. *The structural engineer,* 60(1), pp. 311-319.

Easterby-Smith, M., Thorpe, R. & Jackson, P., 2015. *Management and Business Research.* 5th ed. London: Sage.

Fabeane, R., Kripka, M. & Pravia, Z. M. C., 2017. COMPOSITE BRIDGES: STUDY OF PARAMETERS TO OPTIMIZED DESIGN. *International Journal of Bridge Engineering,* v(2), pp. 1-20.

Gallagher, R. H. & Zienkiewicz, O. C., 1973. *Optimum Structural Design.* 1 ed. London: John Wiley & Sons.

Grix, J., 2004. *The Foundations of Research.* 1st ed. London: Palgrave.

Hanson, R. D., 2004. A research C# compiler. *Software Practice and Experience,* Issue 34, p. 1211–1224.

Himani, A. & Monisha, S., 2015. OPTIMIZATION OF NTRU CRYPTOSYSTEM USING ACO ALGORITHM. *International Journal of Engineering Research-Online,* III(2), pp. 357-368.

Kazakis, G., Kanellopoulos, I., Sotiropoulos, S. & Lagaros, N., 2017. Topology optimization aided structural design: Interpretation, computational aspects and 3D printing. *Heliyon,* III(1), pp. 1-33.

Kazakis, G., Kanellopoulos, I., Sotiropoulos, S. & Lagaros, N. D., 2017. Topology optimization aided structural design: Interpretation, computational aspects and 3D printing. *Heliyon,* 3(10), pp. 1-33.

Kothani, R. C., 2004. *Research Methodology: Methods and Techniques.* 2nd ed. New Delhi: New Age International Publishers.

Leedy, P. D. & Ormrod, J. E., 2016. *Practicle Research: Planning and design.* 12 ed. London: Pearson.

Lythell, M. & Stenberg, J., 2020. *Cost optimization of composite bridges,* Stockholm: KTH Royal Institute of Technology.

Majid, K., 1994. *Optimum Design of Structures.* 3rd ed. London: Butterworth & Co Ltd.

Momtahan, A. & Hicks, S. J., 2013. *Steel-concrete composite bridge design guide,* Wellinton: NZ Transport Agency.

Mourabit, S. E., 2016. *Optimization of Concret Beam Bridges,* Stockholm: KTH.

Numan, G., 2012. *Design and optimization of steel portal frames according to Eurocode using genetic algorithm,* Lunds: Lunds University press.

Pedro, R. L., Miguel, L. F. F., Demarche, J. D. & Lopez, R. H., 2017. An efficient approach for the optimization of simply supported steel-concrete Composite I-Girder Bridges. *Advances in Engineering Software.*

Petr, H., Matti, M. & Fülöp, L., 2010. Advanced design and optimization of steel portal frames. *Journal of Structural Mechanics,* 43(1), pp. 44-60.

Shodhganha, 2000. *Optimization techniques in persperctive.* s.l.:s.n.

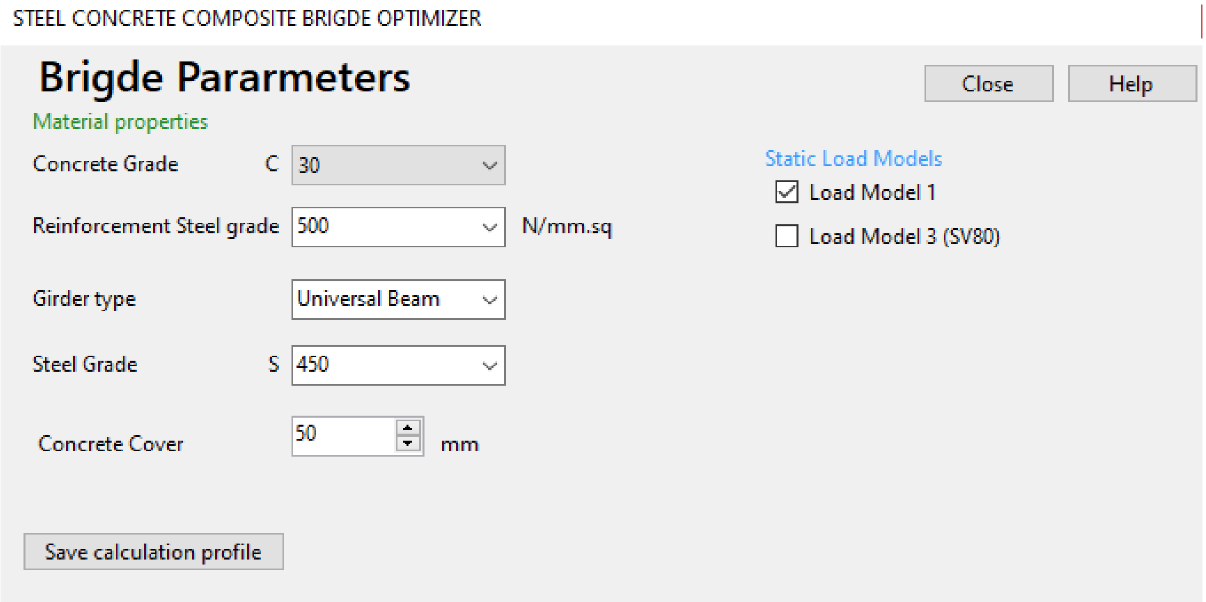
Singiresu, R. S., 2019. *Engineering Optimization: Theory and Practice.* 5th ed. Hoboken: John Wiley & Sons Inc..

Skiena, S. S., 2020. *The Algorithm Design Manual.* 3rd ed. Cham: Springer.

Skiena, S. S., 2020. *The Algorithm Design Manual (Texts in Computer Science).* 3rd ed. New York: Springer.

SteelConstruction.info, 2019. *SteelConstruction.info.* [Online] Available at: steelconstruction.info/Multi-girder_composite_bridges [Accessed 10 April 2022].

ANNEX 1: GUI OF COMPOPT – FORM 1 & 2



STEEL CONCRETE COMPOSITE BRIGDE OPTIMIZER

Brigde Pararmeters

Material properties

Concrete Grade C 30

Reinforcement Steel grade 500 N/mm.sq

Girder type Universal Beam

Steel Grade S 450

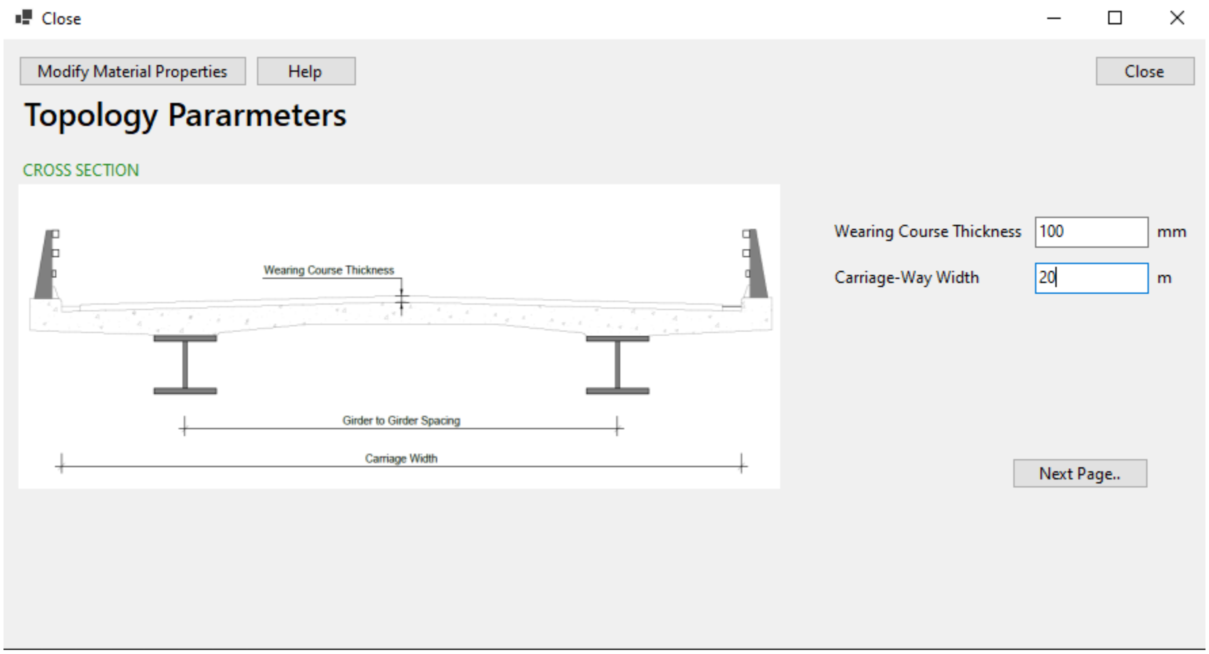
Concrete Cover 50 mm

Static Load Models

☑ Load Model 1

☐ Load Model 3 (SV80)

Form 1: Prompts the user to enter the material properties



Close

Topology Pararmeters

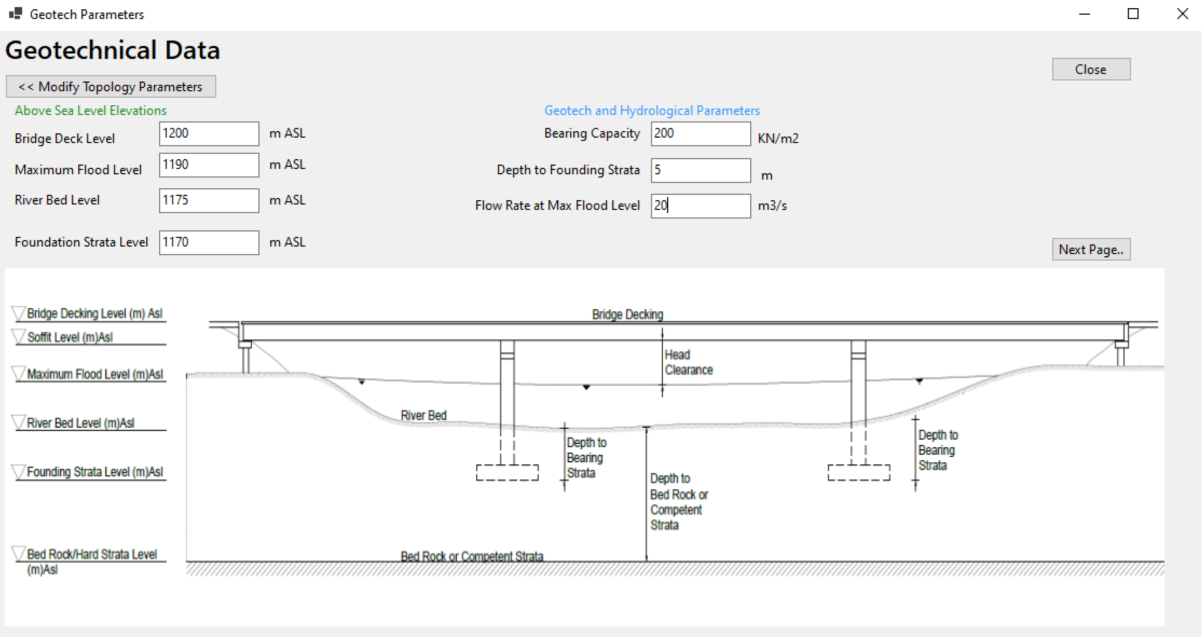
CROSS SECTION

Wearing Course Thickness 100 mm

Carriage-Way Width 20 m

Form 2: Prompts the user to enter the Carriage way width and wearing course thickness

ANNEX 2: GUI OF COMPOPT – FORM 3 & 4



Geotechnical Data

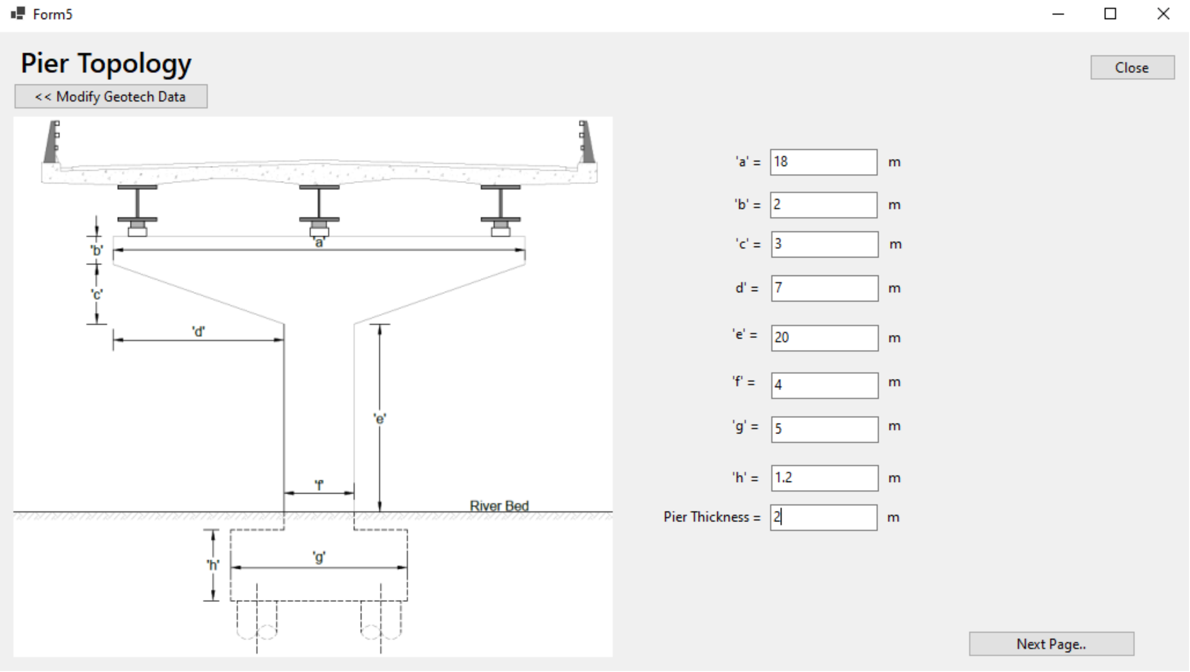
Above Sea Level Elevations

Bridge Deck Level 1200 m ASL
Maximum Flood Level 1190 m ASL
River Bed Level 1175 m ASL
Foundation Strata Level 1170 m ASL

Geotech and Hydrological Parameters

Bearing Capacity 200 KN/m2
Depth to Founding Strata 5 m
Flow Rate at Max Flood Level 20 m3/s

Form 3: Prompts the user to enter the geotechnical data and levels

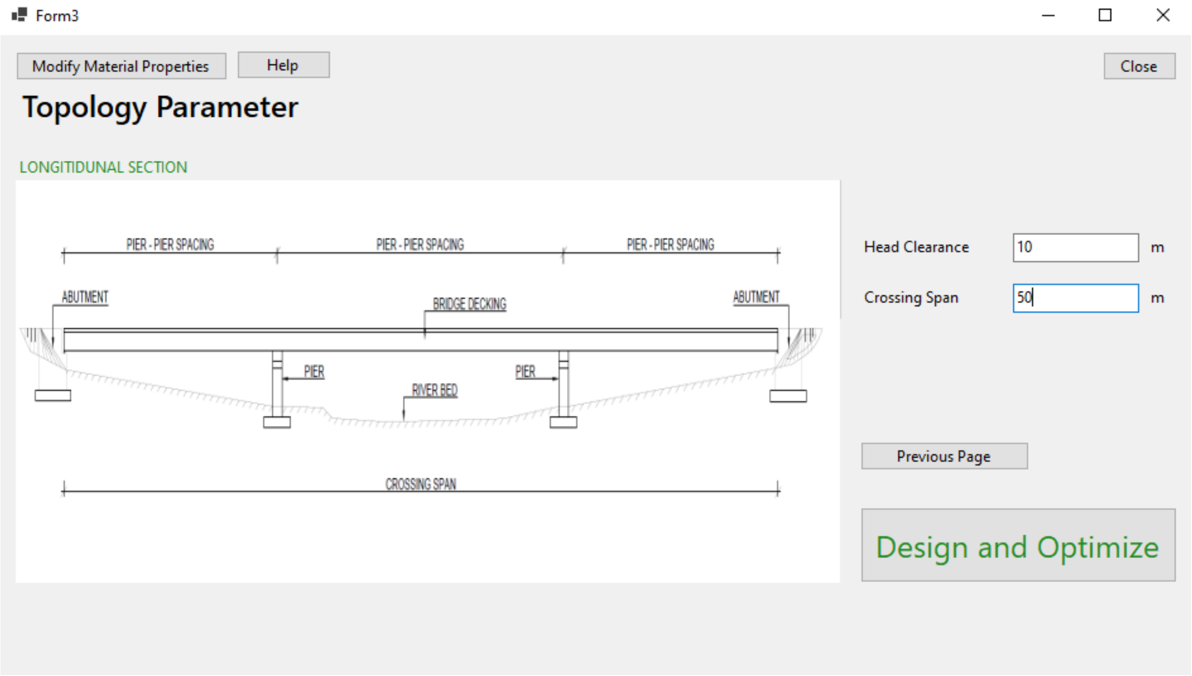


Pier Topology

'a' = 18 m
'b' = 2 m
'c' = 3 m
d' = 7 m
'e' = 20 m
'f' = 4 m
'g' = 5 m
'h' = 1.2 m
Pier Thickness = 2 m

Form 4: Prompts the user to enter Pier Topology parameters

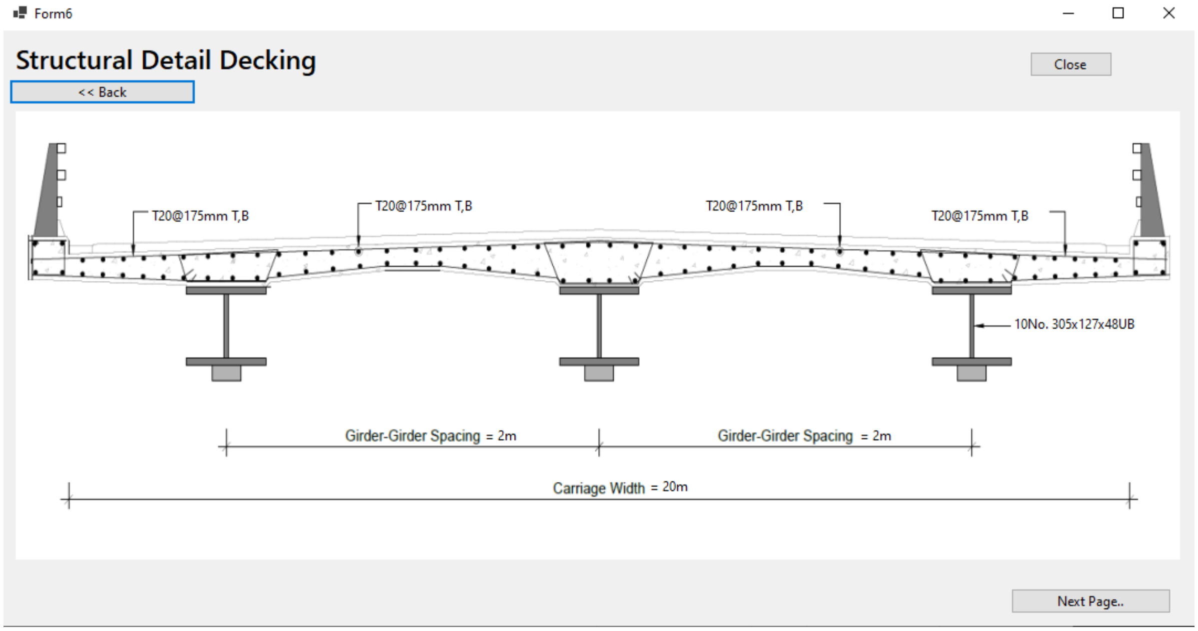
ANNEX 3: GUI OF COMPOPT – FORM 5 & 6



Head Clearance 10 m

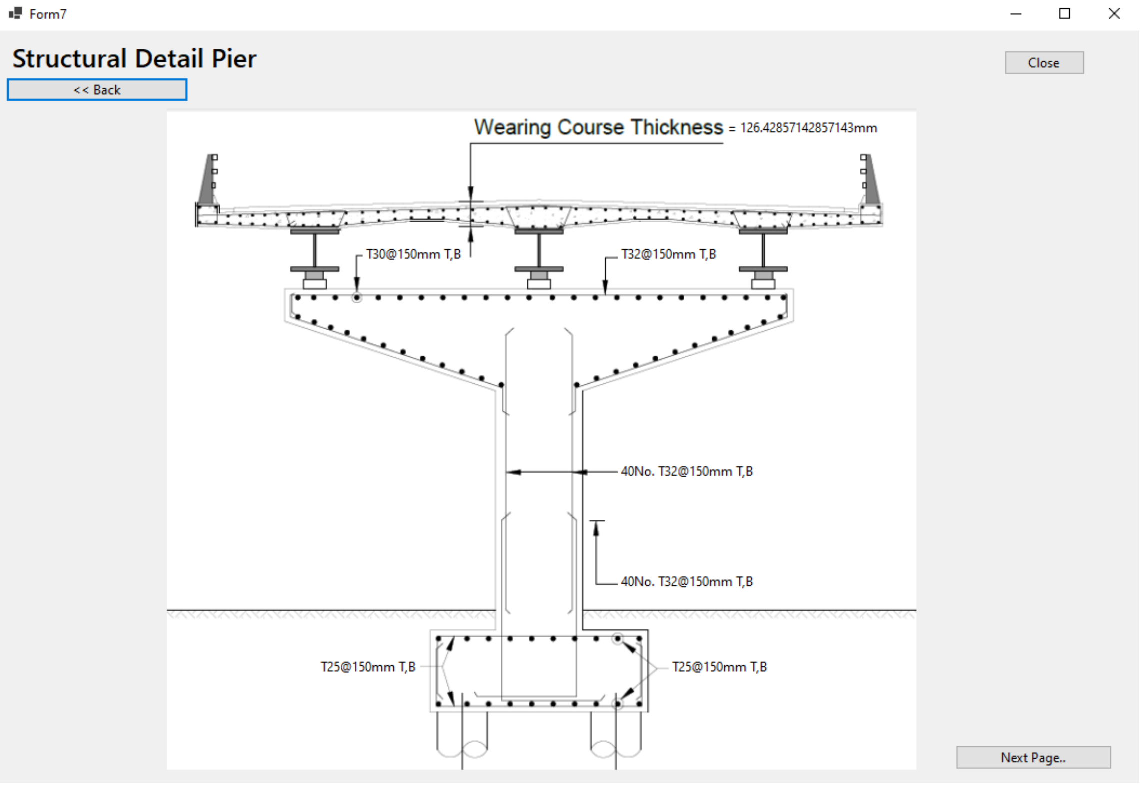
Crossing Span 50 m

Form 5: Prompts the user to enter the longitudinal topology parameters



Form 6: Displays the Cross-Sectional View Superstructure of the Optimal Design

ANNEX 4: GUI OF COMPOPT – FORM 7



Wearing Course Thickness = 126.42857142857143mm

Form 6: Displays the Longitudinal Cross-Sectional View of the Optimal Design

ANNEX 5: ETHICAL APPROVAL

THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka10101 | Tel: +260-211-290 258/291 777
Fax: (+260)-211-290 258/253 952 | E-**mail**: director.drgs@unza.zm | Website: www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465

18th November, 2022

REF NO. NASREC-2022-OCT. -008

Mr. Chikumbuso Lungu,
The University of Zambia,
School of Engineering,
P.O. Box 32379,
LUSAKA.

Dear Mr. Lungu,

RE: “OPTIMIZATION IN THE STRUCTURAL DESIGN OF COMPOSITE DECK BRIDGES”

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	**ORDINARY REVIEW**	**APPROVAL NO. NASREC-2022-OCT.-008**
Approval and Expiry Date	Approval Date: 18th November, 2022	Expiry Date: 17th November, 2023
Protocol Version and Date	Version - Nil.	17th November, 2023
Information Sheet, Consent Forms and Dates	- English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

CONDITIONS OF APPROVAL

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.

- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.

- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.

- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.

- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.

- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.

- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled “late submissions” and will incur a penaltyfee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.

- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.

- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO),both NASREC

- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.

- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.

- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.

- A reprint of this letter shall be done at a fee.

- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,

Dr. Mususu Kaonda

VICE-CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH ETHICS COMMITTEE - IRB

cc: Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies

ANNEX 6: PUBLISHED JOURNAL

JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Paper Optimization in the Design of Steel-Concrete Bridges-COMPOPT

[1]Chikumbuso Lungu, [2]Dr. Michael N. Mulenga
[1]Research Scholar, [2]Research Supervisor
[1]Department of Civil and Environmental Engineering,
[1]University of Zambia, Lusaka, Zambia

Abstract: A study to demonstrate the positive outcome of incorporating optimization techniques in the design procedure for designing steel-concrete composite bridges was conducted. Optimization algorithms have the capability of finding optimal or near optimal solutions in complex problems. In order to accomplish this task, a software known as COMPOPT, was developed in C# programming language to optimize composite bridge designs based on a classical method of optimization known as 'direct search'. The software output was then compared to structural designs that would be obtained through the typical 'traditional' design procedure. Traditional design procedure is a term in this study that alludes to normal procedure of design that practicing structural engineers follow in the design process, including use of design aids such as structural analysis and design software like Prokon and Robot. In summary, the output structural designs from the developed C# application were compared to typical structural designs from selected practicing structural engineers in Zambia. The results showed that the design output from COMPOPT performed better than the typical designs on several key parameters.

Key words: **Optimization Techniques; Direct search method; Steel-Concrete Composite Bridges; Bridge Optimization;**

1. Introduction

Optimization is the process of finding the best or most effective use of a situation 'optimal solution' with a given a set of limitation. The mathematical tools and concepts used to arrive at this 'optimal solution' are termed as optimization techniques. This has been a growing area of interest to civil engineers because of its applicability. (Himani & Dr. Monisha, 2015)

Optimization can be applied to various types of structures in civil engineering design. Pedro, et al (2017) noted that structural optimization is a very relevant field and has been a growing focus on research. Initial emphasis had been given to truss structures and some important advances were carried out. However, it is essential to note that the main focus of these studies was the implementation and development of different optimization procedures applied to academic examples. (Pedro, et al., 2017)

There is a general sense that this field hasn't received adequate attention. The slow progress in this field is largely attributed to tedious procedures involved in the calculation. But the emergence of computers has brought some significant interest in application of these techniques to structural engineering problems. (Numan, 2012)

However, this research focused on the application of optimization techniques to Structural Design of Concrete-Steel Composite Bridges. This type of bridge is mainly composed of a reinforced concrete decking supported on steel girders. Standard rolled section steel beams are rarely used as main girders, instead plate girders are usually used and have proven to be more economical since the plate size and thickness chosen for efficiency.

In the design of multi-girder composite bridges, a number of similarly sized longitudinal plate girders are arranged at uniform spacing across the width of the bridge, as shown in the typical cross section in Figure 1.1. The deck slab spans transversely between the longitudinal girders and cantilevers transversely outside the outer girders. The girders are braced together at supports and at some intermediate positions. Composite action between the reinforced concrete deck slab and the longitudinal girders is achieved by means of shear connectors welded on the top flanges of the steel girders. Figures 1.1 and 1,2 show a cross section and longitudinal profile of a composite bridge.

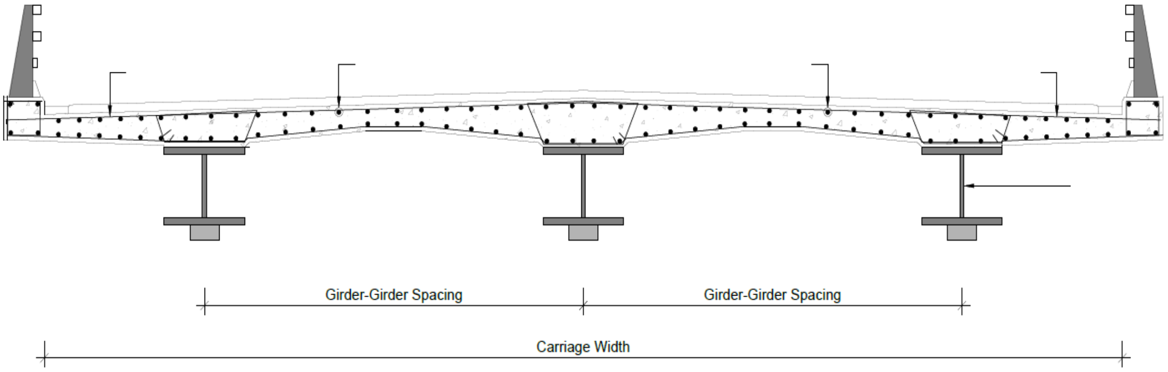


Figure 1.1: Cross Section View

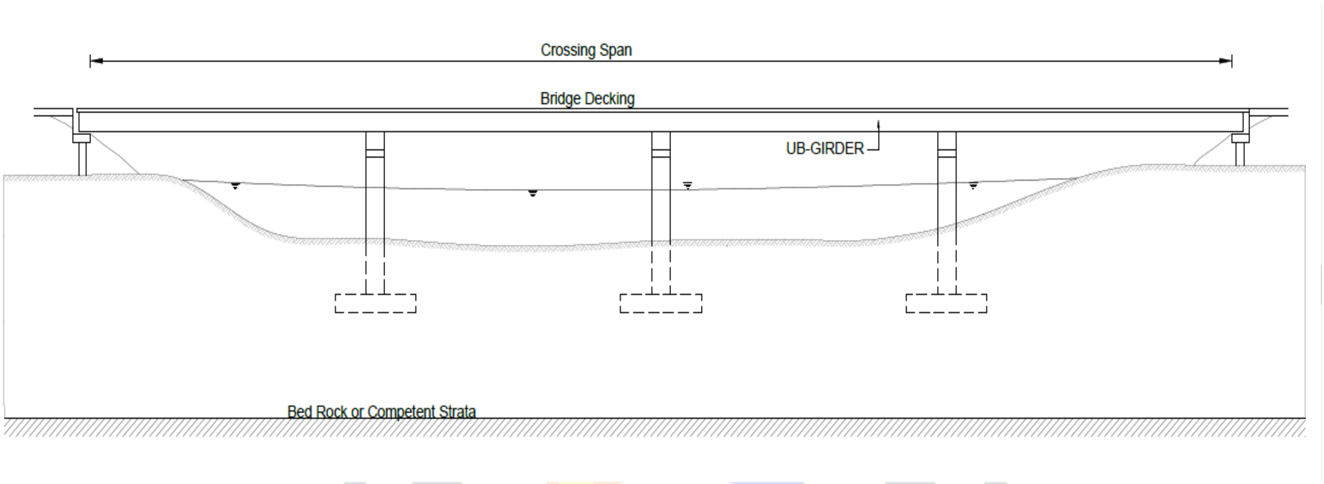


Figure 1.2.: Longitudinal profile of a bridge

Therefore, this study developed an optimization software tool that: (1) optimizes the selection of girders and reinforced concrete decking, (2) Optimize the topology of the bridge spatial parameters such as the spacing in between piers, and (3) compared output design from the software to typical design that would be produced by a practicing structural engineer.

2. Existing Approaches to Structural Optimization of Composite Bridges

There have been significant strides in researching optimization techniques and their application. Most research has been attempting to demonstrate how advanced optimization techniques could be used on various engineering structures. It is important to note that recent technological revolution has enabled the use of optimization techniques. Before the advent of computers, the tedious iterative nature of calculations involved in optimization hindered engineers to adopt optimization techniques. But with the increase in computing power brought in by the electronic era, using these techniques has made possible and easy. (Himani & Dr. Monisha, 2015); (Numan, 2012)

Among the most recent published papers, Fabeane et al (2017), probably defined the optimization problem very well in terms of composite bridges. They presented the problem as follows: Finding $X = \{X_1, X_2, \dots, X_n\}^T$ that minimizes (or maximizes) the function $f(X)$ under the following constraints:

$$g_j(X) \leq 0, \quad where\ j = 1,2, \dots, m \quad Equation\ 2.1$$

$$l_j(X) \leq 0, \quad where\ j = 1,2, \dots, p \quad Equation\ 2.2$$

$$X_i^l \leq X_i \leq X_i^u \text{ .... Equation 2.3}$$

$f(X)$ represents the objective function of the problem which could be, for instance ‘least weight of the bridge’ or the ‘most economical bridge design’. Equations 2.1 and 2.2 represents the constraints on the problem that should be respected so that the obtained solution falls in between these specified bounds. An example of a constraint in bridge design would be deflection. The optimum design needs to have a deflection that falls within the bounds of the permissible deflection allowed by standard codes. Equation 2.3 is called lateral restriction. (Fabeane, et al., 2017)

Now, the current tradition approach to optimization in the structural design industry is limited to the experience and knowledge of the designer. In their paper, Kazakis, et al., noted that what practicing structural engineers deem as an “optimal design” is their choice among rather limited set of design alternatives, dictated by their experience and intuition. (Kazakis, et al., 2017)

Optimization techniques nested in numerical mathematics however a plethora of alternative designs than what the traditional approach presents. Traditional optimization is limited to the designer’s knowledge and experience but advanced optimization techniques can analyse over a thousand alternative design in a second (this is made possible with advanced computing power).

2.1. *Metaheuristics approach vs Classical approach*

There are two (2) main categories of optimization techniques in numerical computation namely: Classical optimization techniques and advanced optimization techniques. Classical optimization techniques use techniques of differential calculus in locating optimum solutions. These methods are relatively old, and could be dated as far back as the Newtonian era. Metaheuristics optimization techniques on the other hand, were developed quite recently. They're based on certain characteristics and behaviour of biological, molecular, swarm and neurobiological systems. (Singiresu, 2019)

Examples of metaheuristic algorithms include: genetic algorithms, simulated annealing, particle swarm optimization, ant colony optimization and neural network methods of optimization. Metaheuristics optimization methods mimic the way nature approaches optimization in these systems. This has allowed researchers in this field to benefit from the billions of years' nature has had experimenting on this problem and finding a workable solution to it. For instance, the Ant colony optimization is based on the behaviour of real ant colonies, which are able to find the optimal path from their nest to a food source.

Natures problems are riddled with a multitude of variables and constraints which make the optimization problem very complex. But nature has found a way around this and this makes the algorithms based on nature very powerful and useful in engineering problems. Metaheuristic algorithms have been popular due to their ability to provide solution to complex engineering problem. A lot research recently conducted in the study of optimization has been mostly exploring the use of application of metaheuristics optimization techniques. However, these algorithms have limitations on applications. Despite been able to handle a lot of variables, convergence to an optimum solution isn't always assured and there is no guarantee that the solution will be found globally. (Chopard & Tomassini, 2018)

In comparison to metaheuristic algorithms, classical optimization techniques have an advantage in that convergence is always assured, given that the problem isn't too complex and objective function is 'continuous and differentiable'. The methodology of this study led to use of this type of algorithm given the nature of the problem. A classical method known as direct search method was adopted.

2.2. *Direct methods*

Singiresu (2019), posits that a function of one variable $f(x)$ is said to have a local minimum at $x = x^*$ if $f(x^*) \leq f(x^* + h)$ for all positive and negative values of h. Similarly, $f(x)$ is said to have a local maximum at $x = x^*$ if $f(x^*) \geq f(x^* + h)$ for all values of h significantly close to zero. By Singireu's definitions, it follows that, a function $f(x)$ has an absolute global optimum at $x = x^*$ if $f(x^*) \geq f(x)$ or $f(x^*) \leq f(x)$ in the domain over which $f(x)$ is defined. This is the mathematical basis upon which all optimization methods are based on including the direct search methods (Singiresu, 2019)

Direct search methods are applicable to multi-dimensional unconstrained optimization problems. Given that these methods also don't require gradient function, direct search methods could be used in problems where the data set is scattered and there's no easily identifiable function. Example of direct methods include: Random search method and 'univariate and pattern searches' (Chapra & Canale, 2015)

This study endeavoured to use a derivation of this method through a C# program. C# programming language is an object-oriented language. Object oriented programming is a paradigm based on the concept of 'objects' which can contain data and code. With this capability, the direct search method was implemented on the C# platform. (Hanson, 2004)

2.3. *Composite Bridge optimization*

A number of research has been done on application of optimization techniques applied to composite bridges. Most of it actually attempts to use metaheuristic optimization techniques, comparing the rates of convergence or simply testing them on a design parameter. Another criterion by which the research on this topic can be categorized is by observing which variables are of interest. There are studies investigating the optimization of topological parameters and those optimizing cross section parameters.

Kazakis, et al. (2017), defined structural topology optimization as a procedure of rearranging of structural elements and material into a design domain, thereby eliminating unnecessary material volume. In a composite bridge, this means the spatial arrangement of piers and and positioning of girders. (Kazakis, et al., 2017)

A study conducted by Lythell & Sternberg (2020) on cost optimization of composite bridges noted that most design offices adopt a trial-and-error based approach when designing composite bridges. They hypothesised that implementing this iteration in a computer software with an optimization algorithm would produce more cost-effective preliminary designs. When tested, their results showed that the software was a viable tool for preliminary designs. (Lythell & Stenberg, 2020)

In summary, a recurring theme was observed in the literature reviewed which is: Optimization techniques ultimately improve design results. Additionally, all the papers reviewed posited that introduction of an optimization improved the design results. The only disadvantage is that redundancy on the resulting solution is reduced.

3. Methodology

The study took a two-fold approach to attaining the set objectives of this research. The first step involved developing an optimization tool based on the direct search method, using C# programming language. The second step in the methodology was designed to test the output from the developed software tool, that has incorporated an optimization technique in its design procedure. The output from the software was compared to typical designs that would be obtained using the conventional method, which is, the usual way such a structure would be design by a practicing structural engineer.

3.1. *Formulation of the Optimization Algorithm*

An algorithm, as defined by Skiena (2020) is a procedural sequence of steps laid out to perform a specific function. An optimization algorithm therefore is a sequence of steps that outlines a procedure which when followed, seeks to find the optimal solution according to the objective function. (Skiena, 2020)

The general optimization algorithm generally takes the form:

Objective function: $C = f(x_1, x_2, \dots \dots, x_n)$ …. Equation 3.1

Constraint function: $g_j(x_1, x_2, \dots \dots, x_n) \leq 0, j = 1, \dots, m \text{ where } x_i \text{ are the variables}$ …. Equation 3.2

In this research, the authors goal was to make a computer program that uses an optimization technique in the design process for structural design of bridges. The logic steps that the program followed are outlined in figure 3.1.

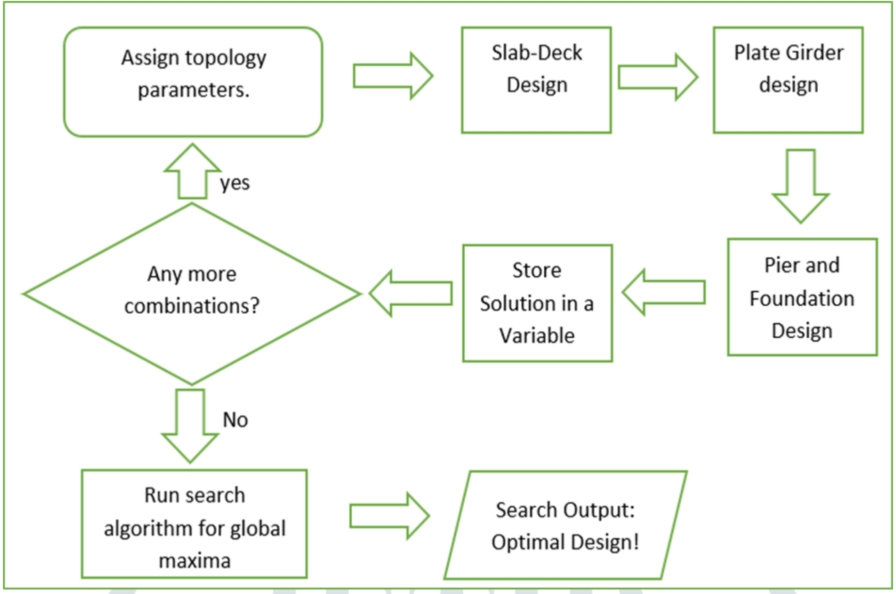


Figure 3.1. Logic Steps

The logic steps in figure 3.1 were implemented in COMPOPT. The algorithm is designed in a loop. With each loop, a solution is stored and after all possible designs (combinations) have been exhausted, the program runs an optimization function through the data set of all feasible designs and finds the most economical design. The objective function in this program, seeks the design that has the least weight.

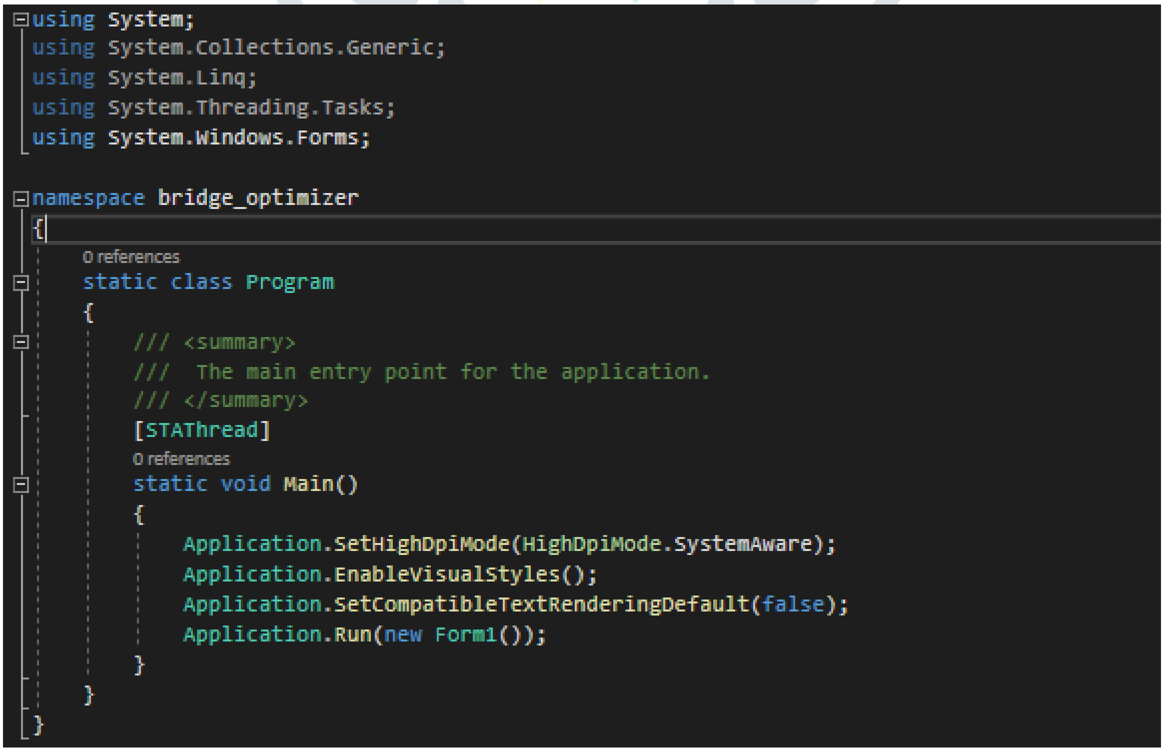
Least weight criteria was used because of it direct correlation to economy of the design. The relationship is presented as follows:

Weight of bridge design
(accumulative weight of individual elements) α Cost of Design………Equation 3.3

COMPOPT has 7 forms in total. 6 of these forms have been devoted to prompt the user to enter certain bridge parameters required for the program to execute the functions. The description of each step is as follows:

Step 1: Start

The 'Static Void Main ()' functions initiates the program, as shown in figure 3.2.



```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace bridge_optimizer
{
    0 references
    static class Program
    {
        /// <summary>
        ///  The main entry point for the application.
        /// </summary>
        [STAThread]
        0 references
        static void Main()
        {
            Application.SetHighDpiMode(HighDpiMode.SystemAware);
            Application.EnableVisualStyles();
            Application.SetCompatibleTextRenderingDefault(false);
            Application.Run(new Form1());
        }
    }
}
```

Figure 3.2: Program.cs_Program Initializer

Step 2: Assignment of Parameters

Six (6) forms have been dedicated to prompt the 'User' to enter the topology, material and cross-sectional parameters required for structural design calculations. Topology variables are variables that define the spatial layout of solid structure. Material parameters define material properties for use in the program (Kazakis, et al., 2017).

The topology parameters of a composite bridge coded in the software include:

- Distance between Piers,
- Carriage way width,
- Positioning and orientation of girders,
- Thickness of the decking and
- Head clearance.

Examples of material properties include

- Concrete strength class (i.e.C15, C20, C25, C30 and so on),
- Steel grade
- Reinforcement grade

Implementing the instruction in C# required both Back-End and Front-End programming. Front end constituted 'user interface' graphics design and arrangement of items on the forms. Back end programming constituted coding the 'engine' running calculations logics steps, as shown in figures 3.3 and 3.4.

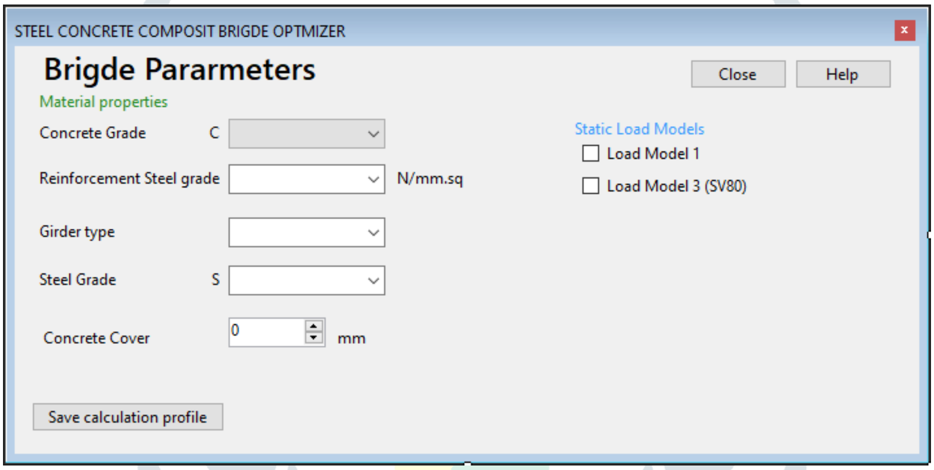
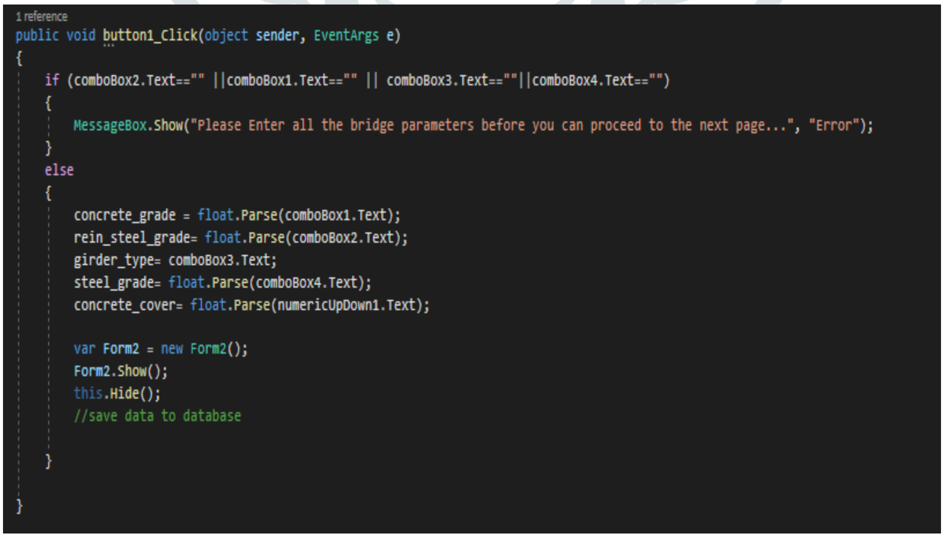


Figure 3.3: Form 1 showing Front End programming (User Interface Design)



```
1 reference
public void button1_Click(object sender, EventArgs e)
{
    if (comboBox2.Text=="" ||comboBox1.Text=="" || comboBox3.Text==""||comboBox4.Text=="")
    {
        MessageBox.Show("Please Enter all the bridge parameters before you can proceed to the next page...", "Error");
    }
    else
    {
        concrete_grade = float.Parse(comboBox1.Text);
        rein_steel_grade= float.Parse(comboBox2.Text);
        girder_type= comboBox3.Text;
        steel_grade= float.Parse(comboBox4.Text);
        concrete_cover= float.Parse(numericUpDown1.Text);

        var Form2 = new Form2();
        Form2.Show();
        this.Hide();
        //save data to database

    }

}
```

Figure 3.4: Illustration of Back end programming (Event handler for the 'Next Button')

Step 3: Slab Decking Design

Concrete slab deck design comes after the topology parameters are assigned by the user. Both live loads and dead loads are considered in this step. The bridge decking is the structural component that receives the live loading first. Therefore, logic entails that it be design first.

Live load models outlined in the Eurocode are considered and the slab deck is designed using unit strip method accounting for the dead loading as well.

Design of the slab decking serves as a constraint function in the optimization general function. The following check had to be satisfied for a design the program could to the next step.

1. Check for the cover

The program checked if the entered value for the cover was greater or equal to the cover derived from provisions given in BS EN 1992-1-1:2004 Equation 3.4 (British Standards Institute, 2004)

$$C_{nom} = C_{min} + \Delta C_{dev} \;\; \ldots . Equation\ 3.4$$

Where values for $C_{min,dur}$ were taken obtained from BS 8500-1. (British Standard Institute, 2006)

2. Actions on the Bridge Decking

Permanent actions considered in the design include:

- Reinforced concrete slab with unit weight of 25kN/m^3
- Surfacing with a unit weight of 24kN/m^3

Variable action considered in the include

- Traffic Load Model 1 following the provisions shown in BS EN 1991-2 2003. (British Standards Institute, 2003)

3. Flexural Design Checks

The program also checked if the slab deck section had adequate moment by use of Equation 3.5.

$$M_c \geq M_{ult} \;\; \ldots . Equation\ 3.5$$

where M_c is the flexural strength of the section and M_{ult} is the ultimate moment imposed in the slab decking.

4. Shear Checks

Similary, the program checked for shear capacity of the section by use of Equation 3.6.

$$V_c \geq v \;\; \ldots . Equation\ 3.6$$

where V_c is the shear capacity of the section and v is the applied shear force.

5. Deflection checks

The program lastly, checked if the maximum deflection was less than the permissible deflection.

Step 4: Steel Girder Design

The structural design of the steel girders came after the ‘slab decking design’ step. This is because the girders receive the loads from the slab decking and are obviously the next structural element in the load path.

Standard sections were used instead of plate girders to limit the scope and to increase variations in options. The methodology approach assumed that the beams are fully retrained due to the shear studs in composite bridges. The following checks were made in each iteration:

1. Resistance of cross section to bending ULS

The program made the following check:

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0 \;\; \ldots . Equation\ 3.7$$

where M_{Ed} is the design value of the bending moment and M_{cRd} is the design resistance for bending about one principal axis which takes different forms depending on the classification of the section.

2. Resistance to shear forces and buckling ULS

Equation 3.8 below checked for section resistance to shear loading.

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0 \;\; \ldots . Equation\ 3.8$$

where V_{Ed} is the design shear force imposed on the member and $V_{c,Rd}$ is taken as the design shear resistance of the section.

The shear buckling check utilized Equation 3.9. (clause 5.1, EC 3-5)

$$\frac{h_w}{t_w} > 72\frac{\varepsilon}{\eta} \;\; \ldots . Equation\ 3.9$$

3. Resistance to flange induced buckling ULS

For flange induced buckling check, Eurocode 3-5 requires that the ratio h_w/t_s should satisfy the following expression:

$$\frac{h_w}{t_w} > k\frac{E}{f_{yf}}\sqrt{\frac{A_w}{A_{fc}}} \ \ldots\ldots Equation\ 3.10$$

where A_w is the area of the web, A_{fc} is the area of the compression flange, and f_{yf} is the yield strength of the compression flange.

4. Resistance of the web to transverse forces ULS

Design resistance of webs of standards sections was checked according to Clause 6 of Euro Code 3-5. Equation 3.11 is the expression for local buckling.

$$F_{Rd} = \frac{f_{yw}L_{eff}t_w}{\gamma_{M1}} \ \ldots . Equation\ 3.11$$

where F_{Rd} is the design resistance of webs to local buckling, t_w is the thickness of the web, γ_{M1} is the partial safety factor = 1.0 and L_{eff} is the effective length of the web.

5. Defection SLS

Permissible deflection was as per Equation 3.12.

$$Permissible\ deflection \leq \frac{Span}{360} \ \ldots . Equation\ 3.12$$

3.2. *Development of COMPOPT*

A number of factors had to be considered when undertaking this task. The following steps were taken when developing COMPOPT.

1. Development of an algorithm that the program was to follow.
2. Secondly, choice of programming language the ‘optimization program’ had to written in.
3. Using the appropriate syntax, the code for each block of instructions following the order of the algorithm developed in step one (1) was written.
4. The program was compiled and packaged. The errors noticed were corrected until the program ran smoothly.

3.3. *Experimental Design Example*

In order to test the Output Solution obtained from the Software, a comparative study was done. COMPOPT solution were compared with a typical design that would be obtained using the conventional method. Design Solutions obtained using the conventional method, five (5) practicing structural engineers were asked to design a Composite bridge, given the same conditions. Their results were then compared to the output from the software, for the design problem described below.

Design Problem: Design a simply supported Concrete-steel composite bridge. The deck carries a 100mm thick surfacing, together with traffic load (LM1) udl with 5.5 kN/m^2 and tandem axle load of 100 kN (300 kN/3m lane width). You may use any number of Piers you deem necessary for the crossing and also any number girders supporting the slab decking, given the following parameters for the crossing:

- Crossing span: 20m
- Carriage way width: 10m
- Use Universal Beams as Girders

For the purposes of comparison, the engineer’s solutions are summarized in Table 4.2. The comparison was based on the following:

- Weight of concrete for the decking,
- Area of tension reinforcement per unit width,
- Total weight of girders required, and
- Number of piers required.

3.4. *Comparison of Results and discussion*

3.4.1. *Design Output from COMPOPT*

The results from the Optimization Tool are summarized in Table 4.1.

Table 4.1. Summary of Design Solution from COMPOPT

Parameters	**Results**
Bridge Topology Parameters	
Crossing Span	20m
Carriage way width	10m
Pier - Pier Spacing	5m c/c
Main Girder-Girder Spacing	2.5m
Slab Decking	
Slab thickness	233.57mm
Tension Main Reinforcement	T32@250mm
Tension Reinforcement Area	3220mm^2/m run
Girder System	
Main Girder Section	4No. 356x171x67UB
Main Girder Spacing	2.5m
Piers	
Pier-Pier Spacing	3No. Pier @ 5m

From the above results, the following calculations were determined:

1) Weight of Concrete required for the Decking

$$Weight\ of\ Concrete = 24(Crossing\ Span\ \times\ Carriage\ way\ width\ \times slab\ thickness)$$
$$Weight\ of\ Concrete = 24kN/m^3\ \times\ 20m\ \times 10m\ \times 0.25m$$
$$Weight\ of\ Concrete = \mathbf{1200\ kN}$$

2) Area of Tension Reinforcement per unit width

$$Area\ of\ tension\ rebar\ required = \mathbf{3220mm^2/m\ run}$$

3) Total weight of girders required

-Girder Selected: 4No. 356x171x67UB
-Unit weight: 67.1kg/m

$$Total\ weight\ of of\ girders = Unit\ weight\ \times crossing\ span\ \times No.\times 10m/s^2$$
$$Total\ weight\ of of\ girders = 67.1kg/m\ \times 20m\ \times 4No.\times 10m/s^2$$
$$Total\ weight\ of of\ girders = \mathbf{53.68\ kN}$$

4) Numbers of Piers

$$Number\ of\ Piers = \mathbf{3No.}$$

3.4.2. Comparison of Results from Structural Engineers and COMPOPT

Table 4.2 and Figure 4.2.1 to 4.2.4 summarize the comparisons.

Table 4.2: Comparison of Results

	Optimization Tool (COMPOPT)	Engineer 'A'	Engineer 'B'	Engineer 'C'	Engineer 'D'	Engineer 'E'
Deck slab thickness	250mm	400mm	300mm	300mm	250mm	300mm
Weight of Decking (kN)	1200	1920	1440	1440	1200	1440
Area of Tension Rebar Required (mm^2/m run)	3220	4600	3930	5360	4600	5360
Girder Section Chosen	356x171x67 UB	533x210x109 UB	406x178x74 UB	457x152x67 UB	406x178x67 UB	533x210x82 UB
No. of Girders (No.)	4	4	5	3	4	4
Total Girders Weight (kN)	53.67	87.2	74.2	67.2	62.68	65.76
No. of Piers Required (No.)	3	1	2	3	3	3

3.4.3. Weight of Concrete Deck Comparison

A comparison of the weight of the decking from each solution is shown in Figure 4.2.1. it is observed that the solution from ‘Engineer A’ had the heaviest bridge decking with a weight of 1920kN. This decking had the highest depth of 400mm. The solutions from ‘Engineer C’ and the ‘COMPOPT’ had the least weight of 1200 KN for a deck depth of 400mm. It was also clear that the depth of the bridge deck slab was found to be the highest contributing factor to the overall weight of the deck.

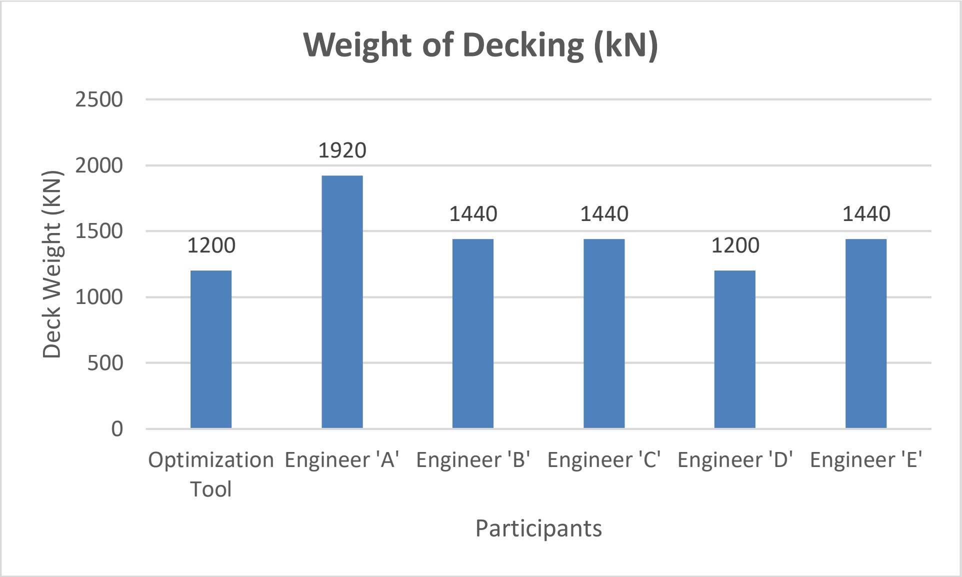


Figure 4.2.1. Weight of Bridge Decking

3.4.4. Comparison of Area of Tension Reinforcement Required

Figure 4.2.2 is a bar chart comparing the area of reinforcement required on each solution.

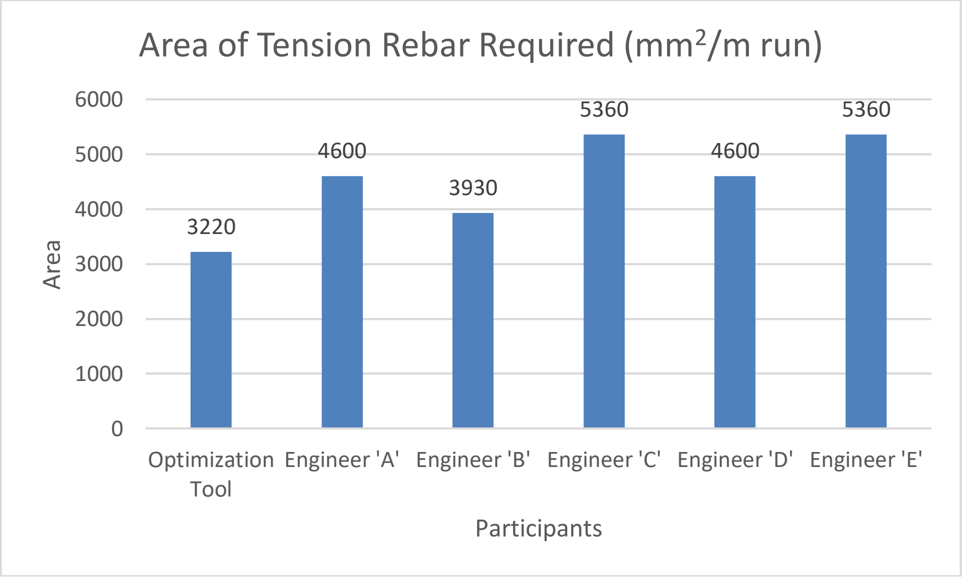


Figure 4.2.2. Area of Tension Rebar Required for each solution

Engineers E and C obtained the highest amount of Tension reinforcement per unit strip of the bridge decking. The solution from COMPTOPT gave the least required area of Tension Rebar.

3.4.5. Comparison of Total Weight of Girders Required

Figure 4.2.3 is a comparison of the girder sizes obtained in each solution. COMPTOPT gave the least weight of girders whilst Engineer A obtained the heaviest girders.

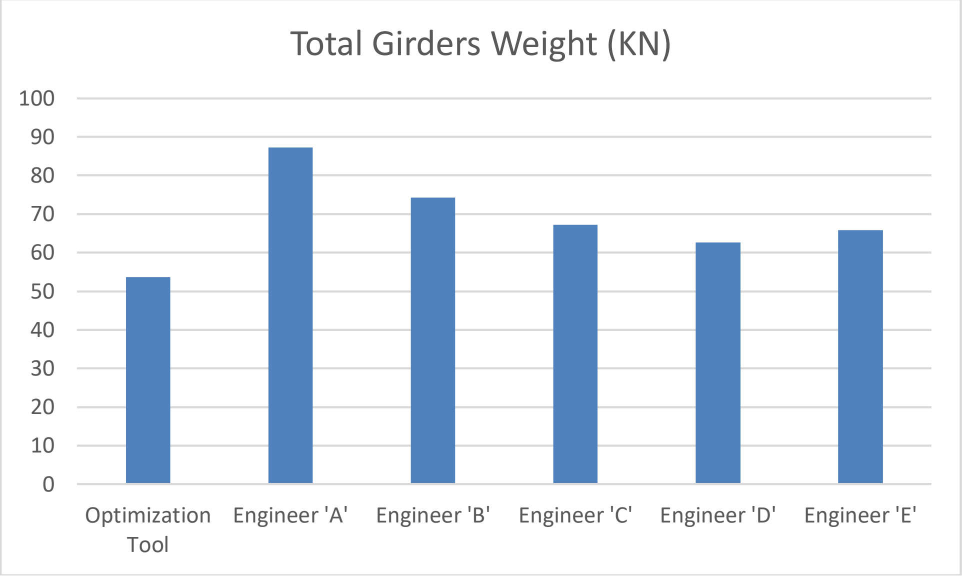


Figure 4.2.3. Comparison of Total Girder Weight in each solution

3.4.6. Comparison of the Total Number Piers Required

Figure 4.2.4 compares the number of piers used per each design output. It is clear that the solution from the optimization tool agrees with most of the solutions from the practicing Engineers.

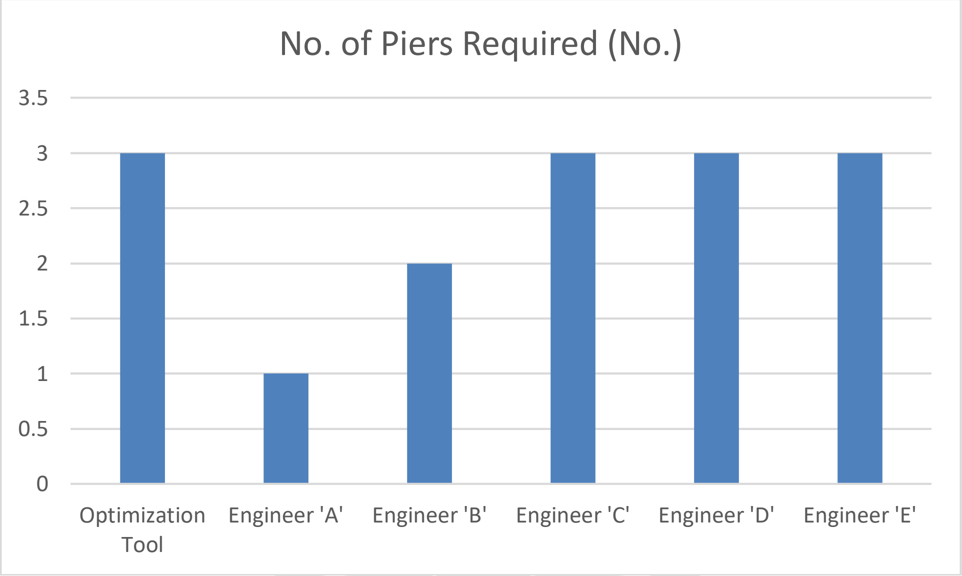


Figure 4.2.4. Comparison of Number of piers Required

4. Conclusions and Recommendations

The aim of the comparative study was to test the output from the optimization tool against conventional designs. As anticipated, the output from the optimization tool performed well on most of the parameters as discussed in the previous chapter. This chapter outlines the conclusions, recommendations and limitations of the study.

4.1. Conclusions

4.1.1. Identifying the design criteria used for concrete-steel composite bridges.

Literature was reviewed on the methods used to design concrete –steel composite bridges. The literature showed that the methods used here in Zambia conform to the Eurocode and the British standard, BS 5400.

For bridge deck design, the unit strip method was used by all 5 Practicing Engineers who participated in the study. Even though two of them used Prokon and Robot as design aids, their main design approach for deck design is the Unit Strip method. The girders were all designed using the checks outlined in the codes.

4.1.2. Identifying optimization techniques and algorithms that are useful in composite bridge design.

From the desk study conducted, the research revealed that there are broadly two categories of Optimization Techniques namely, Advanced Optimization techniques and Classical Optimization techniques. The study focused on the latter due to practicality of the solutions (Design Output) given the design problem presented in section 3.3. The study also showed that most of classical methods are more useful and practical of the two categories. These are able to reach optimum solutions deterministically given that the problem isn't too complex. Advanced methods are more applicable to complex problems where an optimum solution can't be found analytically. Moreover, advanced techniques only guarantee a near optimum solution.

To demonstrate the use and practicality of classical methods, a software tool to optimize topology parameters in the given bridge was developed. The tool is based on the direct search method using nested for-loops in C-Sharp programming language.

4.1.3. Development of a software tool for optimizing the sizing of girders and topology of the composite bridge design.

This specific objective was met by developing the optimizing software tool described in section 3. The program is able to optimize the bridge deck slab, Universal Beam selection and spatial position of piers. The solutions from this tool were compared to various design solutions obtained from practicing structural engineers in the industry.

4.1.4. Comparison of the 'optimal design' with that obtained from the conventional design.

A comparative study was based on four (4) parameters as described in Section 4.7. The parameters included:

- Weight of concrete deck.
- Area of Tension Reinforcement
- Weight of Girders in the solution
- Number of Piers in the solution

4.2. Recommendations

The comparative study showed that COMPOPT scored favorably on all four parameters. The study also showed that the concrete decking contributes most significantly to the overall weight of the bridge and that the software is useful for preliminary design stage. For further studies, more features can be added to COMPOPT to include optimal preliminary design of piers and foundations

References

[1] British Standard Institute, 2006. *BS8500-1: Concrete-Complementary British Standard to BS EN 206-1: Method of Specifying and guidance to the Specifier*, London: BSI.

[2] British Standards Institute, 2003. *Eurocode 1: Actions on structures- Part 1.2: Actions on structures. Traffic Loads on Bridges*, London: BSI. Print.

[3] British Standards Institute, 2004. *Eurocode 2: Design of Concrete Structures- Part 1-1: General rules and rules for buildings*, Londoon: BSI. Print.

[4] Chanakya, A., 2009. *Design of Structural Elements: Concrete, Steelwork, Masonry and Timber Designs to British Standards and Eurocodes.* 3rd ed. New York: Spon Press.

[5] Chapra, S. C. & Canale, R. P., 2015. *Numeral Methods for Engineers.* 7th ed. New York: Mcgraw-Hill Education.

[6] Chopard, B. & Tomassini, M., 2018. *An Introduction to Metaheuristics for Optimization.* 1st ed. Cham: Springer.

[7] Fabeane, R., Kripka, M. & Pravia, Z. M. C., 2017. COMPOSITE BRIDGES: STUDY OF PARAMETERS TO OPTIMIZED DESIGN. *International Journal of Bridge Engineering*, v(2), pp. 1-20.

[8] Hanson, R. D., 2004. A research C# compiler. *Software Practice and Experience*, Issue 34, p. 1211–1224.

[9] Himani, A. & Dr. Monisha, S., 2015. OPTIMIZATION OF NTRU CRYPTOSYSTEM USING ACO ALGORITHM. *International Journal of Engineering Research-Online*, III(2), pp. 357-368.

[10] Kazakis, G., Kanellopoulos, I., Sotiropoulos, S. & Lagaros, N., 2017. Topology optimization aided structural design: Interpretation, computational aspects and 3D printing. *Heliyon*, III(1), pp. 1-33.

[11] Kazakis, G., Kanellopoulos, I., Sotiropoulos, S. & Lagaros, N. D., 2017. Topology optimization aided structural design: Interpretation, computational aspects and 3D printing. *Heliyon*, 3(10), pp. 1-33.

[12] Lythell, M. & Stenberg, J., 2020. *Cost optimization of composite bridges*, Stockholm: KTH Royal Institute of Technology.

[13] Numan, G., 2012. *Design and optimization of steel portal frames according to Eurocode using genetic algorithm*, Lunds: Lunds University press.

[14] Pedro, R. L., Miguel, L. F. F., Demarche, J. D. & Lopez, R. H., 2017. An efficient approach for the optimization of simply supported steel-concrete Composite I-Girder Bridges. *Advances in Engineering Software.*

[15] Singiresu, R. S., 2019. *Engineering Optimization: Theory and Practice.* 5th ed. Hoboken: John Wiley & Sons Inc..

[16] Skiena, S. S., 2020. *The Algorithm Design Manual.* 3rd ed. Cham: Springer.