CHALMERS
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Adoption of Life Cycle Cost Analysis in Early Design Phases of Road Bridges

Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology

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ABSTRACT

The last years, the concern of life cycle cost of new bridges has increased. The Swedish Transport Administration has introduced the idea of using life cycle cost as a decisive factor in their procurement of bridges in order to use resources in the most efficient way, which is both economically and environmentally preferable.

A full life cycle cost analysis requires large amounts of data and knowledge in order to be thoroughly performed. The aim of this thesis was to construct a tool to perform a simplified life cycle cost analysis of Swedish bridges. To be able to meet the aim, a literature study concerning bridges, life cycle cost analysis and procurement of infrastructure in Sweden, was carried out. Further, investment costs of existing bridges in Sweden were gathered and analysed together with data of performed maintenance measures, also from existing records.

The result was an Excel-based program, *SimpleBridgeLCC*, that consisted of two parts. The first part calculated the investment cost, based on cost records of already built bridges. The second part calculated the total maintenance cost as net present value based on maintenance performance intervals and the cost of maintenance measures.

The main outcome of the thesis was an indicative LCCA-program, *SimpleBridgeLCC,* specified for road bridges in Sweden, which was easy to use for a person with basic bridge knowledge.

Key words: Life Cycle Cost, LCC, LCCA, Bridge, Procurement, Maintenance, Investment

Implementering av Livscykelkostnadsanalys i Utformning av Vägbroar

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SAMMANFATTNING

Under de senaste åren har intresset för livscykelkostnad för nya broar växt. Trafikverket har introducerat idén om att använda livscykelkostnad som en avgörande faktor i upphandling av nya broar. Detta för att använda resurser på det mest effektiva sättet vilket är fördelaktigt både ur ekonomisk och miljömässig synpunkt.

En fullständig livscykelkostnadsanalys kräver stora mängder information och kunskap för att kunna genomföras på ett korrekt sätt. Syftet med denna mastersuppsats var att finna ett verktyg som kunde utföra förenklade livscykelkostnadsanalyser av svenska vägbroar. För att kunna genomföra detta på bästa sätt utfördes en litteraturstudie med fokus på upphandling av broar, livscykelkostnadsanalyser och vägbroar. Efter litteraturstudien samlades data rörande investeringskostnader av redan byggda broar samt existerande data avseende underhållsåtgärder och deras respektive utförandeintervall.

Resultat var ett Excel-baserat program, *SimpleBridgeLCC,* som i sin tur var uppdelat i två delar. Den första delen räknade ut investeringskostnaden för broar baserat på existerande kostnader av redan byggda broar. Den andra delen var utformad så att den räknade fram den totala underhållskostnaden som ett nuvärde av alla framtida underhållsåtgärder på bron. Den senare delen av programmet är baserat på tidsintervall och kostnader för underhållsåtgärder.

Det huvudsakliga resultatet var ett indikativt LCCA-verktyg, *SimpleBridgeLCC,* för svenska vägbroar, som är lättillgängligt för de flesta med en grundläggande brokunskap.

Nyckelord: Livscykelkostnad, LCC, Livscykelkostnadsanalys, Bro, Upphandling, Underhåll

CONTENTS

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Göteborg, June 2016

Håkan Haglund

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ABBREVIATIONS

BaTMan	Bridge and Tunnel Management
EAC	Equivalent Annual Cost
LCA	Life Cycle Assessment
LCM	Life Cycle Measures
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
NPV	Net Present Value
SEK	Swedish Krona
STA	Swedish Transport Administration

1 Introduction

1.1 Background

In this day and age, sustainable development is one of the major challenges for the humankind (Fulekar, et al., 2014). It is being addressed in global climate meetings, education and at parliaments all over the world. In order to achieve sustainable development, a long term view of investments and political change is needed. During the second half of the 20th century a long-term outlook took form called life cycle cost (LCC), which takes into account all costs of a product or asset during its entire life (Dhillon, 2010). These costs span from the costs to produce drawings to costs for environmental impact. LCC is a useful tool to systematically analyse investment in a long-term perspective and can be very useful in the future.

In a report ordered by the European Commission, (Davis Langdon, 2007a) argues that LCC is a useful tool in the procurement of infrastructure. This view is supported in a project undertaken in the Scandinavian Countries (ETSI, 2013) and in a collaboration between the Swedish Transport Administration (STA) and the Royal Institute of Technology (Safi, 2013). The STA is a public agency that is responsible for procuring and managing all public infrastructure in Sweden (Swedish Transport Administration, 2015). The public agencies in Sweden are required to follow the Swedish Public Procurement Act which exists to ensure that the public funds are used in the most cost-efficient way, and to allow free competition between contractors (Konkurrensverket, 2014). In traditional procurement, the winning bid is the one with the lowest investment cost (Safi, 2013), but recently the STA has taken measures to implement LCC in the procurement process. To gain the most of LCC in the procurement, LCC should be implemented in the early design phases, when feasible bridge proposals are designed and evaluated.

The implementation of LCC in procurement of infrastructure will change the bridge designers way of designing their proposals (Safi, 2013). Instead of just considering the investment cost, they will also have to consider the costs during the entire lifespan. However, there exists a big gap between the methods described in the literature and the practical use of LCC in design (Davis Langdon, 2007a). The lack of common methods and practical programs is an obstacle in implementation of LCC in the design process.

1.2 Aim and Objectives

The aim of this thesis was to develop a program that enables the use of LCC for bridge designers in the early design phases, as an indicative tool to which bridge type to design.

To fulfil the aim of the thesis, a number of specific objectives needed to be completed.

- Make the program simple enough, so that it could be used by bridge designers with limited experience of LCC
- Find reliable sources of information regarding investment and maintenance cost
- Identify the most expensive bridge parts and details from a maintenance perspective, for a bridge during its life span
- Show the need of LCC in the design phase by a comparison between three different bridge cases

1.3 Limitations

This thesis was limited to analyse road bridges in Sweden with a total span length between 10 and 95 meters. The bridges were constructed as slab, frame or beam bridges in either reinforced concrete or as composite structures with steel beams and concrete deck.

The study focused on the economic aspects of life cycle analysis, as environmental and society aspects were more difficult to measure. Also, the study centered on analysing existing cost records, and not performing simulations. Finally, the analysis was made to offer a comparable value between different bridge types, and not provide actual costs.

1.4 Method

In order to achieve the outlined aims of this thesis, a literature study focusing on LCC, infrastructural procurement in Sweden and general bridge knowledge was carried out. A deeper understanding of the LCCA-process as well as identifying previous work in the area were key parameters to be able to find, describe and develop a LCC-program. It was also of importance to identify eventual demands set by the STA to be able to adopt the LCC-program in the early planning stage in bridge procurement.

Historical cost records of more than 800 road bridges, built in Sweden, was collected from the STA and sorted into 14 different bridge types. These cost records were used to create an Excel-based program to calculate the life cycle cost of a bridge. The program was divided into two parts where one part calculated the investment cost of the bridge based on cost records of previous built bridges. While the other, predicted the life span maintenance cost based on the size of structural members and the life span. Crucial parts or structural members regarding maintenance cost were identified in order to predict the foremost cost drivers regarding the maintenance. Also, a guide of how to use the program was created.

2 Life Cycle Cost

Life cycle cost can be defined as the total cost of a product or asset over its entire life span (Swedish Standards Institute, 2008). Previous studies have argued, that implementation of LCC as a decisive parameter in the procurement of new infrastructure is an important development (Dhillon, 2010), (Safi, 2013) and (Davis Langdon, 2007a). Life cycle cost analysis (LCCA) is a method of summing up the LCCs for a specific object and present them as a cost in net present value (NPV) or equivalent annual cost (EAC) (Dhillon, 2010). LCCA is a suitable tool to compare different alternatives, which would provide the same service for the user. Although a vast amount of literature exists in the field of LCCA, the majority of the literature describes LCCA in a conceptual form, but there are few examples on the use of LCCA in practice (Davis Langdon, 2007a) (Safi, 2013). In a comprehensive literature review by (Davis Langdon, 2007a) it was concluded that a common application of LCCA did not exist in Sweden, which also was supported in a doctoral thesis by (Safi, 2013).

The costs that should be included in an LCCA is different for different areas of application (Dhillon, 2010). The most common costs used in infrastructure procurement and management are: *agency cost,* which describes all direct costs for the agency during a life span, *user cost,* which describes the benefits or losses of the users and *society cost,* which evaluates the aesthetic and cultural values as well as the environmental impact, see Figure 2.1 (ETSI, 2013), (Safi, 2013) and (Thoft-Christensen, 2012).

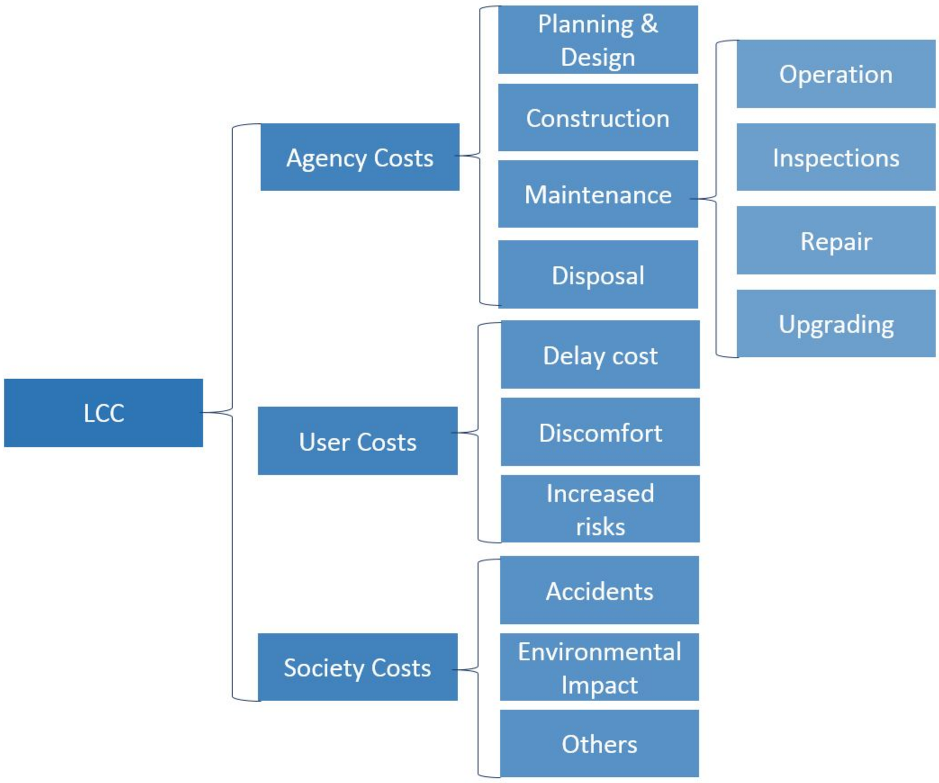


Figure 2.1 Outline of a complete LCCA (ETSI, 2013)

2.1 Agency Cost

The agency cost represents all the costs acquired by the bridge owner during the entire life span of the bridge (Safi, 2012). This includes categories such as investment costs, maintenance costs and demolition costs. Agency cost would be relatively easy to predict, if a life cycle plan is established. A life cycle plan is an estimation of the life cycle measures

(LCM), such as operation and maintenance during the service life of the bridge, and this data can be acquired from a bridge management system (Safi, 2013). In Sweden the STA provides an online database called BaTMan (Bridge and Tunnel Management) where information about Swedish bridges from 1944 can be found and used in the life cycle plan.

2.2 User Cost

The user cost considers the indirect costs of the users, for example drivers and transported goods, that occurs in case of maintenance (Hawk, 2003). Maintenance activities can limit the functionality of the bridge causing increased costs for the users because of longer traveling time or detours. User cost is characterised by driver delay and vehicle operation cost, where the first considers lost hours for the driver, whilst vehicle operating cost is the additional operation time of the vehicle (ETSI, 2013).

2.3 Society Cost

Society cost represents the costs or benefits imposed on the society, usually consisting of vaguely defined parameters such as aesthetics, which is difficult to put a monetary value on (Safi, 2013). Society cost also include environmental aspects, where the use of non-renewable materials is one (ETSI, 2013). However, environmental aspects are difficult to measure economically since they are based on vaguely defined parameters and has to be converted to assessable values in order to be included in the LCCA (Safi, 2012). Easier to measure is the traffic accidents and their society costs in form of health-care and deaths (ETSI, 2013).

2.4 Life cycle Cost Analysis Methodology

In the literature about LCC, a number of different methodologies are introduced (Hawk, 2003) (Davis Langdon, 2007b) (Dhillon, 2010) (Thoft-Christensen, 2012) (ETSI, 2013) (Safi, et al., 2015). The methodology introduced by (Davis Langdon, 2007b) is thorough and applicable to all kinds of projects, including infrastructure. It follows twelve consecutive steps, were for some cases, several steps may be combined to reduce the amount of work.

The twelve different steps are as follows:

1. Identifying the main purpose of the LCCA
2. Identify the initial scope of the analysis
3. Identify the extent to which sustainability analysis relates to LCC
4. Identify the period of analysis and the methods of economic evaluation
5. Identify the need for additional analyses e.g. sensitivity analysis
6. Identify project and asset requirements
7. Identify options to be included in the LCC exercise and cost items to be considered
8. Assemble cost and time data to be used in LCCA
9. Verify values of financial parameters and period of analysis
10. Perform required economic evaluation
11. Interpret and present initial results in required format
12. Present final result in required format and prepare a final report

2.5 Economic Models

Investments made over a longer period of time will raise the need to consider costs that occurs both in the past, present and future (ASEK, 2015). The fact that money at hand today is more valuable than they are in the future makes it necessary to present alternative methods to account for this. The net present value method (NPV) and the equivalent annual cost method (EAC) will be described in Section 2.5.1 and 2.5.2. EAC is preferable when comparing investments with different life spans (Safi, 2012). For projects lasting longer than a year, the construction costs should be considered as end values of that period, so that the present value is calculated from the date where the asset is put to use (ASEK, 2015). An important factor when calculating NPV and EAC is the discount rate, which considers the changing pace of costs over time. STA has set the discount rate to be used for infrastructural projects in Sweden to 3.5 percent (ASEK, 2015).

2.5.1 Net Present Value

The Net Present Value is a method converting future costs to a present value (ASEK, 2015). By doing so for all costs that occur during the life span, a present, comparative cost of the investment is obtained. NPV is the most common way to account for future costs and can be calculated as in Equation (1) according to (Safi, 2012).

$$NPV = \sum_{n=0}^{L} \frac{C_n}{(1+r)^n} \qquad (1)$$

Where:

NPV – Life cycle cost expressed as Net Present Value

L – Service life span

n – Year of consideration

C_n – Sum of all cash flow in year n

r – Discount rate

2.5.2 Equivalent Annual Cost

Equivalent annual cost is expressed as the annual cost of a long time investment, which makes it more suitable to compare investments with different life spans (ASEK, 2015). Naturally, the alternative with the lowest annual cost is the most preferable option and the EAC is calculated by multiplying the NPV with the annuity factor, see Equation (2) (Safi, 2012).

$$EAC = NPV \times A_{t,r} = NPV \times \frac{r}{1-(1+r)^{-L}} \qquad (2)$$

Where:

EAC – Equivalent Annual Cost

$A_{t,r}$ – Annuity factor

r – Discount rate

L – Service life span

2.6 Cost prediction

The results from an LCCA is highly dependent on the costs associated with the assets lifespan (Dhillon, 2010). Therefore, it is essential that the costs used as input data into the analysis are valid and correct. However, prediction of future costs is difficult and sometimes impossible to carry out. This may cause a problem for LCCA as it can make the results from the analysis misleading. The uncertainty in prediction of costs can for maintenance costs be helped with a database including historical records of similar work. This database is something that already exists in Sweden and many other countries (Davis Langdon, 2007a). For society and user cost it is much more difficult since the costs themselves are the results of economic models based on assumptions that can be more or less accurate (ETSI, 2013). The long service-life of a bridge makes these costs even more uncertain, as it is hard to predict factors like average daily traffic 80 years from now.

2.7 Sensitivity Analysis

As mentioned in Section 2.6, almost all costs in the future are assumptions and predictions based on more or less reliable data (Dhillon, 2010). The problem with cost prediction can be divided into two parts, risk and uncertainty (ASEK, 2015). Risk is when the probability of certain outcomes is known, whereas uncertainty describes a situation when the probability of certain outcomes is not known. Risk is handled in the LCCA by using expected values of the costs, and these expected values are based on the different values of the cost and the probability that they will occur. However, it is common that the probability of the costs occurrence is unknown and therefore a sensitivity analysis is needed.

In sensitivity analysis a number of different LCCA are performed were one variable is changed at a time (ASEK, 2015). The results of these calculations are assessed to find out how sensitive the results of the LCCA are to the changes of specific variables. Using this analysis can let the decision makers know what importance uncertainty has on their decision.

3 Procurement of Infrastructure in Sweden

Most procurement and management of infrastructure in Sweden is managed by the STA (Swedish Transport Administration, 2015). The STA is a public agency and as such it has to follow the Swedish Public Procurement Act (PPA) (Konkurrensverket, 2014). This act exists to make sure that public funds are spent in the most cost-efficient way, and it is applicable when the public authorities purchase a service or a product (Konkurrensverket, 2014). For bridge procurement, the decisive parameter is usually the investment cost, including costs for design, material and labour, while not involving costs for maintenance and reparation (Safi, et al., 2015). This means that bridges that are cheap to build, but expensive to maintain are favoured over bridges that could be more cost-efficient over their entire life span. However, with the use of LCC as the decisive parameter a more cost-efficient bridge could be procured. Therefore, the STA initiated a research project in collaboration with the Royal Institute of Technology to implement LCC in the procurement process (Safi, 2013). The main focus of this research project was to implement LCC in the procurement process, and was targeting the Design-Build process rather than the Design-Bid-Build process. One of the outcomes of the project was a technique called "LCC added-value" that was used in a real bridge procurement. This procurement and the technique are presented in Section 3.3.

3.1 Design-Bid-Build

When the client is responsible for the design of the bridge and a contractor is being procured only to construct the bridge a Design-Bid-Build contract is usually used (Nilsson & Pydokke, 2007). The client produces and provides drawings, quantities of building materials, labour time and details of how the work is going to be carried out. The contractor that delivers the lowest bid of this is awarded the project. The process is illustrated in Figure 3.1.

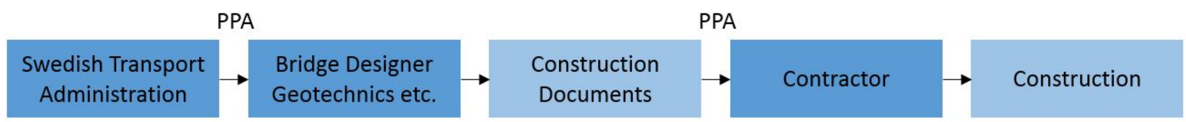


Figure 3.1 Outline of bridge procurement during a Design-Bid-Build process

The benefits of using this contract form is that the client is certain of what it will get, but it is argued to be both slow and ineffective (Lingegård, et al., 2012).

3.2 Design-Build

In the case of a Design-Build contract the client procures the contractor in an early stage to allow them to both design and build the bridge (Nilsson & Pydokke, 2007). Before the tendering process the client procures a bridge designer, produces a schematic description of the bridge that specify location, length, width and functionality demands. In some cases, one or more preliminary design proposals of the bridge can be included. In the tendering process, contractors and bridge designers work together to present the cheapest bridge to be built and the lowest bid (i.e. the lowest investment cost) is the winning one. The Design-Build process can be seen in Figure 3.2.

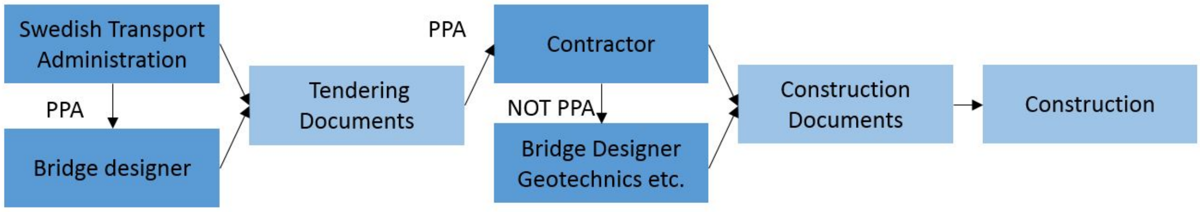


Figure 3.2 Outline of bridge procurement during a Design-Build process

This contract form enables a better use of the contractors knowledge of how to build a bridge in a more cost-efficient manner and can therefore provide a cheaper bridge than what could have been achieved in a Design-Bid-Build procedure (Safi, et al., 2015).

3.3 LCC Procurement in Practice

The use of LCCA in the procurement of infrastructure in Sweden today is scarce (Safi, et al., 2015). One of the biggest obstacles to overcome is the Public Procurement Act that creates a number of problems concerning the implementation of LCCA because the contractors' bids have to be reviewed transparently. Since the contractors are often only responsible for the erection of the bridge and have no responsibility regarding maintenance or reparation they could underestimate the LCM costs. If the client where to examine the LCCs from the different contractors this would also cause a problem since different analyses could come to different results.

There are some examples of how LCCA could be implemented in bridge procurement according to (Safi, et al., 2015). One is to use it in the Design-Bid-Build where the client performs a LCCA in the early planning stage to compare feasible bridge proposals. The most cost-efficient bridge proposal is selected and described in the tender documents as the target design. The contractors are then able to hand in their tenders and the lowest bid wins the tendering process. This approach is easy to perform but may result in a less cost-efficient bridge, mainly because of the uncertainty in the initial LCCA.

Another approach presented in the article by (Safi, et al., 2015) is a novel technique, to use LCCA in the Design-Build process, called LCC added-value analysis. The technique is meant to allow bridge procurers to form a number of monetary LCC-benchmarks for the tendering documents.

LCC added-value is used in the early phase of bridge procurement before the contractors are contacted to presents their tenders (Safi, et al., 2015). In this phase a number of feasible bridge types are examined using records of existing bridges with similar dimensions and demands. The records are used to asses the investment cost and the cost of the LCMs for each proposal to determine which is the most cost-efficient choice. The winning bridge proposal is established as a set point in the analysis and depending on if the other alternatives have higher or lower cost of the LCMs, they receive an added or subtracted value in the tender documents. When the contractors hand in their offers of the cost of constructing the bridge, their bids are added or subtracted with the value corresponding to the bridge type they have chosen. The winning bid is therefore not the one with the lowest investment cost, but rather the one with the lowest LCC. This technique makes it possible to use the contractors' knowledge in bridge construction and therefore a more cost-efficient bridge may be procured.

In the work by (Safi, et al., 2015) a hypothetical example of how this technique can be applied is presented, see Table 3.1. In this example the client considers five bridges in the early planning stage, but the contractors only delivers bids on four of them. No contractor delivers bids on bridge E, even though it is the most cost-efficient. This is probably because that bridge could have been harder to build or that the contractors are more used to work with the other bridge types. The winning bid is the one delivered by contractor three who plans to build bridge C.

Bridge	A	B	C	D	E
Anticipated Investment Cost (Client)	170	115	117	124	115
NPV of LCM Cost	21	22	18	17	16
NPV of Total LCC	191	137	135	144	131
Cost-effectiveness rank	Fifth	Third	Second	Fourth	**First**
LCC added-value	5	6	2	1	0
Contractor (Bridge)	1 (A)	2 (B)	3 (C)	4 (D)	
Contractors bid	164	125	122	146	
LCC	169	131	124	145	
Cost-effectiveness rank	Fourth	Second	**First**	Third	

Table 3.1 Hypothetical Example of LCC added-value technique (Safi, et al., 2015). All costs in million SEK

4 Bridges in Sweden

Bridges can be divided and named in a number of different manners (Swedish Transport Administration, 1996). The most common way in Sweden is to divide after the type of traffic that travels the bridge (trains, cars, pedestrians), what material that has been used to construct the bridge (reinforced concrete, prestressed concrete, steel), and how the bridges' load carrying systems works (beam, slab, arch, supsension). Also, the bridges are divided according to their support conditions (fixed, simply supported, continuous).

In this chapter the most common bridge types for car traffic with total span length between 10 and 95 meters are presented.

4.1 Frame Bridge

Frame bridges are the most common bridge type in Sweden (Swedish Transport Administration, 1996). They are composed of either a slab or a beam structure fixed at the supports, see Figure 4.1, and are referred to as a slab-frame bridge or a beam-frame bridge, respectively. Both the slab-frame bridge and the beam-frame bridge can be constructed of reinforced and prestressed concrete and are used mainly for single span bridges. The slab-frame bridge with reinforced concrete is argued by (Swedish Transport Administration, 1996) to be the most economically preferable bridge type at moderate span lengths up to 25 meters. However, with prestressed concrete the span lengths can be increased up to 35 meters.

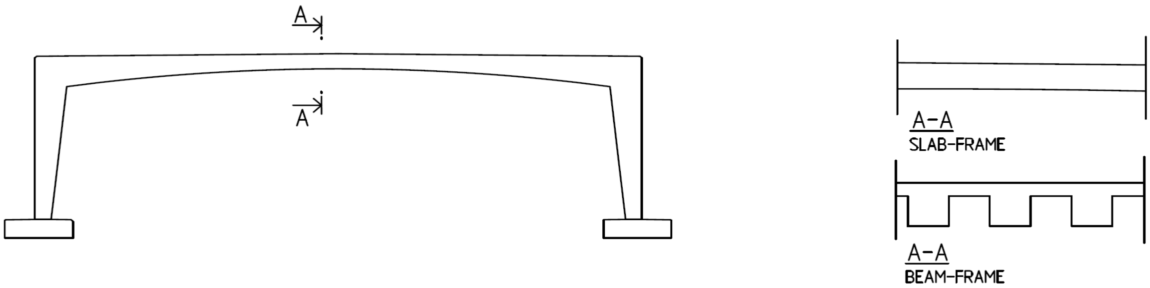


Figure 4.1 Schematic figure of a slab-frame and a beam-frame bridge

4.2 Simply-Supported Bridge

A simply supported bridge can be constructed as either a beam or a slab structure resting on bearings at the supports (Swedish Transport Administration, 1996). This bridge type is mostly used for single span bridges, and it is suitable when there are expected settlements at the supports. This bridge type is advantageous because of the ability to handle movements due to, for example temperature changes. However, these movements can be quite large, so to ensure that the bridge is functional an expansion joint is needed. The slab bridge is preferred when a small construction height is necessary but is argued to be less economical compared to a beam bridge when the span lengths are over 18 meters. In Figure 4.2 a schematic example of a single span simply supported bridge can be seen.

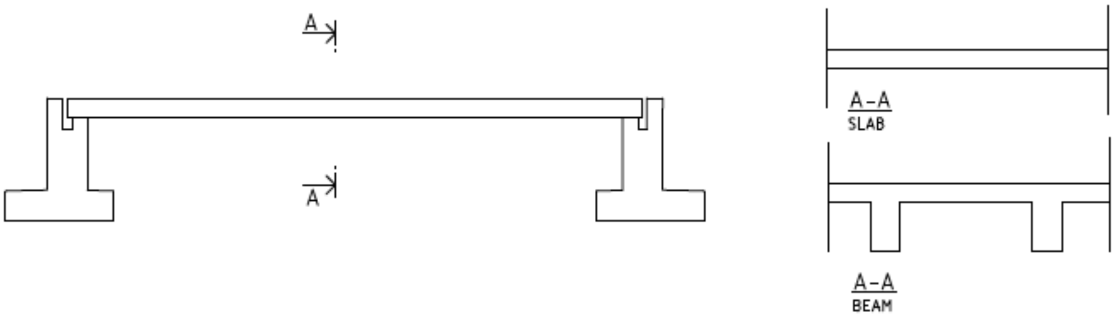


Figure 4.2 Schematic figure of a slab and beam bridge

Aside from the slab bridge and beam bridge, the simply supported bridge could also be made out of a concrete deck resting on a steel structure, i.e. composite bridge, see Figure 4.3 (Swedish Transport Administration, 1996). This bridge type is claimed to be faster to construct because of the possibility to lift the lighter steel structure in place without having to use any scaffolding. Nevertheless, the steel structure is more sensitive to collisions, so the height from the road underneath often needs to be increased.

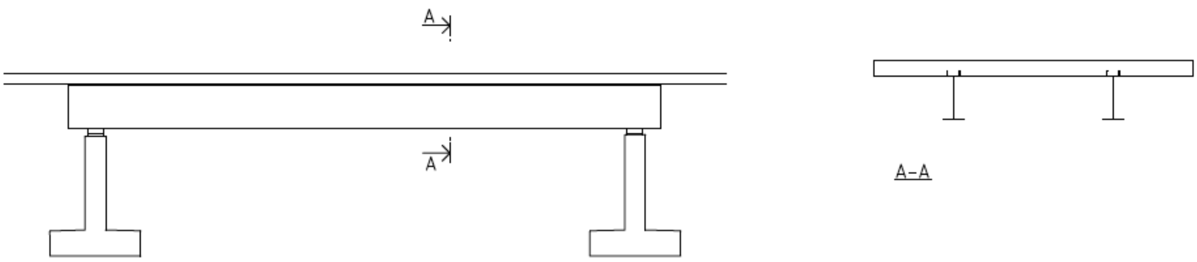


Figure 4.3 Schematic figure of a steel bridge with concrete deck

4.3 Continuous Bridge

A continuous bridge is a bridge type comprised of more than one span and is needed when the total span length of a bridge becomes to large (Swedish Transport Administration, 1996). The continuous bridge can be performed both as a slab and beam bridge, and as both simply supported and fixed at supports, even though it is more common with simply supported supports. The piers are often designed as plates as wide as the bridge for the slab bridges, and for the beam bridges they are often designed as cylinders or cuboids.

4.4 Bridge Structural Members

The most common bridge members are presented and described below according to the (Swedish Transport Administration, n.d.) and Figure 4.4, Figure 4.5 and Figure 4.6 distinguishes the specific members and their location on the bridge.

Superstructure	*The part of the bridge that supports traffic and rests on piers and abutments. Includes deck, slab, girders, edge beams, expansion joints, railings and bearings*
Substructure	*Situated between the superstructure and the foundation. Includes abutments and piers*
Foundation	*Transfers the loads from the substructure to the ground*

Railing	*Restricts lateral movement of traffic on the bridge*
Bearings	*Transfers load from superstructure to substructure, while sometimes allowing movements of the bridge*
Girders	*Distributes load from slab to bearings*
Abutment	*Supports the superstructure at its ends and retains the soil*
Pier	*Supports the superstructure at the end of its spans*
Approach slab	*A link between the approaching road and the bridge*

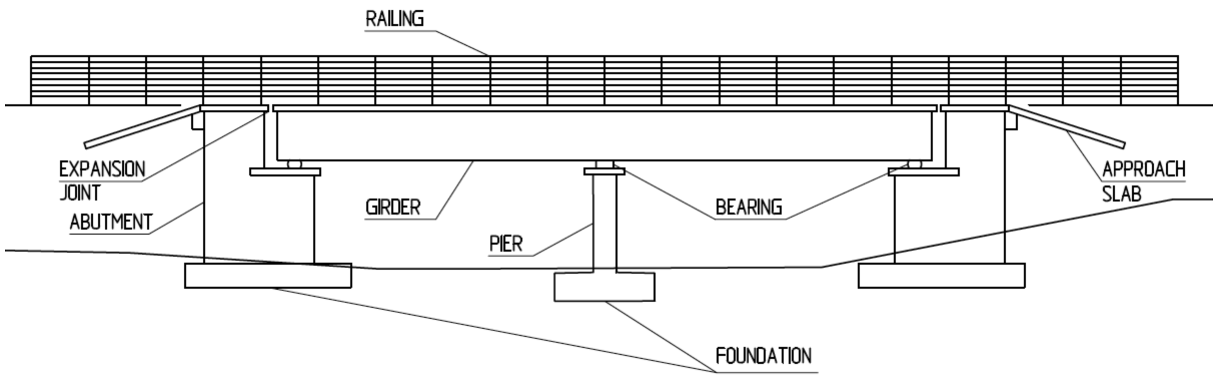


Figure 4.4 Profile of simply supported bridge

Edge beam	*Sometimes works as a structural member, but mainly serves as an attachment member for the railing*
Surfacing	*Distributes traffic loads and protects the slab*
Slab	*Transfers the traffic load to the main load bearing elements*
Drainage system	*Transports water of the bridge*

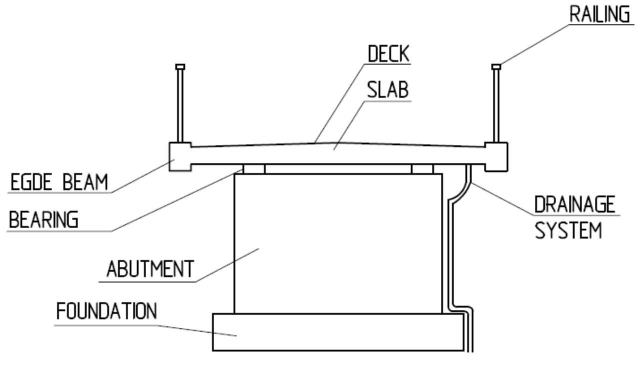


Figure 4.5 Cross section of the bridge deck

Expansion joint *Handles the longitudinal movements of the bridge deck and protects the underlying parts*

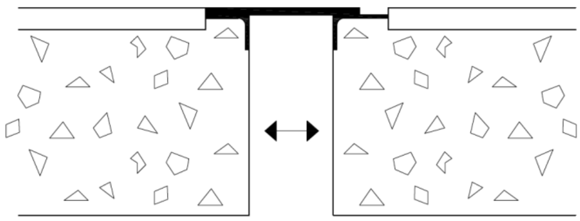


Figure 4.6 Example of an expansion joint design

5 Development of SimpleBridgeLCC

An Excel-based program, called *SimpleBridgeLCC,* that calculated the anticipated LCC of Swedish road bridges was developed. The program was split into two parts, where one part calculated the investment cost and the other part calculated the maintenance cost during the life span of the bridge. The investment cost was based on cost records of existing bridges. Meanwhile, the maintenance part considered the most common maintenance measures, combined with the costs and planned intervals of the measures.

5.1 Background

Performing LCCA is problematic since future costs and events has to be predicted (ETSI, 2013). This could be solved by looking into historical data and analyse it to predict the future, or, as previous LCC software tools has handled it, by using simulations and statistical models. However, the user has to be very experienced in order to perform these simulations in an accurate way (Davis Langdon, 2007a). Furthermore, these simulation software tools need a lot of input data to provide accurate results, therefore they are unfit to use when a simple estimation is desired.

In Sweden, a bridge management system exists in the form of an online database called BaTMan. It contains information about repair, strengthening and maintenance, as well as cost records of both these actions and construction on over 30 000 bridges (Swedish Transport Administration, 2016). The costs that are presented in BaTMan is usually a total amount that represent several expense items, but those expenses are rarely stated in detail why it usually is hard to make out specifications within the costs that are presented in BaTMan.

In the early design phase of a bridge project, little information is specified about the bridge, and it is at this phase the largest savings regarding LCC can be obtained (Safi, 2013). At this stage of the project the focus is to find the most efficient bridge type to the given setting, and this is primarily based upon length, width, number of spans and annual average daily traffic. Although, user cost and society cost are important aspects of an LCCA they require a more thorough and time consuming analysis. Furthermore, as the user cost mainly focuses on delays and detours due to maintenance work, focus of this thesis was on concrete bridges and user cost.

5.2 Investment Cost Part

The investment cost of a bridge is the total cost of constructing the bridge. The investment cost part of *SimpleBridgeLCC* was designed to predict the investment cost of different bridge types based on the input length and width.

5.2.1 Data Collection

Data of interest for the part was extracted from BaTMan with the assistance from employees at the STA. The data was presented in the following categories:

- Construction number
- Construction length
- Construction year
- Construction type
- Type of traffic on the bridge
- Investment cost
- Bridge area
- Width
- Construction material
- Number of spans
- Length of spans

5.2.2 Sorting of Data

As BaTMan contains information of over 30 000 bridges and only certain types of bridges were of interest for the study, a selection of what data to include was carried out. First, all items with insufficient information was removed (no investment cost, the structure was not a bridge and unclear cost specification). Second, only bridges with car traffic as main traffic load were selected, since the traffic loads and demands on other kinds of bridges are different. Third, only bridges with total span length between 10 and 95 meters were chosen. Fourth, only bridges with concrete as a main construction material was included. Finally, end spans with length below five meters were not included in the category of number of spans as they were most likely overhangs to the main spans.

After sorting out the data, a total number of 891 bridges remained. These bridges were split into categories based on load-carrying system, support condition, construction material and number of spans. This categorization resulted in 21 different bridge types, and the main categories were simply supported beam and slab bridges, as well as, slab-frame and beam-frame bridges. The majority of the bridges were made out of either reinforced concrete or prestressed concrete, but several simply supported beam bridges were composite bridges. Also, bridges with up to four spans were represented in the selection.

The investment costs in BaTMan are based on the information that was admitted at the finalization of a bridge project. In order to create a comparable pricelist, the investment cost was calculated to an equivalent value of the present year 2016. Even though the methods described in Section 2.4 could be used to provide this value, a more reliable source of information was Statistics Sweden. Statistics Sweden has collected information about prices in Sweden since 1914 and provides conversion factors to convert historical cost to a present value (Statistics Sweden, 2014). Using the Net Price Index as a conversion factor, the investment cost of all bridges could be calculated to a present value in order to be comparable to each other. The Net Price Index covers the years from 1980, so for bridges built before that year the Consumer Price Index from Statics Sweden is used (Statistics Sweden, 2016).

The width and the length of the bridges had a strong impact on the investment cost of the bridges. Therefore, to find a comparable value between the bridges, the investment cost was divided by the bridge area and the cost per square meter was determined. Furthermore, a 95 percent confidence interval was applied to the cost per square meter, length and width respectively for each specific bridge type. This was done in order to ensure that extreme values would not have a large effect on the results of the calculations.

After removing the data outside of the confidence interval, only 14 bridge types were deemed to have enough information to perform an analysis on. For two bridge types, slab bridge in reinforced concrete and composite beam bridge, multiple spans were combined into one category. When the sorting was completed 681 bridges remained to analyse. The cost data for the remaining bridge types was plotted against the width and the total span length and these figures can be seen in Appendix A.

5.2.3 Development

Two different approaches to estimate the investment cost were developed in Excel. The first one was based on trend lines for each specific bridge type. The second approach matched bridges with similar width and total span length to calculate a mean investment cost. The first approach was rejected due the fact that it provided insecure and misleading results, while the other provided more transparent and accurate results.

5.2.3.1 Trend Line Based Approach

By dividing the investment cost by the bridge area a comparable value in SEK/m^2 was achieved and these costs were plotted against the total span length and width of the bridge, respectively. Using linear regression analysis by inserting linear trend lines in the plots, equations of how the cost varied according to total span length and width, respectively, were acquired. As two equations were provided, one for *cost - total span length* and another for *cost – width*, a mean value of the two were chosen since they were rated as equally important. The bridges were separated into categories based on bridge type, construction material and number of spans, and equations were obtained for each combination. The result is an Excel based program providing the cost from the equations (SEK/m^2) for 14 different bridge types based on the inputs bridge length and width.

Not a single bridge type had a cost interval represented in the whole allowed span of length (10 to 95 meters) or in the acquired span of width (3 to 30 meters). A consequence of this was that the program could not predict an accurate cost if the input data was too far outside out the bridge types cost interval. So, a warning device was installed in the program, letting the user know if the specified input data was outside of the cost interval for a specific bridge type.

To ensure that the trend lines were accurate, the coefficient of determination (R^2) was calculated for all bridge types. The R^2-value describes how well a scatter can be predicted by a trend line. The value can be between one and zero, where one is if all points can be described by the line and zero displaying a scatter more similar to a shot gun. However, as none of the bridge types had a R^2-value above 0.5 and the majority was below 0.1, see Appendix B, the results from the program was untrustworthy and a new approach was elaborated.

5.2.3.2 Similar Attributes Approach

In the second approach a different Excel-based program was developed to predict the investment cost of the 14 different bridge types. In this program the cost data for bridges with similar dimensions would be sorted out from the rest and used to calculate a mean value.

In order to predict the cost for the bridge types based on total span length and width, the program was designed to find the cost records for bridges with length and width inside a specified interval based on the input provided by the user. The intervals were based on the standard deviation for each specific bridge type, which meant that all bridge types had different sizes on their intervals. The cost records chosen to calculate the mean investment cost had to be related to a bridge that had both length and width inside these intervals.

To make the program more transparent, the intervals for each specific bridge type was presented along with the number of cost records used to calculate the mean value. The warning sign declaring if the input values was outside of a bridges allowable cost interval was kept the same as for the trend line program, with a small addition. For the *similar attributes approach,* the input data was allowed to be outside of the cost interval, to some extent. For total span length, the interval was extended to include the nearest five meters, and for width it was extended to include one meter outside of the interval. The width and length for which the bridge types are valid is presented in Figure 5.1 and Figure 5.2.

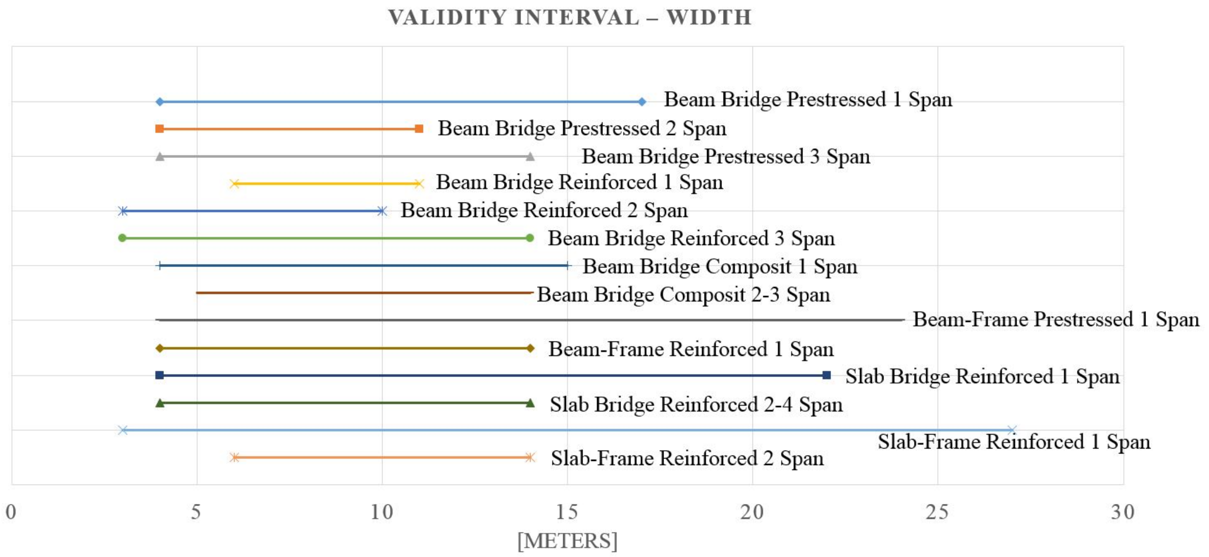


Figure 5.1 Validity interval – Width

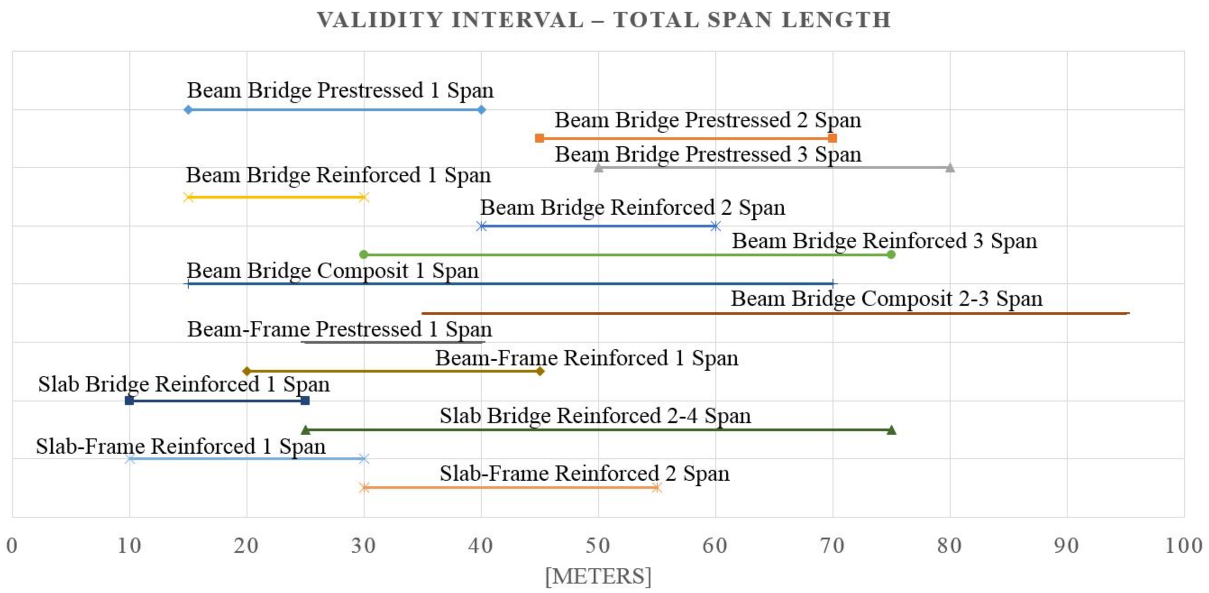


Figure 5.2 Validity interval - Length

To make the program more adjustable, the intervals for searching matching bridges could be increased or decreased based on the number of standard deviations to include. If the number of standard deviations included provided a larger number of bridges than desired in the selection it could be decreased and vice versa.

In Figure 5.3 and Figure 5.4, it is presented how the program uses the standard deviation in order to select which bridges to use in the calculations. It is shown for both width and total span length, and in each figure the bridges that matched both the interval for width and length are marked as circles and the other bridges are marked as crosses. The example is a prestressed beam bridge in three spans with a length of 70 meters and a width of 11 meters with the number of standard deviations included set to one.

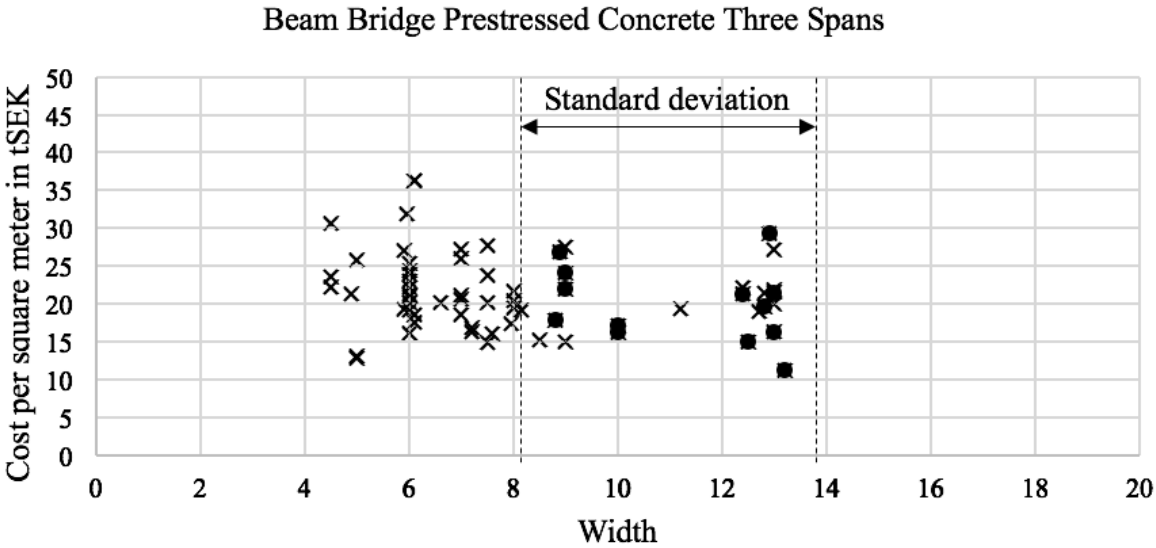


Figure 5.3 Selected bridges, an example of a prestressed beam bridge in three spans - Width

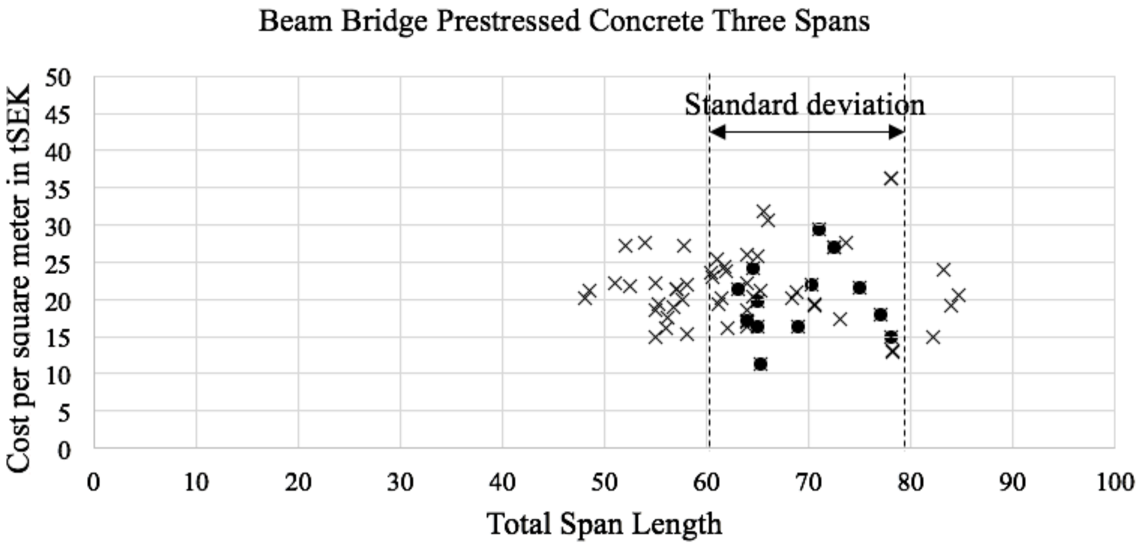


Figure 5.4 Selected bridges, an example of a prestressed beam bridge in three spans - Length

5.3 Maintenance Cost Part

The measures needed during the life span of a bridge are both the planned maintenance, which is rather easy to predict, and reparations due to accidents which are more irregular. The part of *SimpleBridgeLCC* developed to predict the maintenance cost focuses only on the first part, planned maintenance.

5.3.1 Data Collection

The data was based on the same type of bridges as the investment cost, with construction length of 20-100 meters and built later than 1960. The digitalization of maintenance measures at the STA begun in the 1980's and therefore achieved data from BaTMan just covers the years from 1985 to present day. Originally, more than 8 500 measures where gathered in the following categories:

- Construction number
- Construction year
- Type of traffic on bridge
- Year of measure
- Type of measure

The costs of various measures was obtained from the 2015 unit price list for bridge maintenance produced by the STA (Swedish Transport Administration, 2016) and from the case study performed by (Safi, et al., 2015), see Appendix C.

The interval between the execution of different measures was obtained through correspondence with the person responsible for maintenance of road bridges in the western part of Sweden at the STA. The intervals suggested for each measure is presented in Table 5.1. A verification of the intervals was made by comparing STA's intervals with the intervals acquired from BaTMan. The measures collected from BaTMan were plotted in diagrams showing the amount of measures performed each year after construction for each specific maintenance measure, see Appendix D. The only measures that did not correspond well were maintenance of expansion joints and paint improvement of the steel superstructure. The information about the later was in this case unreliable as only 15 measures were reported in BaTMan. Considering the expansion joint, the information from BaTMan was with regard to reparations rather than the yearly maintenance that STA recommends. Hence, the intervals proposed by the STA were chosen.

5.3.2 Sorting of Data

From the vast number of measures that were received from BaTMan some were removed, mainly due to insufficient information (e.g. not specifying construction part), but also the fact that they were performed on pedestrian or railway bridges. Further, the measures were arranged according to type of measure, and from this sorting the most common ones were achieved. The latter selection was based on 5 478 measures taken between 1985 and 2016 and on bridges built from 1961 to 2015. The most common measures are shown in Table 5.1. Measures regarding concrete repair were weighted proportionally according to the severity of the reparation. The unit price list is divided into "Concrete repair 0-30 mm" and "Concrete Repair >30-70 mm" why the weighting was necessary. The weighting process can be seen in Appendix E.

Table 5.1 The most common bridge measures

Bridge Part	Measure	Interval (years) According to STA experience	Interval (years) Chosen as input in *SimpleBridgeLCC*
Expansion Joint	Maintenance	1	1
	Replacement	30-40	35
Edge Beam	Impregnation	15	15
	Replacement	30-40	35
Railing	Replacement	30-40	35
Bearings	Paint Improvement	30-40	35
Drainage system	Supplementation	30-40	35
	Replacement	30-40	35
Superstructure - Steel	Paint Improvement	40	40
Superstructure - Concrete	Concrete Repair	30-40	35
Waterproofing	Replacement	30-40	35
Wearing course	Replacement	15	15
Pier	Impregnation	15	15
	Concrete Repair	30-40	35
Abutments	Impregnation	15	15
	Concrete Repair	30-40	35

5.3.3 Development

In order to get an accurate estimation of the LCCs of the maintenance costs more information than length and width of the bridge was needed. Therefore, this part of *SimpleBridgeLCC* was designed with regards to the size of the structural members of the bridge, rather than just length and width.

In order to get this to work, the unit price of the measures described in Table 5.1 was entered into the program. The cost of a certain measure was then calculated based on the size, length or number of pieces of the structural member and the unit price. This cost was then calculated to a NPV using the approach described in Section 2.5.1. After all the measures had been calculated in this manner they were summed up and presented as LCC. An example of how the costs are calculated and summed up is shown in Table 5.2.

Table 5.2 Calculation of maintenance costs of edge beams over a life span of 80 years and total length of 60 meters

Bridge Part	Measure	Interval (years)	Unit	Unit Price (SEK)	Total Cost	Net Present Cost
Edge Beam	Impregnation	15	m	400	24 000	14 325
	Impregnation	30	m	400	24 000	8 551
	Impregnation	50	m	400	24 000	4 297
	Impregnation	85	m	400	-	-
	Impregnation	100	m	400	-	-
	Replacement	35	m	13 000	780 000	233 982
	Replacement	70	m	13 000	780 000	70 189
	Replacement	105	m	13 000	-	-
					1 632 000	**331 345**

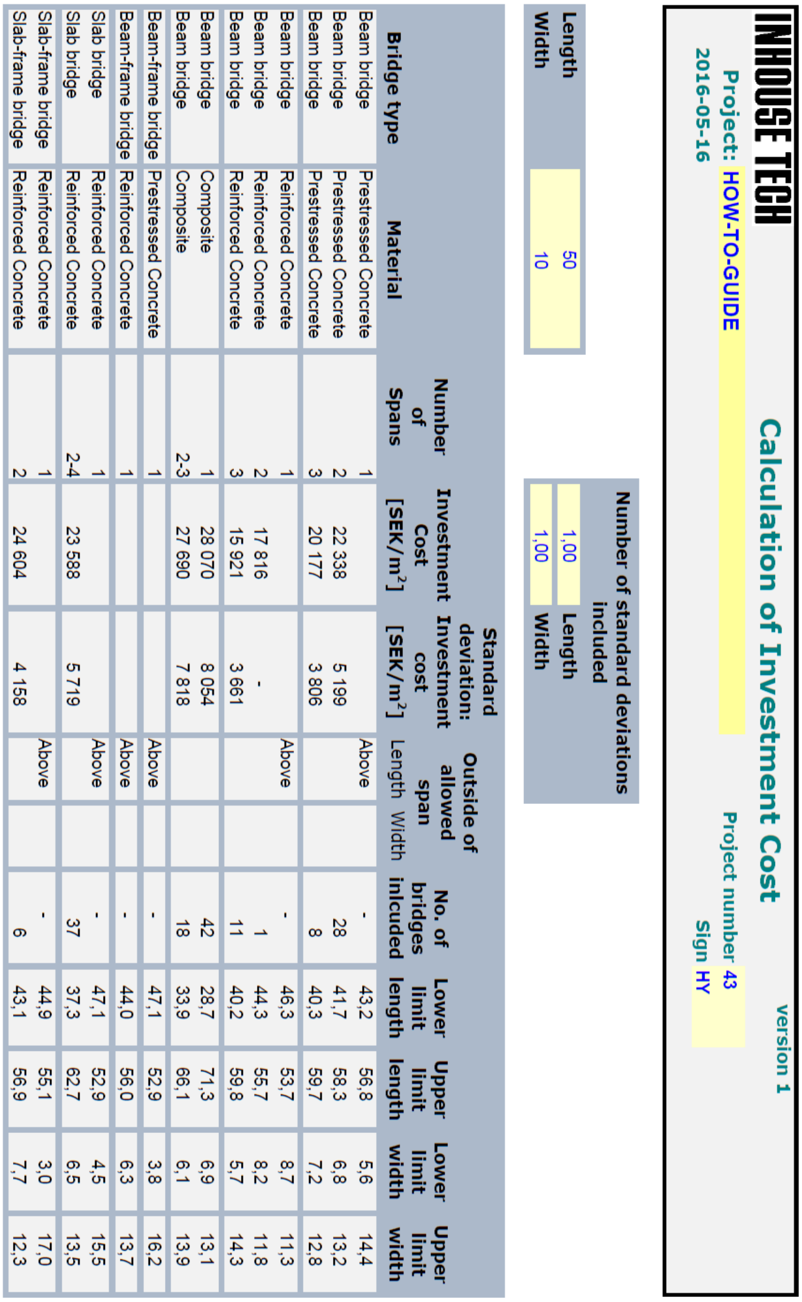
An option considering the exposure class of piers and abutment were implemented with three options, *high* for a member close to the roadway, *low* for a member far from the roadway and also a *medium* choice in between. For a member with high exposure class, 100 percent of the exposed concrete area needs to be repaired, medium needs 50 percent and the low options result in 10 percent concrete repair. A default setting was that the concrete girders and slab were considered to have a low exposure class since they are far away from the de-icing salts, and therefore 10 percent of its area will be repaired.

6 How to Use SimpleBridgeLCC

In order to facilitate the use of *SimpleBridgeLCC,* this short guide was created. For a more thorough description of how the program calculates the costs, see Section 5.2.3.2 and 5.3.3.

6.1 Investment Cost

The preface of the investment cost part program is presented in Figure 6.1. The cells denoted *Project, Project number* and *Sign* were implemented for practical reasons while the inputs *Length* and *Width* were chosen to be the basis of the calculation. Dependent on the input of length and width, the outcome in columns *Investment Cost* and *Outside allowed span* change consequently. A change of the *Number of Standard Deviations Included* input, where 1.0 is the default mode, will affect the *Upper* and *Lower Limits* as well as the *Number of Bridges Included* and the *Standard Deviation of Investment Cost.*



INHOUSE TECH — Calculation of Investment Cost — version 1

Project: HOW-TO-GUIDE — Project number 43
2016-05-16 — Sign HY

Length	50
Width	10

Number of standard deviations included	
Length	1,00
Width	1,00

Bridge type	Material	Number of Spans	Investment Cost [SEK/m^2]	Standard deviation: Investment cost [SEK/m^2]	Outside of allowed span: Length	Outside of allowed span: Width	No. of bridges inlcuded	Lower limit length	Upper limit length	Lower limit width	Upper limit width
Beam bridge	Prestressed Concrete	1			Above		-	43,2	56,8	5,6	14,4
Beam bridge	Prestressed Concrete	2	22 338	5 199			28	41,7	58,3	6,8	13,2
Beam bridge	Prestressed Concrete	3	20 177	3 806			8	40,3	59,7	7,2	12,8
Beam bridge	Reinforced Concrete	1			Above		-	46,3	53,7	8,7	11,3
Beam bridge	Reinforced Concrete	2	17 816	-			1	44,3	55,7	8,2	11,8
Beam bridge	Reinforced Concrete	3	15 921	3 661			11	40,2	59,8	5,7	14,3
Beam bridge	Composite	1	28 070	8 054			42	28,7	71,3	6,9	13,1
Beam bridge	Composite	2-3	27 690	7 818			18	33,9	66,1	6,1	13,9
Beam-frame bridge	Prestressed Concrete	1			Above		-	47,1	52,9	3,8	16,2
Beam-frame bridge	Reinforced Concrete	1			Above		-	44,0	56,0	6,3	13,7
Slab bridge	Reinforced Concrete	1			Above		-	47,1	52,9	4,5	15,5
Slab bridge	Reinforced Concrete	2-4	23 588	5 719			37	37,3	62,7	6,5	13,5
Slab-frame bridge	Reinforced Concrete	1			Above		-	44,9	55,1	3,0	17,0
Slab-frame bridge	Reinforced Concrete	2	24 604	4 158			6	43,1	56,9	7,7	12,3

Figure 6.1 Preface of the investment cost program

The methodology presented below is suggested in order to determine the anticipated investment cost of certain bridge types.

1. Enter the total span length of the bridge
2. Enter the width of the bridge
3. Enter the number of standard deviations to include in the search for matching bridges
4. Check the *note*-column. If a warning is present, the chosen length/width is outside the range for which the data is reliable. Focus on the bridge types without a warning
5. If the number of bridges are high for some bridge type, the number of standard deviations can be altered in order to narrow the range, or vice versa
6. Identify the bridge types' investment costs

6.2 Maintenance Cost

The maintenance cost part of the program was provided with more input parameters concerning the shape and properties of the bridge. To use the maintenance cost part of the program, a general outline of the bridge is needed. In addition to the length and width, the bridge type and life span is also necessary to know in order to get a relevant result. The preface of the maintenance program is presented in Figure 6.2.

The methodology presented below is suiting to get an indication of the total maintenance cost during the life span of a bridge. Note that not all categories need to be filled in, for example a frame-bridge usually does not have bearings.

1. Enter the life span of the bridge, from year of construction until the calculated year of demolition
2. Enter the total length of the expansion joints, usually in both ends of the bridge
3. Enter the total length of the edge beams and railings
4. Enter the total surrounding surface area of the steel girders
5. Enter the exposed surface area of the abutments
6. Choose the exposure class of the abutments and piers from the following categories:
    a. *High* – Exposed to de-icing salts
    b. *Moderate* – Exposed to de-icing salts to some extent
    c. *Low* – Not exposed to de-icing salts
7. Enter the total number of bearings
8. Enter the total number of foundation drains
9. Enter the total number of surface drains
10. Enter the total numbers of downpipes
11. The total maintenance cost, expressed as a net present value, is presented in the table on the right

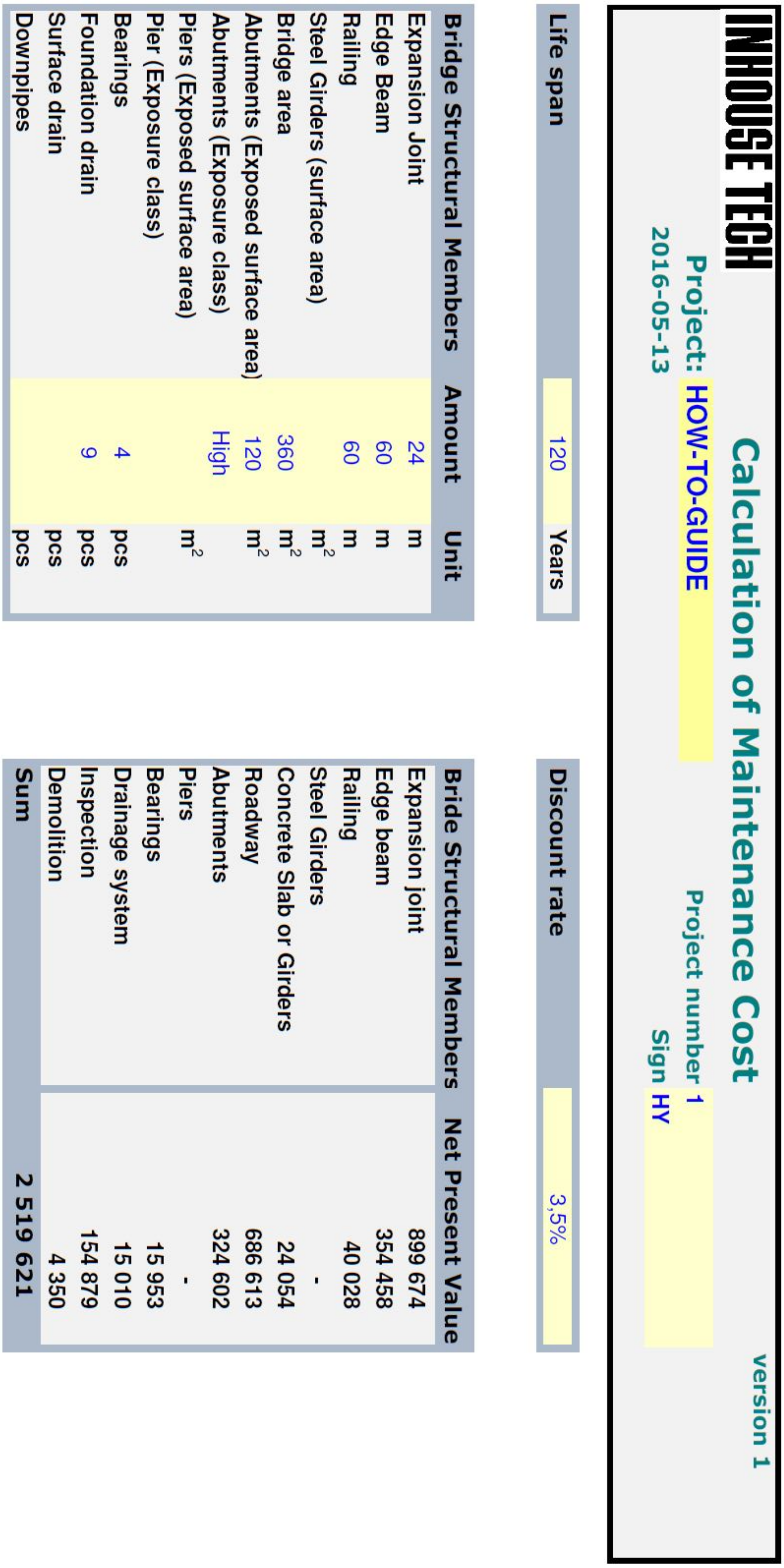


Figure 6.2 Preface of the maintenance cost program

7 Case Result

Three cases were analysed in order to show the usefulness of *SimpleBridgeLCC*. They were specified to be of different length and width to show how the program handles different input data. The three cases had a total span length of 20, 30 and 60 meters and the width was seven, twelve and eight meters respectively. The number of standard deviations included was set to one for all the cases.

7.1 Case 1 – 20 Meters Long and 7 Meters Wide

The first case had a total span length of 20 meters and was seven meters wide, to resemble a single span two lane overpass. The abutments were considered to be five meters high and to have the same width as the bridge. In case of a composite bridge, the steel structure was considered as two parallel I-beams with a web of 900 mm, an upper flange of 400 mm, and a bottom flange of 600 mm.

After running it through the investment cost part of the program, six bridge types remained to analyse, with the maintenance cost part of the program. The life span of the bridges was set to 120 years, and as the bridges were to resemble an overpass, the exposure class on the substructure was set to high. The resulting LCC from the program is shown in Figure 7.1.

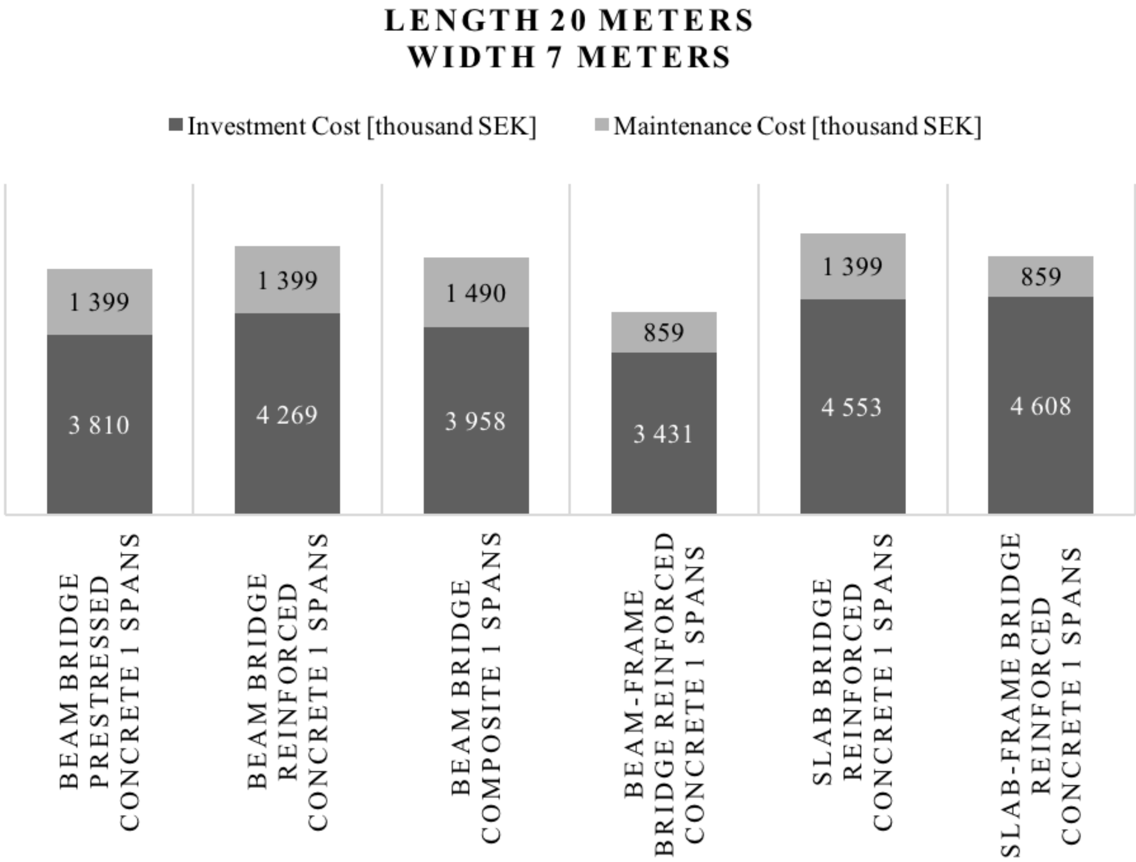


Figure 7.1 Total LCC for bridges in thousand SEK

The result was that the beam-frame bridge in reinforced concrete was the most cost-efficient to choose from an LCC-perspective with a total LCC of 4.3 million SEK. All other bridge types had a total LCC of more than 5 million SEK, but the most expensive ones were the slab-bridge in reinforced concrete and beam bridge in reinforced concrete. Notable, was that the slab-frame bridge in reinforced concrete had the highest investment cost, but the low maintenance cost stopped it from being the most expensive bridge type. The detailed results and input data from *SimpleBridgeLCC* can be seen in Table 7.1

Table 7.1 Input data and results from SimpleBridgeLCC for a bridge with total span length of 20 meters and width of seven meters.

	Unit	Beam bridge Prestressed Concrete 1 Spans	Beam bridge Reinforced Concrete 1 Spans	Beam bridge Composite 1 Spans	Beam-frame bridge Reinforced Concrete 1 Spans	Slab bridge Reinforced Concrete 1 Spans	Slab-frame bridge Reinforced Concrete 1 Spans
Length	m	20	20	20	20	20	20
Width	m	7	7	7	7	7	7
Investment Cost	SEK/m^2	27 217	30 496	28 273	25 504	32 521	32 916
No. of bridges included in INV	Pcs	4	7	51	5	20	51
Expansion Joint	m	14	14	14		14	
Edge Beam	m	40	40	40	40	40	40
Railing	m	40	40	40	40	40	40
Steel Girders (surface area)	m^2	-	-	150	-	-	-
Bridge Area	m^2	140	140	140	140	140	140
Abutments (surface area)	m^2	70	70	70	70	70	70
Abutments (exposure class)	-	High	High	High	High	High	High
Piers (surface area)	m^2	-	-	-	-	-	-
Piers (exposure class)	-	-	-	-	-	-	-
Bearings	Pcs	4	4	4	-	4	-
Foundation Drain	Pcs	6	6	6	6	6	6
Surface Drain	Pcs	-	-	-	-	-	-
Downpipes	Pcs	-	-	-	-	-	-
Life Span	Yrs	120	120	120	120	120	120
Investment Cost	SEK [M]	3.81	4.27	3.96	3.43	4.55	4.61
Standard deviation: Investment Cost	SEK [M]	1.26	1.08	1.10	0.11	1.42	1.28
Maintenance Cost	SEK [M]	1.40	1.40	1.49	0.86	1.40	0.86
Total Cost	SEK [M]	5.21	5.67	5.45	4.29	5.95	5.47

7.2 Case 2 – 30 Meters Long and 12 Meters Wide

For the second case, the total span length was increased to 30 meters and the width to twelve meters. The abutments were considered in the same manner as for case one. In the case of piers, they were also treated in the same way, with a height of five meters and as wide as the bridge. Also, the piers support conditions resembled that of the abutments, so simply supported structures had bearing at all supports and fixed structures were fixed at all supports.

After running the investment cost part of the program, eight different bridge types remained. These were run through the maintenance cost part of the program and the resulting LCC can be seen in Figure 7.2.

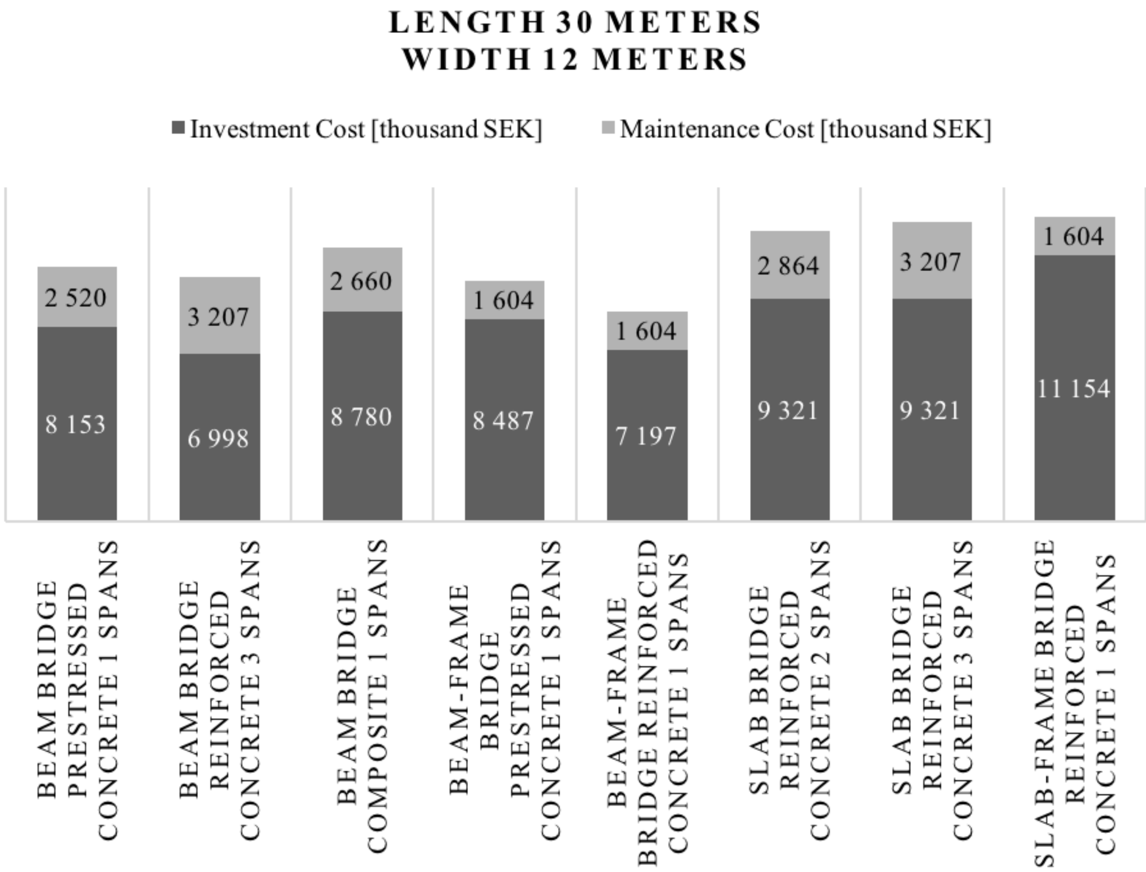


Figure 7.2 Total LCC for bridges in thousand SEK

The most cost-efficient bridge type for case two was the one span beam-frame bridge in prestressed concrete, with a total LCC of 8.8 million SEK. The three span beam bridge in reinforced concrete had the lowest investment cost, but it also had the highest maintenance cost, which resulted in a total LCC of 10.2 million SEK. The least cost-efficient bridge types were the slab-bridges, the total LCC of these bridge types exceeded 12 million SEK. Worst of all was the slab-frame bridge in reinforced concrete, mainly because of its high investment cost. The detailed results and input data for case two can be seen in Table 7.2.

Table 7.2 Input data and results from SimpleBridgeLCC for a bridge with total span length of 30 meters and width of twelve meters

	Unit	Beam bridge Prestressed Concrete 1 Spans	Beam bridge Reinforced Concrete 3 Spans	Beam bridge Composite 1 Spans	Beam-frame bridge Prestressed Concrete 1 Spans	Beam-frame bridge Reinforced Concrete 1 Spans	Slab bridge Reinforced Concrete 2 Spans	Slab bridge Reinforced Concrete 3 Spans	Slab-frame bridge Reinforced Concrete 1 Spans
Length	m	30	30	30	30	30	30	30	30
Width	m	12	12	12	12	12	12	12	12
Investment Cost	SEK/m^2	22 647	19 440	24 388	23 576	19 991	25 893	25 893	30 983
No. of bridges included in INV	Pcs	10	5	19	28	3	9	9	21
Expansion Joint	m	24	24	24	-	-	24	24	-
Edge Beam	m	60	60	60	60	60	60	60	60
Railing	m	60	60	60	60	60	60	60	60
Steel Girders (surface area)	m^2	-	-	234	-	-	-	-	-
Bridge Area	m^2	360	360	360	360	360	360	360	360
Abutments (surface area)	m^2	120	120	120	120	120	120	120	120
Abutments (exposure class)	-	High	High	High	High	High	High	High	High
Piers (surface area)	m^2	-	240	-	-	-	120	240	-
Piers (exposure class)	-	-	High	-	-	-	High	High	-
Bearings	Pcs	4	8	4	-	-	6	8	-
Foundation Drain	Pcs	9	9	9	9	9	9	9	9
Surface Drain	Pcs	-	-	-	-	-	-	-	-
Downpipes	Pcs	-	-	-	-	-	-	-	-
Life Span	Years	120	120	120	120	120	120	120	120
Investment Cost	SEK [M]	8.15	7.00	8.78	8.49	7.20	9.32	9.32	11.15
Standard deviation: Investment Cost	SEK [M]	2.68	1.16	3.05	1.90	0.241	1.37	1.37	3.21
Maintenance Cost	SEK [M]	2.52	3.21	2.66	1.60	1.60	2.86	3.21	1.60
Total Cost	SEK [M]	10.67	10.21	11.44	10.09	8 .80	12.19	12.53	12.76

7.3 Case 3 – 60 Meters Long and 8 Meters Wide

The third case was intended to check the results of a longer bridge. The total span length was extended to 60 meters and the width was decreased to eight meters. The abutments and piers, as well as the support conditions were considered in the same way as for case one and two. Eight bridge types had matching bridges in the investment cost part of the program and were run through the maintenance cost part of the program. The results from the program can be seen in Figure 7.3.

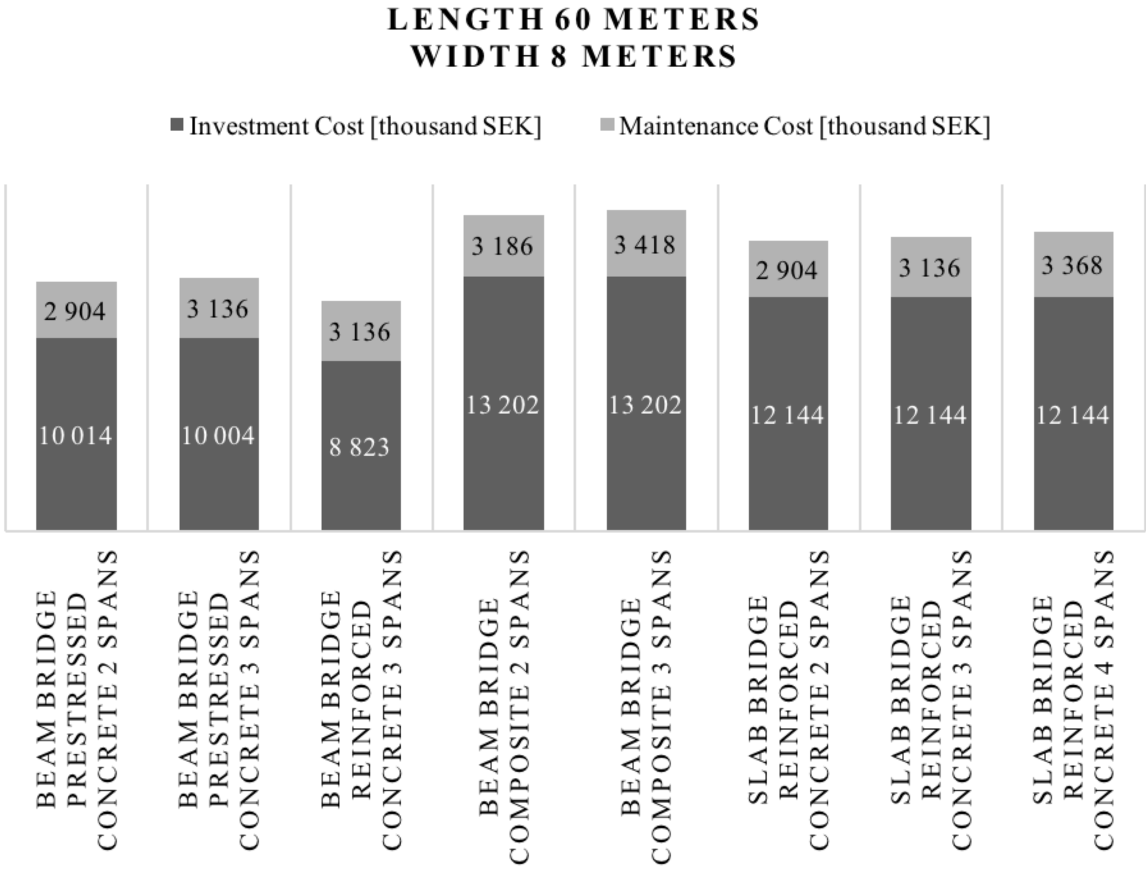


Figure 7.3 Total LCC for bridges in thousand SEK

For case three, the most cost efficient bridge type was the three span beam bridge in reinforced concrete, with a total LCC of 12 million SEK. The other two beam bridges in concrete were quite similar in LCC but were roughly one million SEK more expensive than the most cost efficient. The composite beam bridges in two or three spans were the least cost-efficient with total LCCs well above 16 million SEK. The detailed results and input data is presented in Table 7.3.

Table 7.3 Input data and results from SimpleBridgeLCC for a bridge with total span length of 60 meters and width of eight meters

	Unit	Beam bridge Prestressed Concrete 2 Spans	Beam bridge Prestressed Concrete 3 Spans	Beam bridge Reinforced Concrete 3 Spans	Beam bridge Composite 2 Spans	Beam bridge Composite 3 Spans	Slab bridge Reinforced Concrete 2 Spans	Slab bridge Reinforced Concrete 3 Spans	Slab bridge Reinforced Concrete 4 Spans
Length	m	60	60	60	60	60	60	60	60
Width	m	8	8	8	8	8	8	8	8
Investment Cost	SEK/m^2	20 862	20 842	18 381	27 505	27 505	25 300	25 300	25 300
No. of brigs included in INV	Pcs	63	28	32	20	20	22	22	22
Expansion Joint	m	16	16	16	16	16	16	16	16
Edge Beam	m	120	120	120	120	120	120	120	120
Railing	m	120	120	120	120	120	120	120	120
Steel Girders (surface area)	m^2	-	-	-	468	468	-	-	-
Bridge Area	m^2	480	480	480	480	480	480	480	480
Abutments (surface area)	m^2	80	80	80	80	80	80	80	80
Abutments (exposure class)	-	High	High	High	High	High	High	High	High
Piers (surface area)	m^2	80	160	160	80	160	80	160	240
Piers (exposure class)	-	High	High	High	High	High	High	High	High
Bearings	Pcs	6	8	8	6	8	6	8	10
Foundation Drain	Pcs	19	19	19	19	19	19	19	19
Surface Drain	Pcs	-	-	-	-	-	-	-	-
Downpipes	Pcs	-	-	-	-	-	-	-	-
Life Span	Years	120	120	120	120	120	120	120	120
Investment Cost	SEK [M]	10.01	10.00	8.82	13.20	13.20	12.14	12.14	12.14
Standard deviation: Investment Cost	SEK [M]	2.2	2.03	2.18	4.08	4.08	3.12	3.12	3.12
Maintenance Cost	SEK [M]	2.90	3.14	3.14	3.19	3.42	2.90	3.14	3.37
Total Cost	SEK [M]	12.92	13.14	11.96	16.39	16.62	15.05	15.28	15.51

7.4 Distribution of Maintenance Cost

To get an indication on what measures that are cost-drivers for the maintenance of the bridge types included in this thesis, the maintenance cost for the bridge types presented in cases one to three was plotted in pie charts and the percentage of the total maintenance cost was calculated per structural member.

7.4.1 Case 1 – 20 Meters Long and 7 Meters Wide

For the case with the total span length of 20 meters and the width of seven meters there were three different maintenance costs associated with the six different bridge types. There were one for the frame bridges, one for the simply supported concrete bridges and one for the simply supported composite bridges. The percentage distribution between the different maintenance costs for the frame bridges and the simply supported bridges can be seen in Figure 7.4.

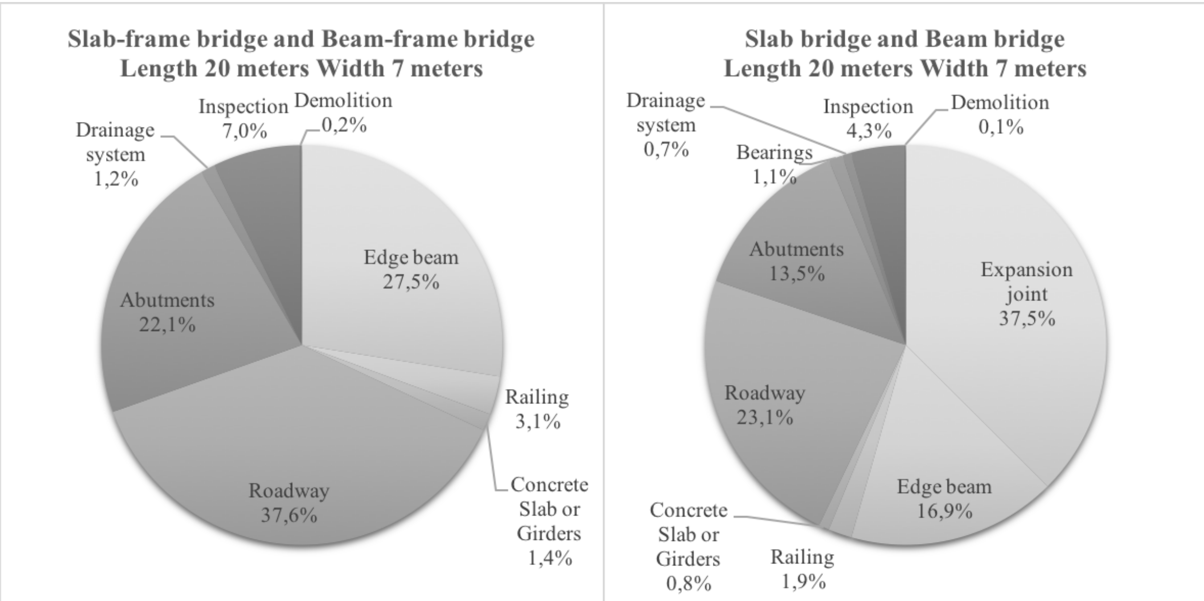


Figure 7.4 Percentage distribution of maintenance costs for frame bridges (left) and simply supported bridges (right)

The total maintenance cost for the frame bridges was SEK 859 K and the big cost items was reparation of roadway (wearing course and waterproofing), impregnation and replacement of edge beams. For the simply supported concrete bridges, the total maintenance cost was SEK 1,399 K. The expansion joint that is needed for the simply supported structures is more than a third of the total maintenance costs. If the simply supported bridge was constructed as a composite bridge, the total maintenance cost increased by around SEK 100 K, but that had no significant effect on the percentage distribution.

7.4.2 Case 2 – 30 Meters Long and 12 Meters Wide

In case two with the increased span length and width, there were five different maintenance costs associated with the eight different bridge types. The percentage distributions for the maintenance costs for frame bridges can be seen in Figure 7.5, for simply supported concrete bridges with one or two spans the maintenance cost is presented in Figure 7.6, and for simply supported concrete bridges with three spans together with one span composite bridge the maintenance cost is presented in Figure 7.7.

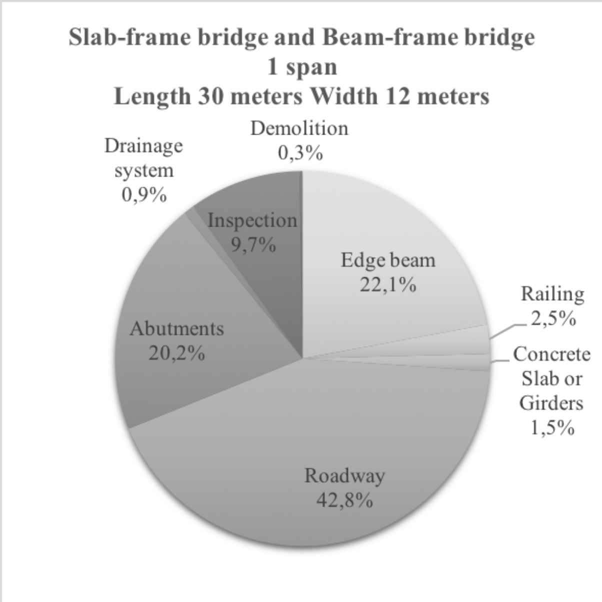


Figure 7.5 Percentage distribution of maintenance costs for frame bridges with one span.

For the one span frame-bridges the total maintenance cost was SEK 1,604 K. The main cost item was maintenance of the roadway, being almost half of the maintenance cost.

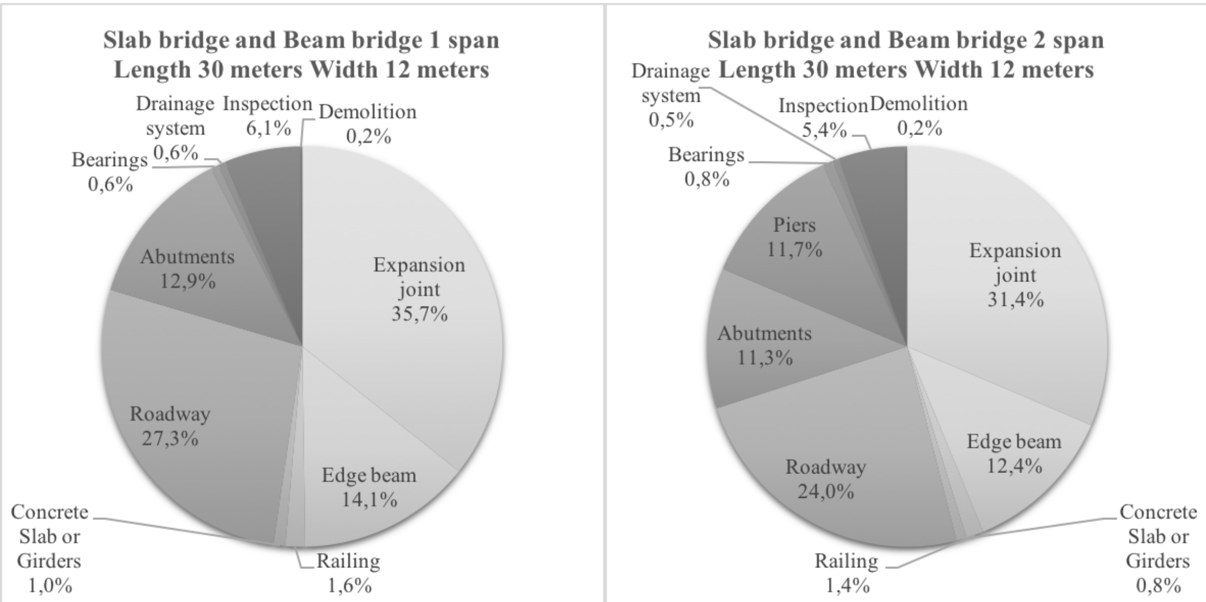


Figure 7.6 Percentage distribution of maintenance costs for simply supported bridges. One span (left) and two spans (right)

The total maintenance cost of the one span simply supported concrete bridge was SEK 2,520 K, and for the two span simply supported concrete bridge it was SEK 2,864 K. For the simply supported bridges, the expansion joint was the largest cost item with almost a third of the maintenance cost. Also, for the two span bridge, the impregnation and reparation of abutments and piers comprised almost a quarter of the maintenance cost.

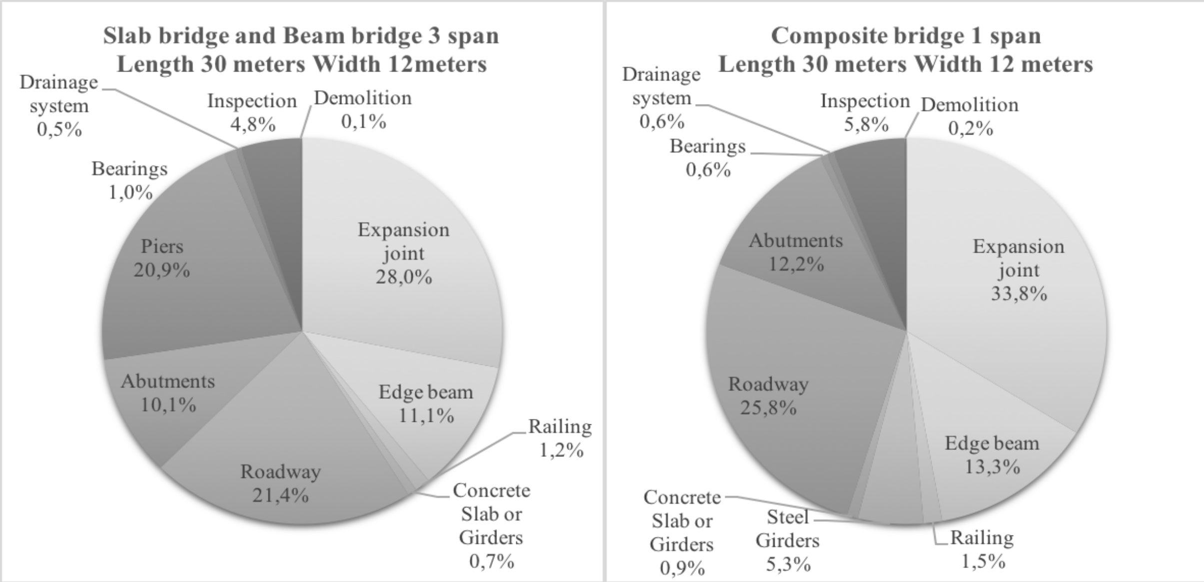


Figure 7.7 Percentage distribution of maintenance costs for simply supported bridges. Three spans concrete (left) and one span composite (right)

The total maintenance cost for the three span simply supported concrete bridge type was SEK 3,207 K and for the one span simply supported composite bridge type it was SEK 2,660 K. For the simply supported bridges with three spans the concrete repair and impregnation of abutments and piers became the largest cost item at 31 percent. For the composite bridge the repainting of the steel structure was 5.3 percent of the maintenance cost, but the expansion joint was still the largest cost item with 33.8 percent.

7.4.3 Case 3 – 60 Meters Long and 8 Meters Wide

With a total span length of 60 meters and a width of eight meters there were five different maintenance costs to the eight bridge types. There were simply supported composite bridges in two and three spans, see Figure 7.8 and simply supported concrete bridges in two, three and four spans, see Figure 7.9 and Figure 7.10.

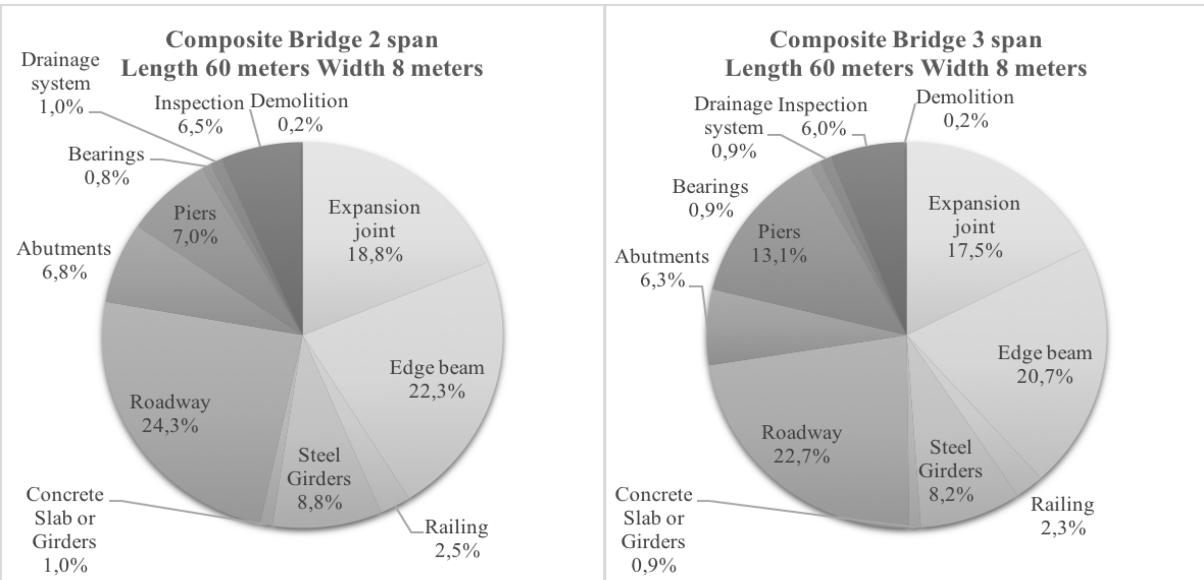
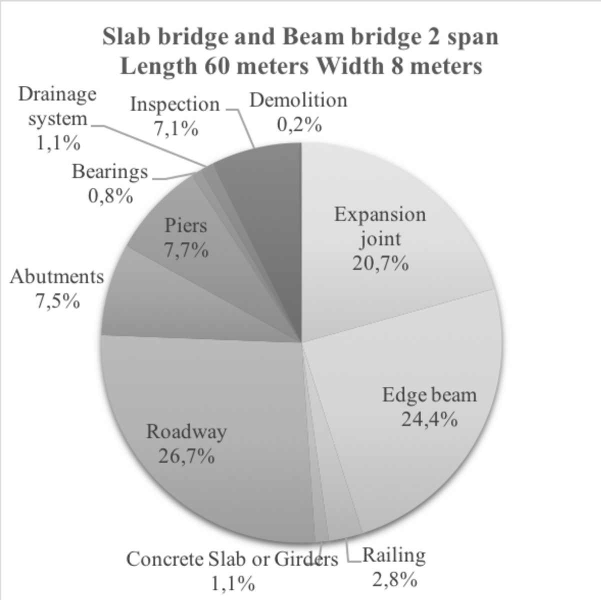


Figure 7.8 Percentage distribution of maintenance costs for simply supported composite bridges. two spans (left) and three spans (right)

The total maintenance cost of the two span simply supported composite bridge was SEK 3,186 K and for the three spans simply supported composite bridge it was SEK 3,418 K. The reparation and impregnation of the edge beam, as well as the reparation of the roadway are the biggest cost items for both of the bridge types in Figure 7.8, whereas the expansion joint was just a few percentage units behind.



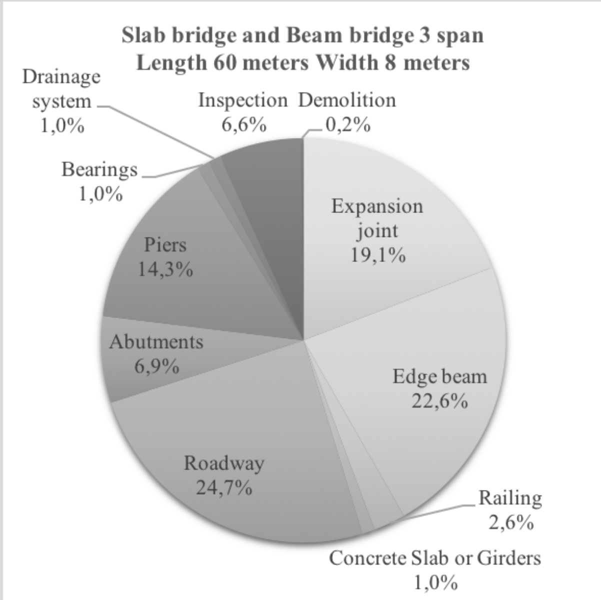


Figure 7.9 Percentage distribution of maintenance costs for simply supported concrete bridges. Two spans (left) and three spans (right)

For the simply supported concrete bridges the two span had a total maintenance cost of SEK 2,904 K and the three span had a total maintenance cost of SEK 3,136 K. The biggest cost items were concrete reparation and impregnation of edge beams and roadway reparation. The smallest cost items were paint improvement of bearings and replacement of drainage system.

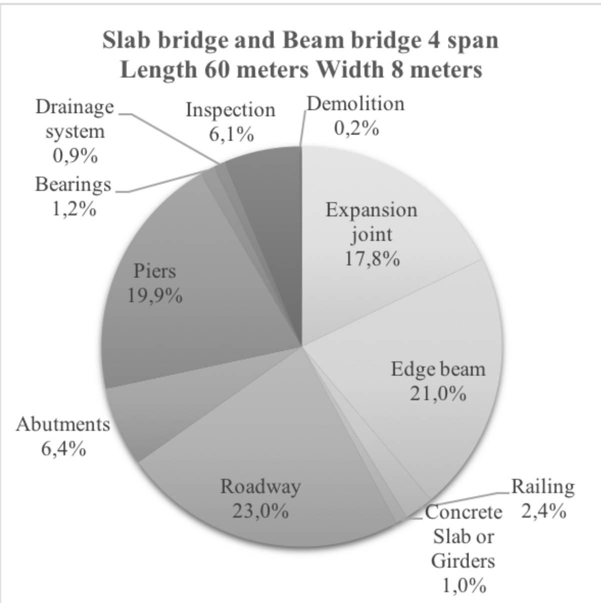


Figure 7.10 Percentage distribution of maintenance costs for simply supported concrete bridge in 4 spans

For the four span simply supported concrete bridges the total maintenance cost was SEK 3,368 K. The largest cost items were the same as for many of the other cases, concrete reparation and impregnation of the edge beam, piers and abutments. The expansion joint was also a big cost item, whilst the bearings, drainage system and concrete reparation of the concrete slab and girders had only minor influence on the total maintenance cost.

8 Discussion

This section contains a discussion about the results from the cases presented in Section 7, the usage of LCCA in early design phases, and the choices made during the development of *SimpleBridgeLCC.*

8.1 Case Results

After analysing Case 1 with a short span length it was observed that of all the bridge types that had cost records for that case, the slab-frame bridge was the second most expensive one, see Table 7.1. This contradicts the prediction of (Swedish Transport Administration, 1996) that claimed the bridge type to be economically preferable for span lengths up to 25 meters. However, the beam-frame bridge for the same case was one of the preferred options according to the program. These results provoke a lot of questions, especially since 37 percent of the bridges built in similar span lengths are slab-frame bridges. A number of reasonable circumstances could have that effect on the outcome. First, what cost items that are included in the investment cost recorded in BaTMan are not specified, why only the total investment cost can be seen. Second, the foundation work for otherwise identical bridges can differ and therefore the costs can be different as well. However, this should have the same effect on all bridge types and not necessarily favour a specific bridge type. Third, as a bridge is more or less unique in its construction, setting and traffic load, individual differences may have a profound effect on the total cost more than what type of bridge that was chosen.

A question that arise after looking at the results of the cases presented in Section 7 is the necessity to perform LCCA for this kind of bridges. For two of the three cases, the cheapest bridge to build was the one with the lowest LCC. It might be more efficient to check for details to avoid in design, such as expansion joints, or ways to improve these details to avoid high maintenance costs. However, the maintenance costs were a substantial part of the total LCC, which supports the claims of (Dhillon, 2010), (ETSI, 2013) and (Safi, 2013) that an LCCA should be performed to compare different alternatives. Therefore, a combination of the two could be favourable if a bridge type with a lot of details is chosen.

8.2 Program Development

In this thesis a new easy-to-use Excel based program that uses historical cost records and maintenance plans to calculate LCCs for road bridges was introduced. The way the program uses the historical cost records to calculate the anticipated investment cost for different bridge types has, to the authors' knowledge, not been done before. This may be a problem since there is no way to validate the actual results from the program. The use of a real bridge as a comparison to the actual results would not provide a fair validation since that bridge is most probably already used as input in the program. Therefore, the results should probably be looked at as indicative values and not as the actual cost to construct the bridge.

The selection of bridges in the investment cost part of the program was made on a statistical basis, where the 95 percent confidence interval was used in order to erase the anomalies. This procedure is commonly used and can therefore express a certain reliability to the method. Further, as the developed program only considers bridges that matched both the length and width input, an adjustable parameter that chose the number of standard deviations used in the calculation was installed. This was done in order to provide the user with a more transparent and user-friendly program where the user could adjust what amount of data that should be included in the calculation. The reason it is based on the standard deviation is that the default mode, with one standard deviation, should be objectively chosen by statistical analysis.

The fact that the investment costs are based upon historical records might be an insecurity since bridge construction is evolving. New construction methods and more cost-efficient methods to produce construction materials might be factors influencing a lower investment cost. As a consequence of this, the usage of Net Price Index to convert historical costs to today's currency may not contain the entire difference between the past and today. On the other hand, some sort of conversion factor to account for this probable decrease of costs over the years might be hard to achieve in a qualified way.

The methodology that was used in order to construct the program follows the outline of the methodology presented by (Davis Langdon, 2007b), presented in Section 2.4. However, a few steps have only been considered to some extent, such as the verification of financial values, and that the program does not allows any changes except from the input data from the user. This could be argued to make the program hard to fit to a specific case, but in order to achieve a simple and easy-to-use program there was a need to reduce the amount of information needed from the user.

Another way to carry out the analysis regarding the investment cost is to gather all the costs related to designing and constructing a bridge. An alternative methodology could be the following.

1. Design a vast number of bridges of different types, span lengths, widths etc. that will be used as the skeleton of the program
2. For each bridge, thoroughly calculate the amount of concrete, reinforcement and other typical equipment like railings, drainage systems etc.
3. Find the unit costs of all those items and parts of the bridge
4. Find records of the general design costs of the respective bridges
5. Find cost records of the construction, i.e. costs for frame work, man hours etc.
6. Find cost records of how different foundation conditions would affect the investment cost of the bridge
7. Design a program that is able to, interpolate between the closest bridge options from a given number of input parameters

This methodology is doable but requires more data and more input parameters in order to be accurate. On the other hand, the ability to alter expensive parameters, such as the foundation work, could have a profound effect on the outcome. However, in order to use a program like this in the correct and intended way, the user has to be more experienced.

In the maintenance cost part of the program, a limited number of cost items are included. The results from the program may have been quite different if other costs were accounted for as well. However, it is nearly impossible to consider all maintenance actions carried out during a bridge's service life, as many of the actions are due to traffic accidents and similar events. Also, since an intensive examination of which maintenance measures that are performed during the bridges' service life was performed to identify the most common measures, the cost items included should represent a reasonable life cycle plan.

The time intervals for certain maintenance work are also subject to certain insecurity. The maintenance plans for bridges differ based on such things as geographical location, traffic loads and surrounding environment. As the NPV of a future cost can increase or decrease significantly, based on at what time the cost appears, the LCC for maintenance work can have quite different results based on at what times the maintenance actions are carried out. This may have an effect on the results between bridge types with different maintenance work associated to them.

A different approach to the maintenance cost program would require a time consuming analysis. It would be to analyse all maintenance actions recorded in BaTMan for all bridge types. Then identify all maintenance actions carried out per bridge type and compare with the total number of existing bridges. That would provide a statistical way of calculating what maintenance actions are needed, the probability of them being needed, and when the actions would be carried out.

9 Conclusions

In this section the conclusions that can be drawn from this study are presented.

The need of considering LCC in the design phase when feasible bridge types are evaluated was not extensively supported based on the three cases performed in this thesis. However, the maintenance cost can be as large as a third of the total LCC for a bridge. This shows that the cost of maintenance is a substantial part of the LCC, why the choice of bridge type should be based on LCC rather than investment cost.

The most expensive bridge parts to maintain are the roadway, the edge beams and the supports (both piers and abutments). The specific bridge part that differ the most between different bridge types is the expansion joint. In particular, for the shorter bridges where the cost of maintaining the expansion joint can be as much as one third of the total maintenance cost.

The choice of using existing cost records from BaTMan as basis for the investment cost part of the program had major advantages. There was large amount of reliable information about many bridge types which enabled a quantitative analysis, and the fact that the costs were based on already constructed bridges gave more credibility to the method. Also, the information in BaTMan is constantly updated and it is available for the public through the STA. Therefore, the program can be updated when new bridges are built. Concerning the maintenance, the use of prices and experience at the STA was a simple and reliable way to get an estimation of the maintenance costs of different bridge types.

In *SimpleBridgeLCC* only a limited amount of information about the bridge is needed in order to perform the LCCA. It was developed in this way, in order to provide a user without any prior experience of LCCA a method to be able to perform this type of analysis.

The part of the program that was developed in order to calculate the investment costs for bridges was mainly constructed in order to give an indication of which bridge type that is, or historically has been, the most favourable for the given input parameters of length and width. Its main area of use is in the early planning stage of the design process where bridge designers should benefit from it. At the same time, the authorities could apply the program as a tool in the procurement procedure.

The part of the program developed to calculate the maintenance cost is demanding more information than the investment cost part of the program to be used properly. In contrast to the investment cost program, the geometry, life span and some basic knowledge of bridge design is needed to perform an accurate prediction of the maintenance cost. This part of the program both targets the authorities and the bridge designers to be used as a tool in the procurement process, in order to consider the whole life cycle cost of a bridge instead of just the investment cost.

In this thesis the main focus has been agency costs associated with bridges. A recommendation for future studies would be to investigate if there is a way to include the society and environmental aspects in this kind of simplified approach.

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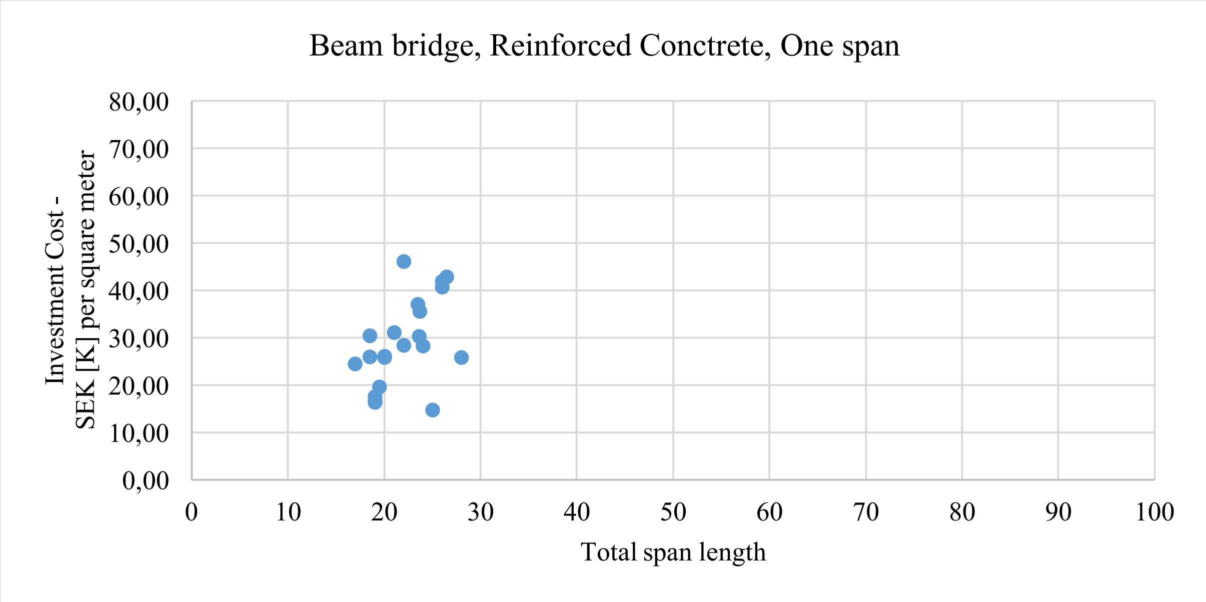
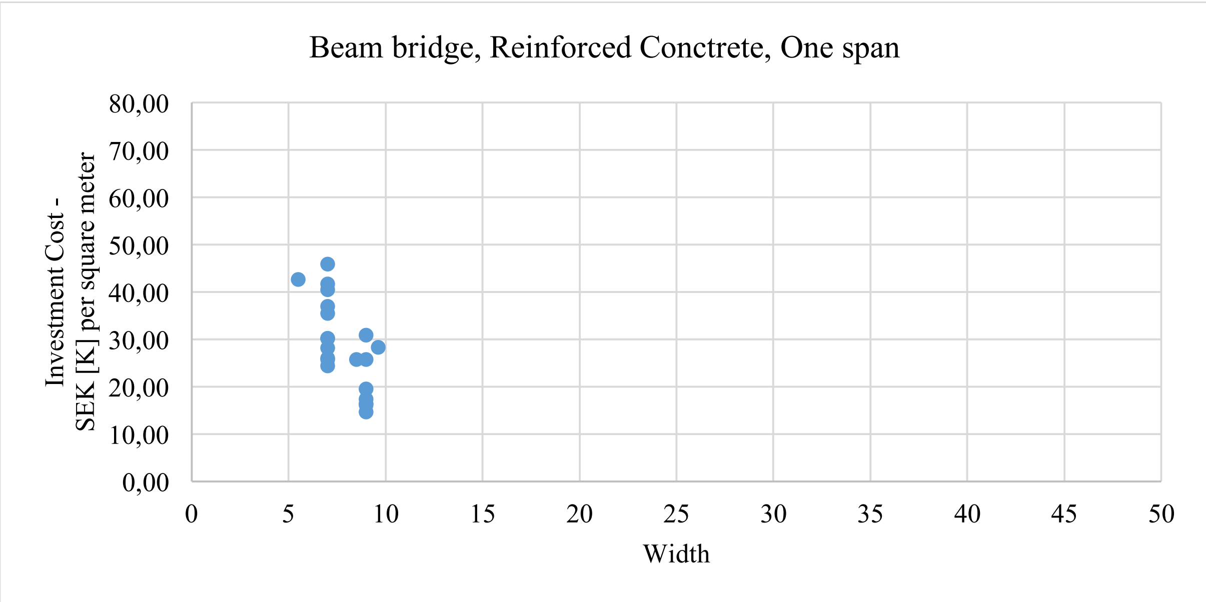
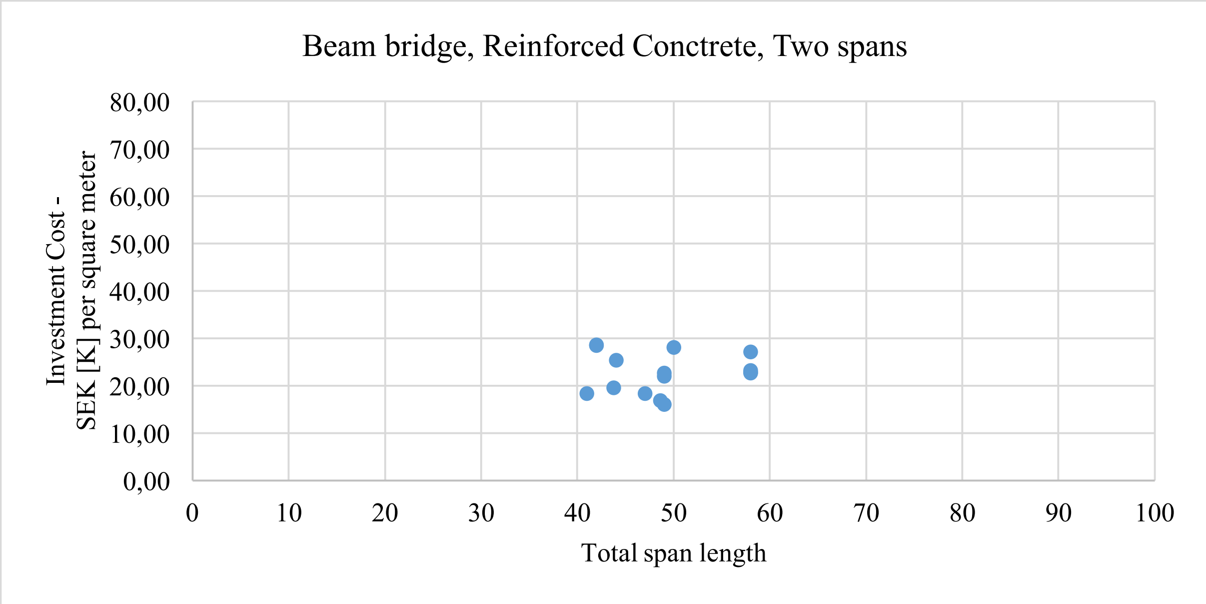
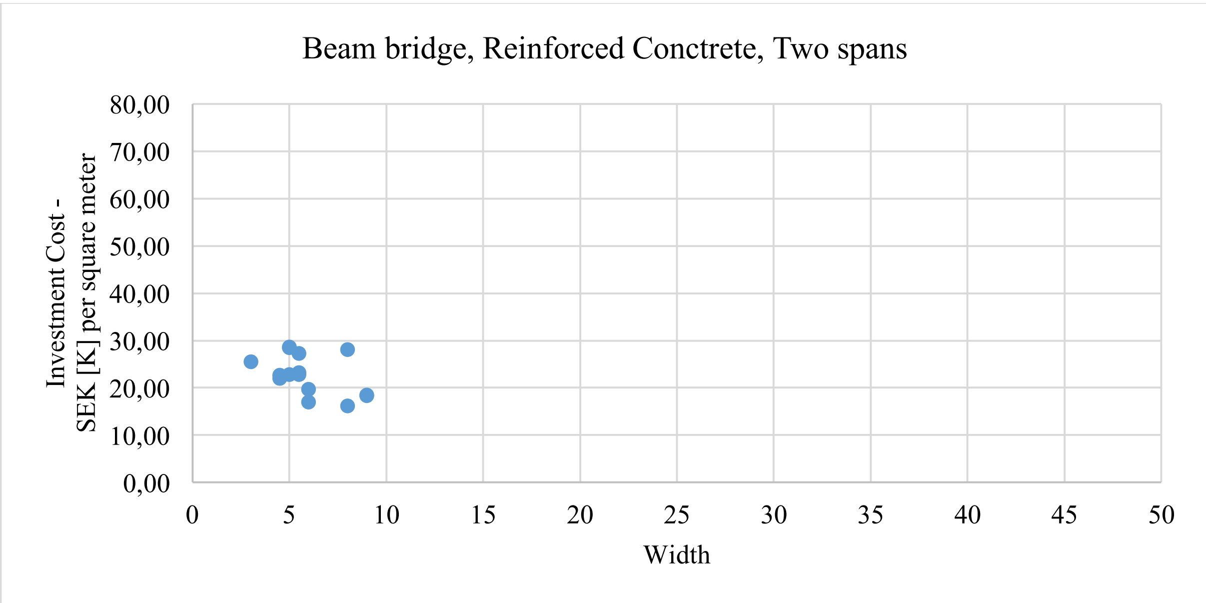
Appendix A – Investment Cost

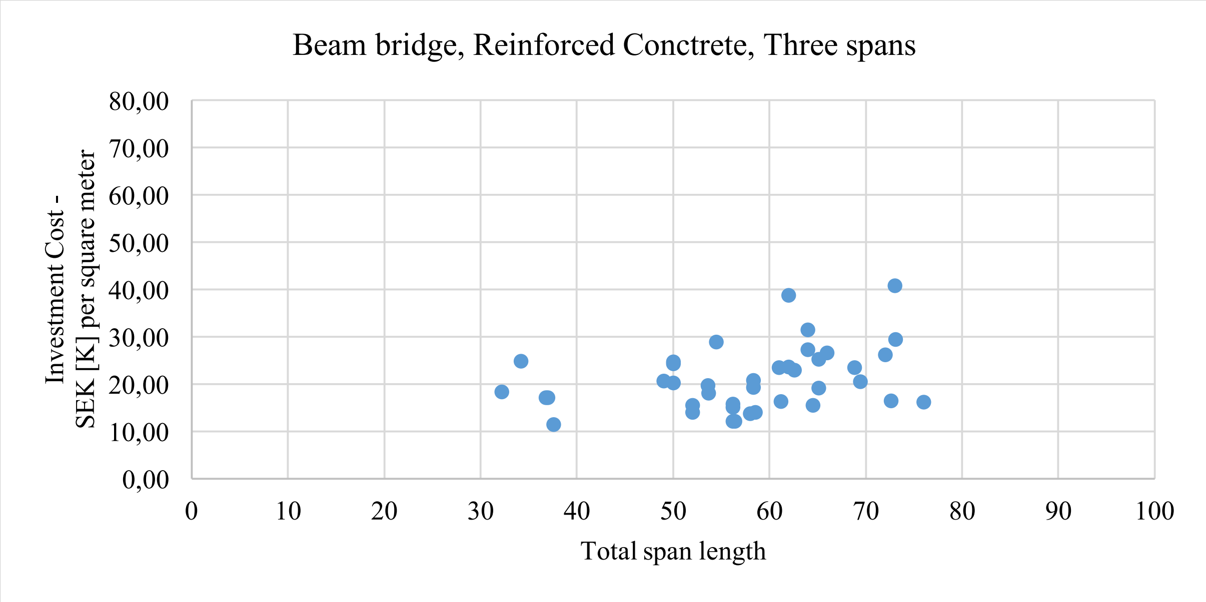
A.1 Beam Bridge, Reinforced Concrete



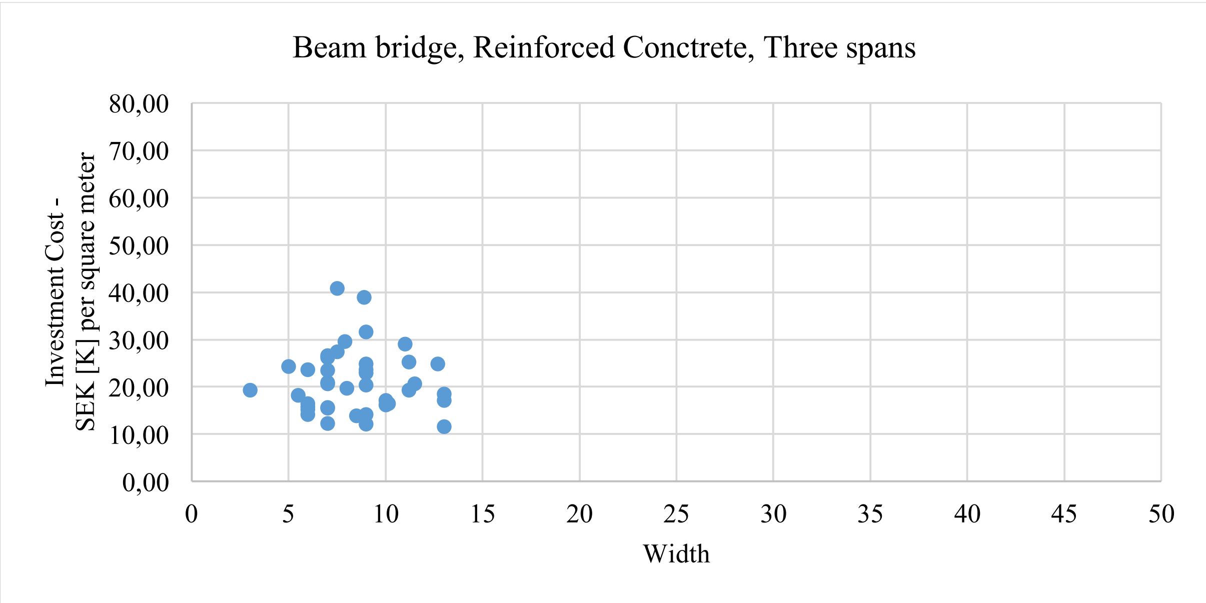



Beam bridge, Reinforced Conctrete, Two spans
Investment Cost -
SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length


Beam bridge, Reinforced Conctrete, Two spans
Investment Cost -
SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

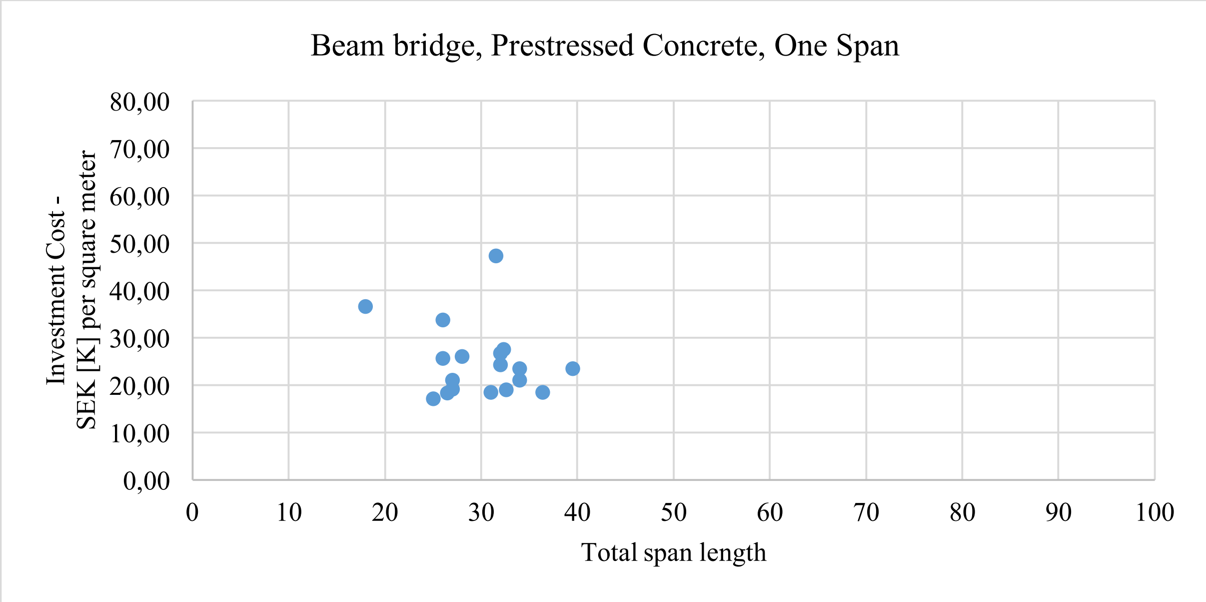


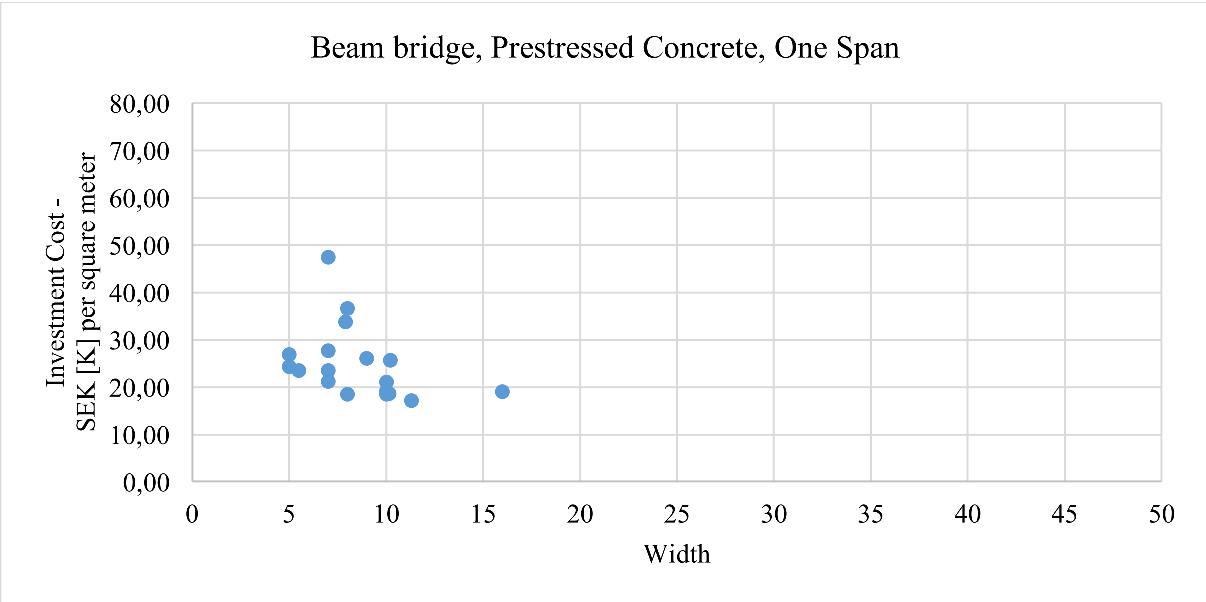
Beam bridge, Reinforced Conctrete, Three spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length

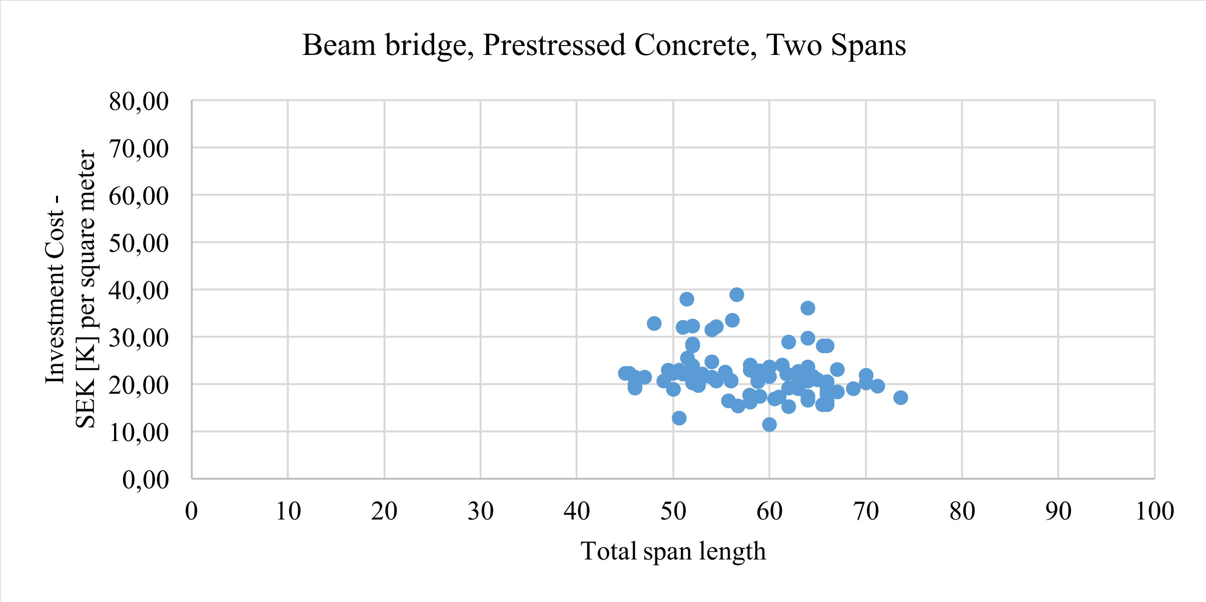


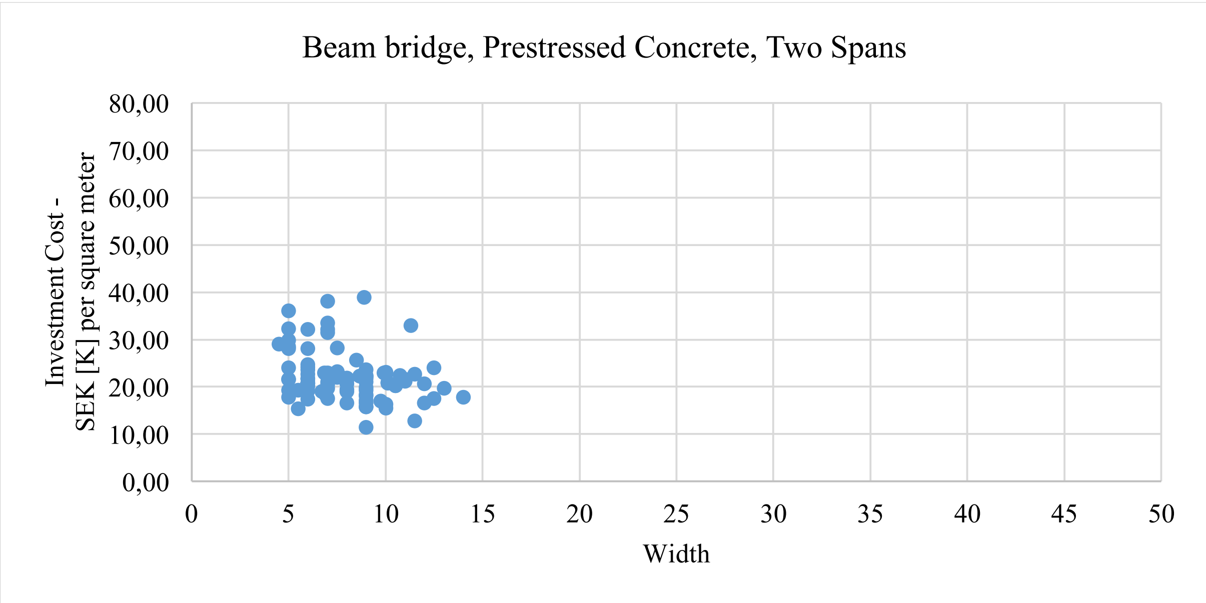
Beam bridge, Reinforced Conctrete, Three spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

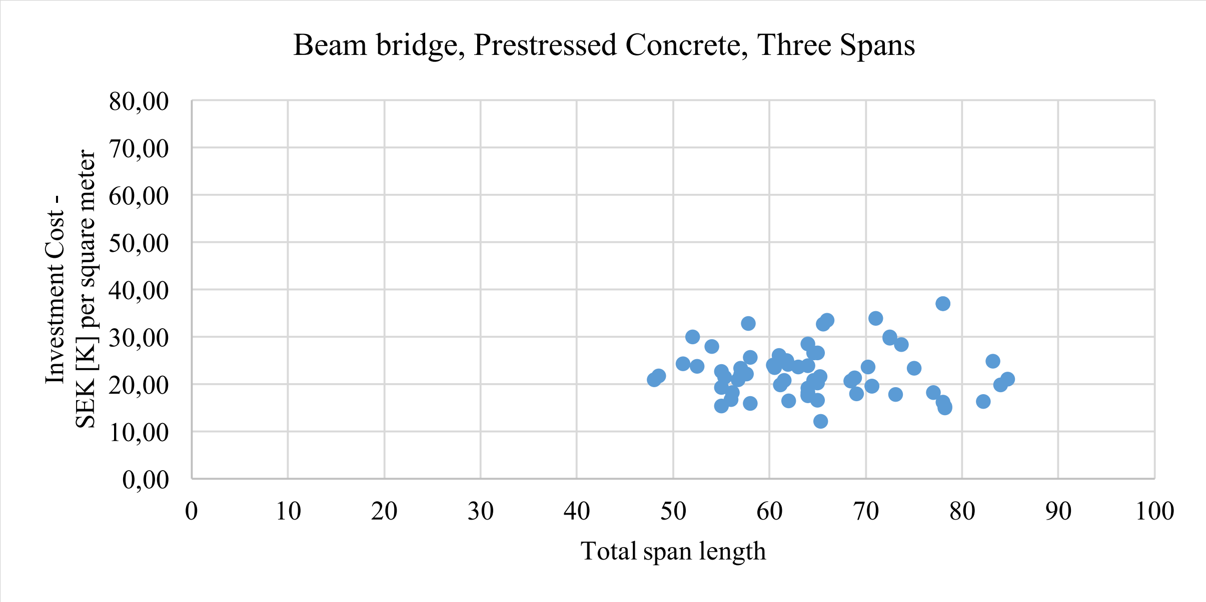
A.2 Beam bridges, Prestressed Concrete



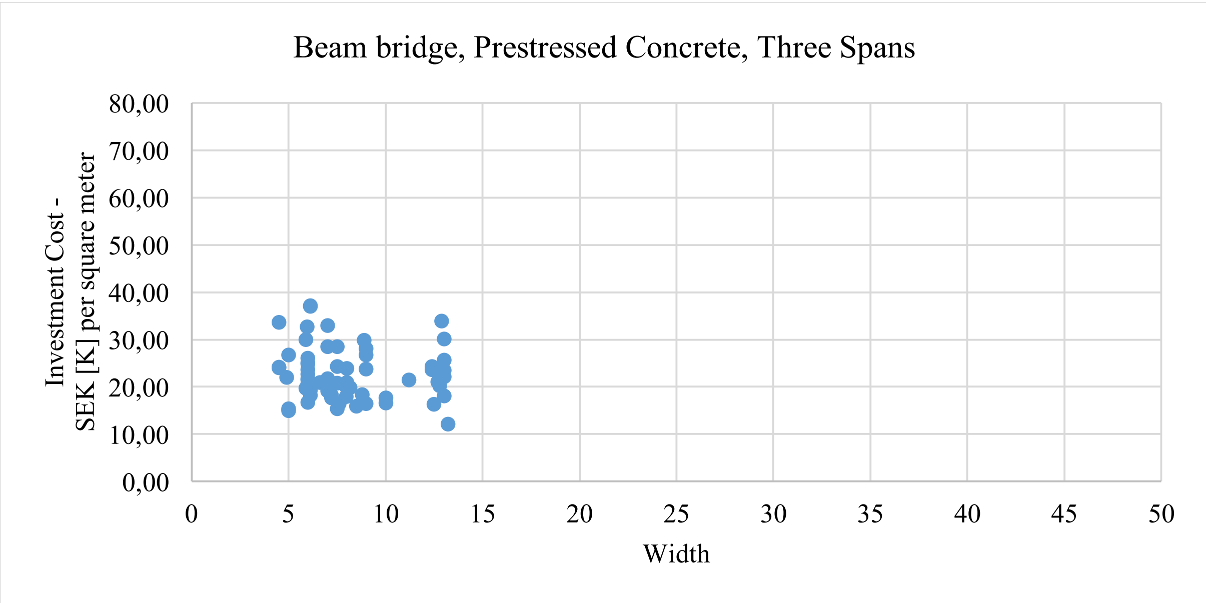



Beam bridge, Prestressed Concrete, Two Spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length


Beam bridge, Prestressed Concrete, Two Spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

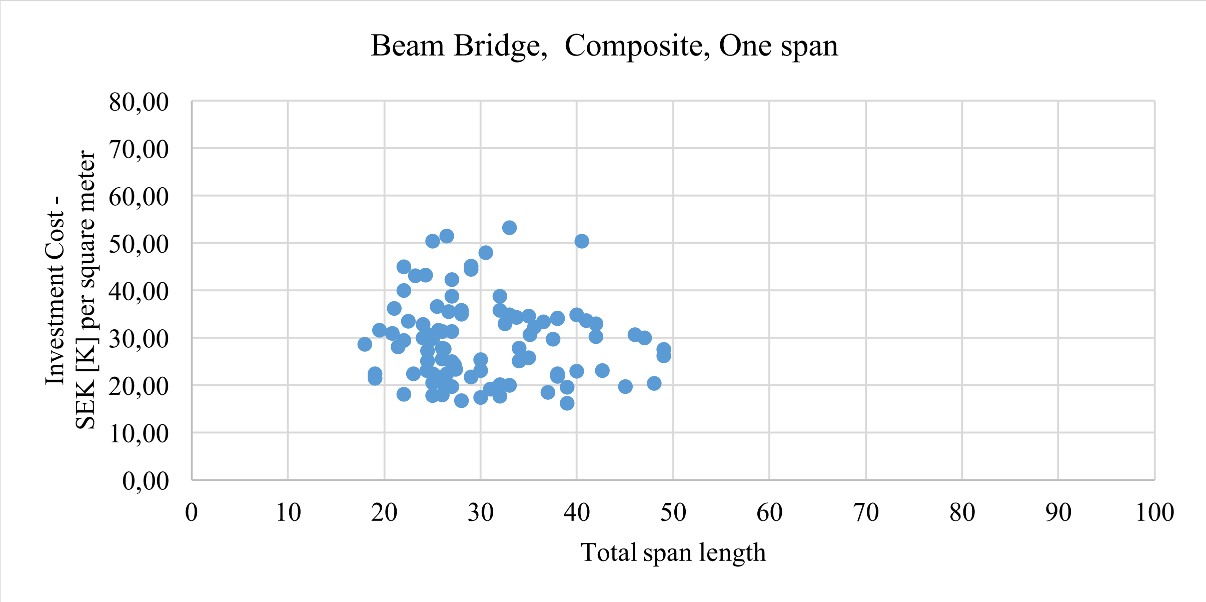


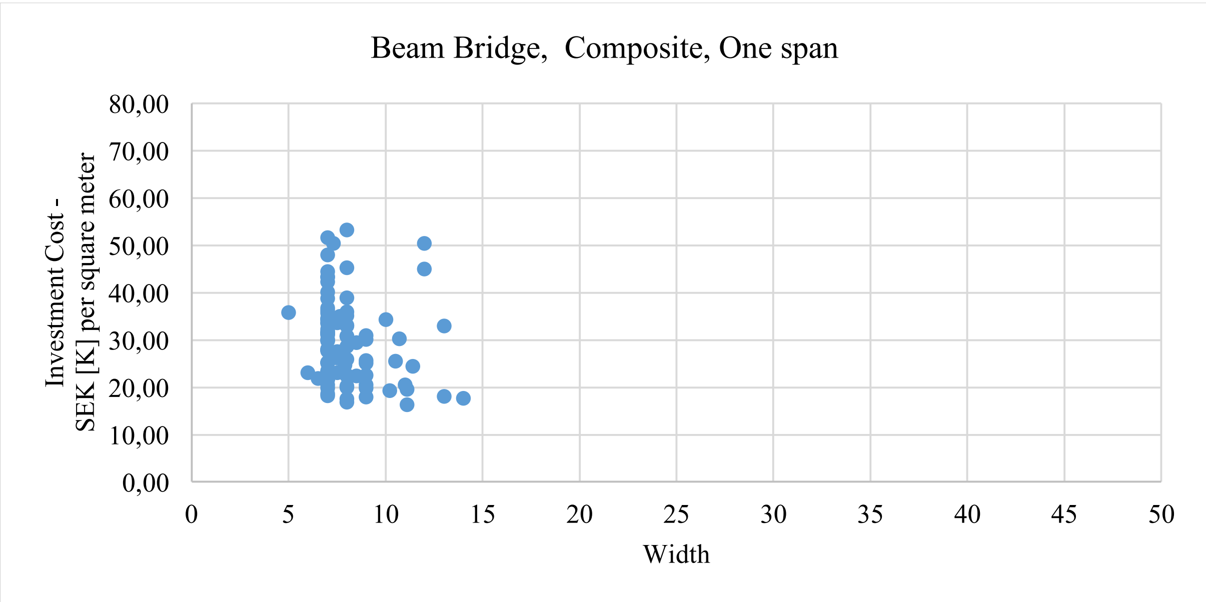
Beam bridge, Prestressed Concrete, Three Spans
Investment Cost -
SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length

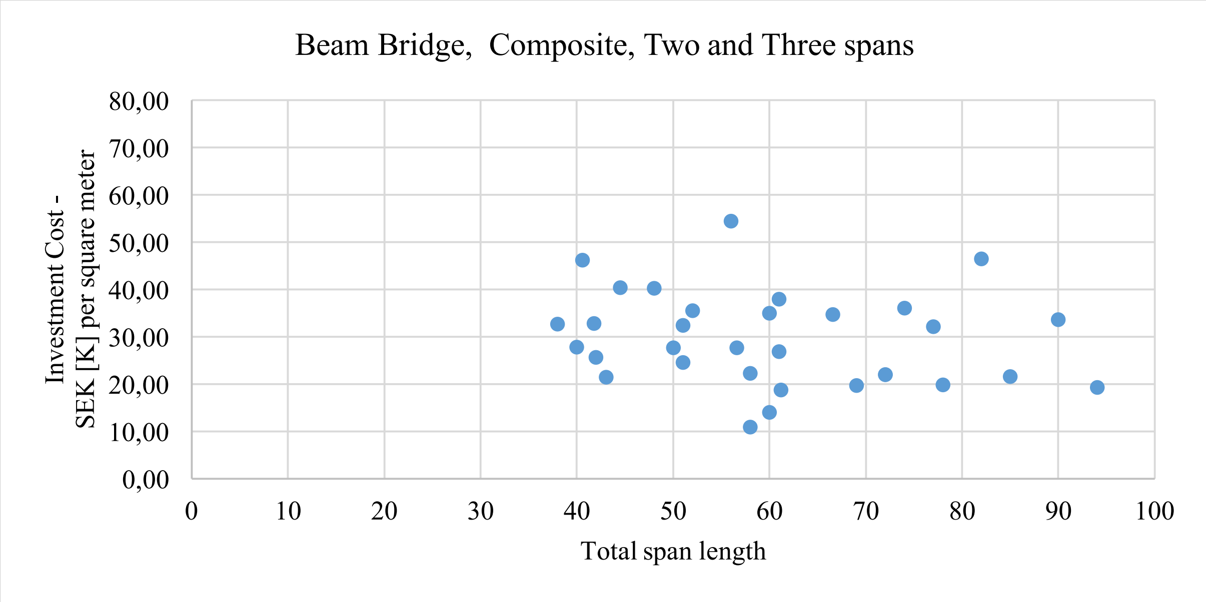


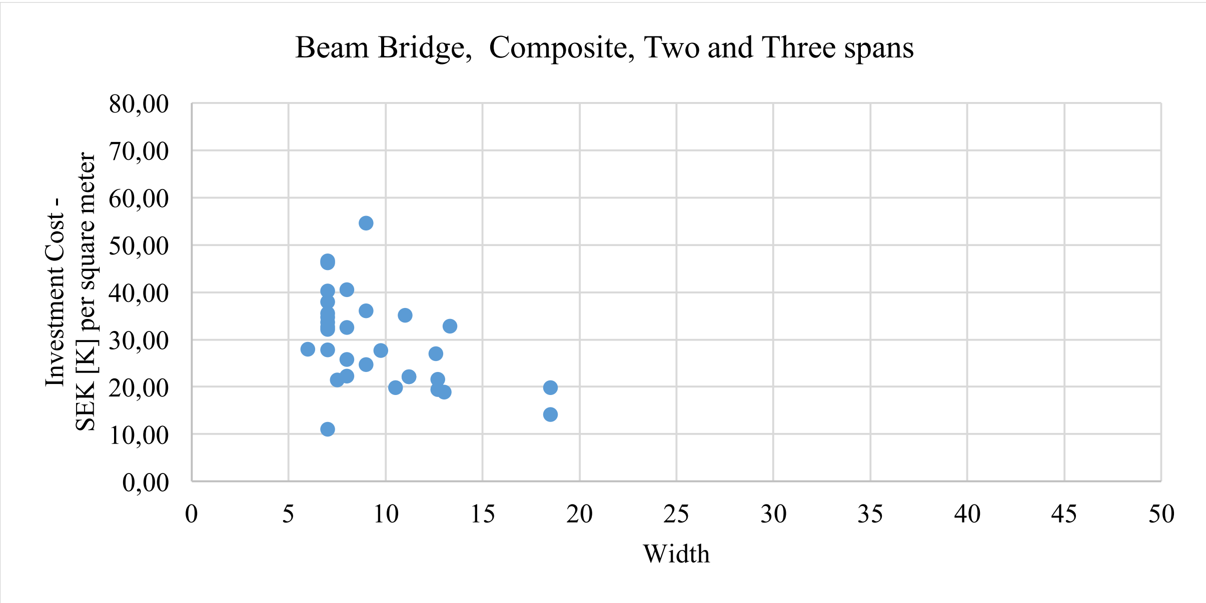
Beam bridge, Prestressed Concrete, Three Spans
Investment Cost -
SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

A.3 Beam bridge, Composite

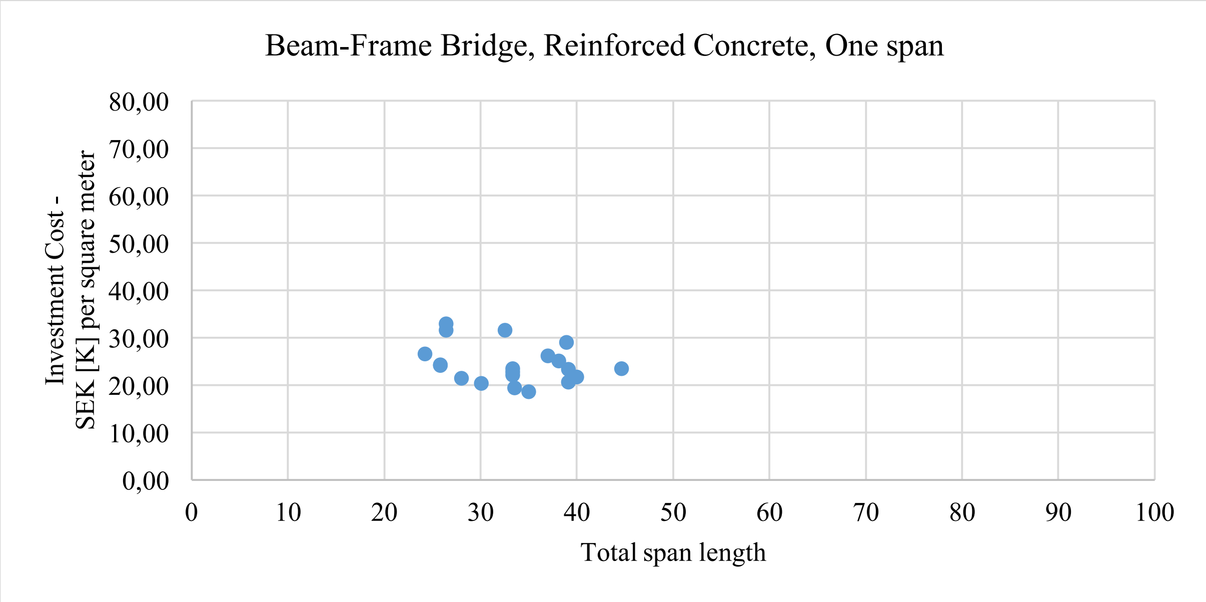


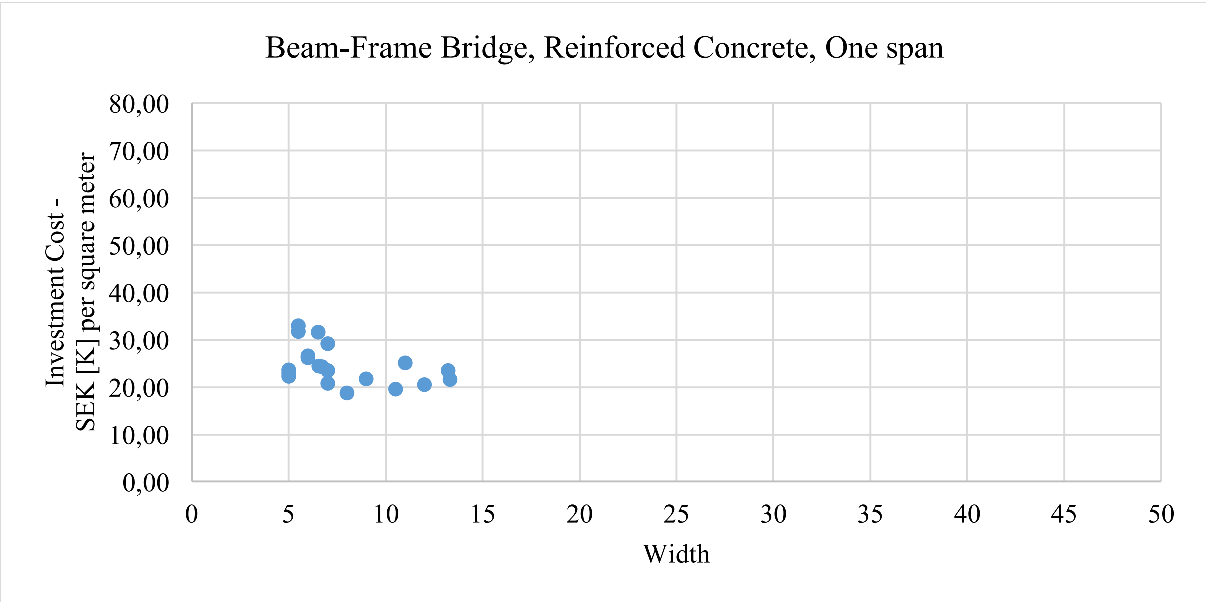



Beam Bridge, Composite, Two and Three spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length

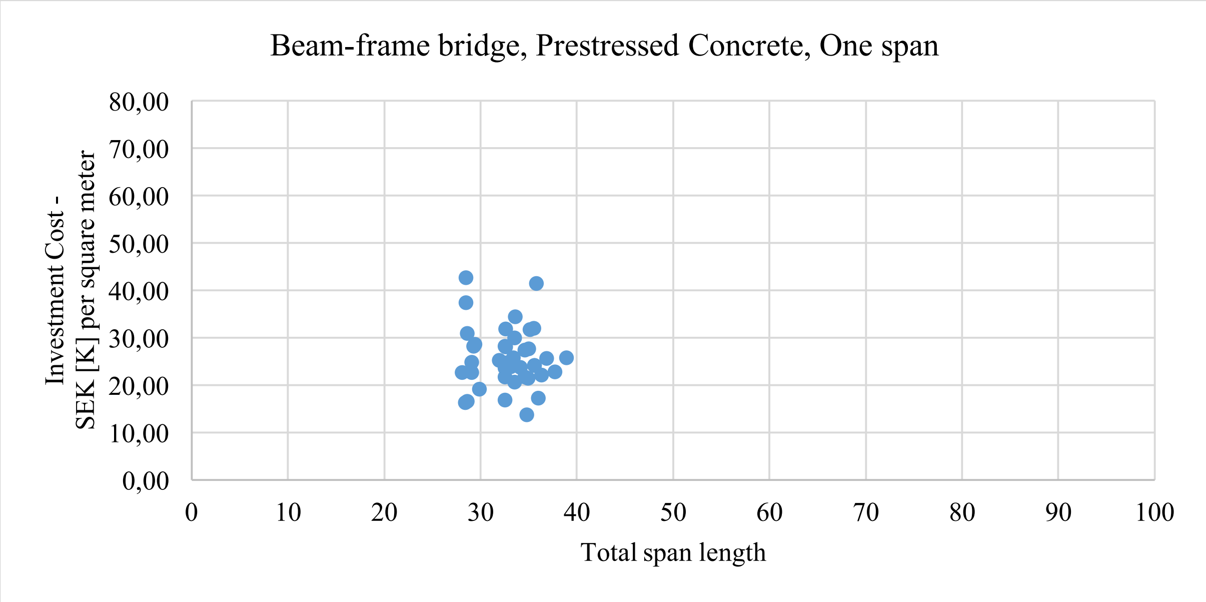

Beam Bridge, Composite, Two and Three spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

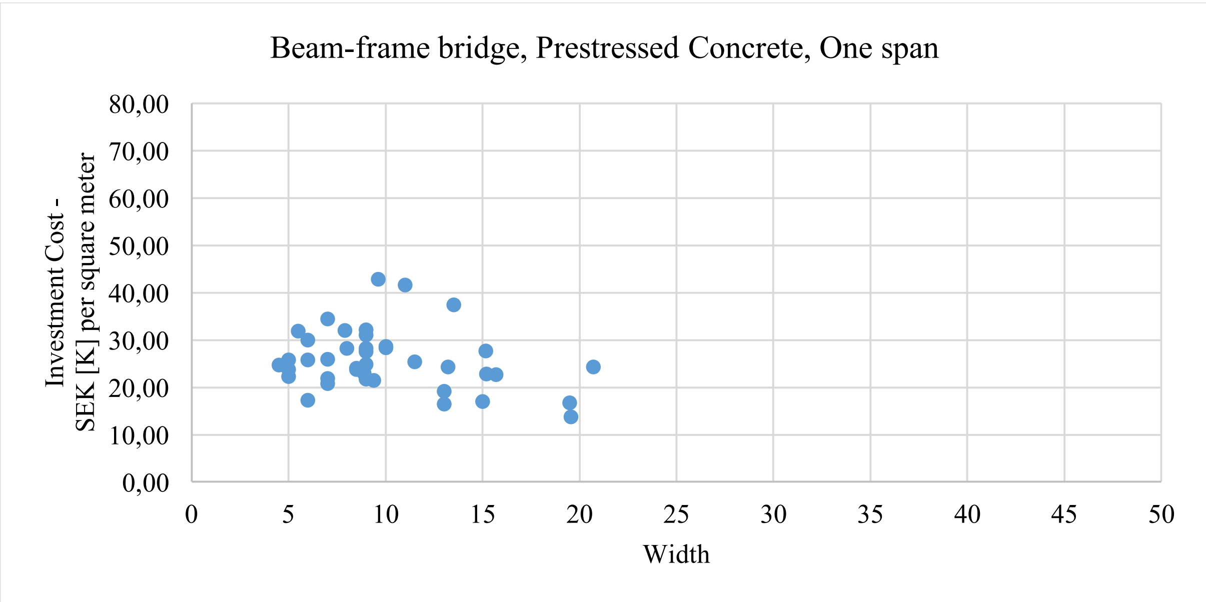
A.4 Beam-frame bridge, Reinforced Concrete



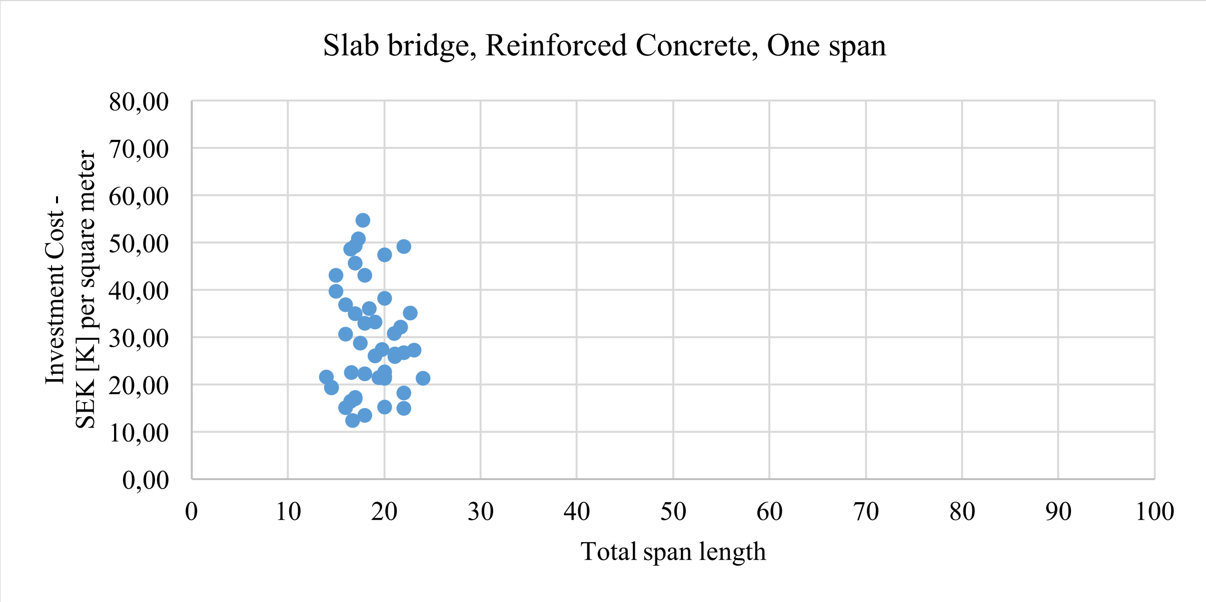


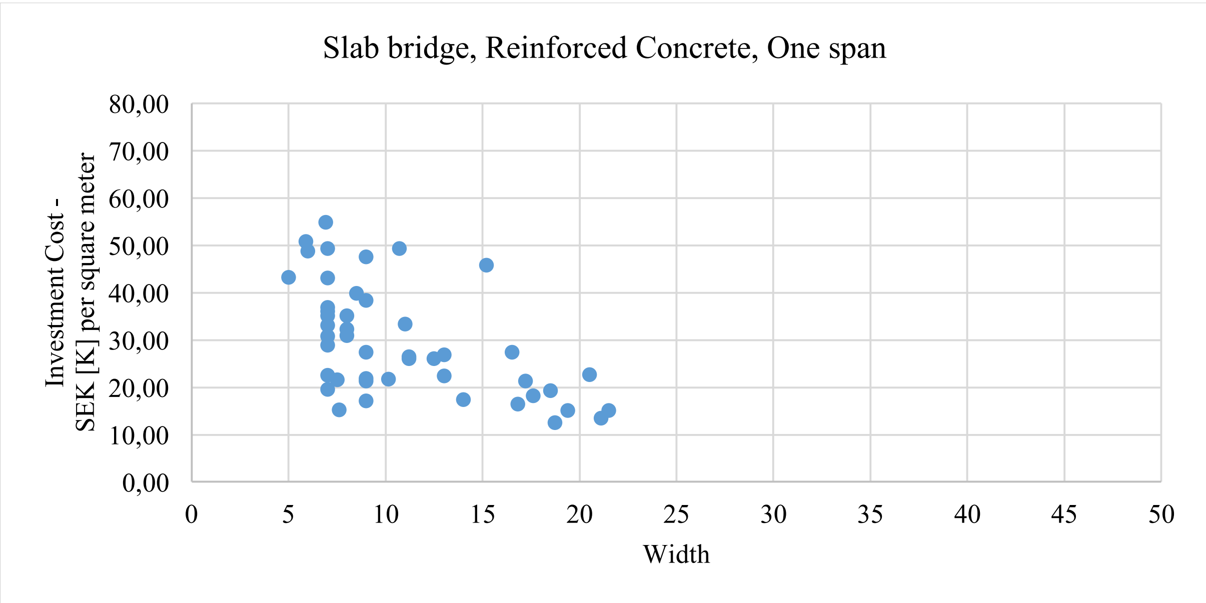
A.5 Beam-frame bridge, Prestressed Concrete

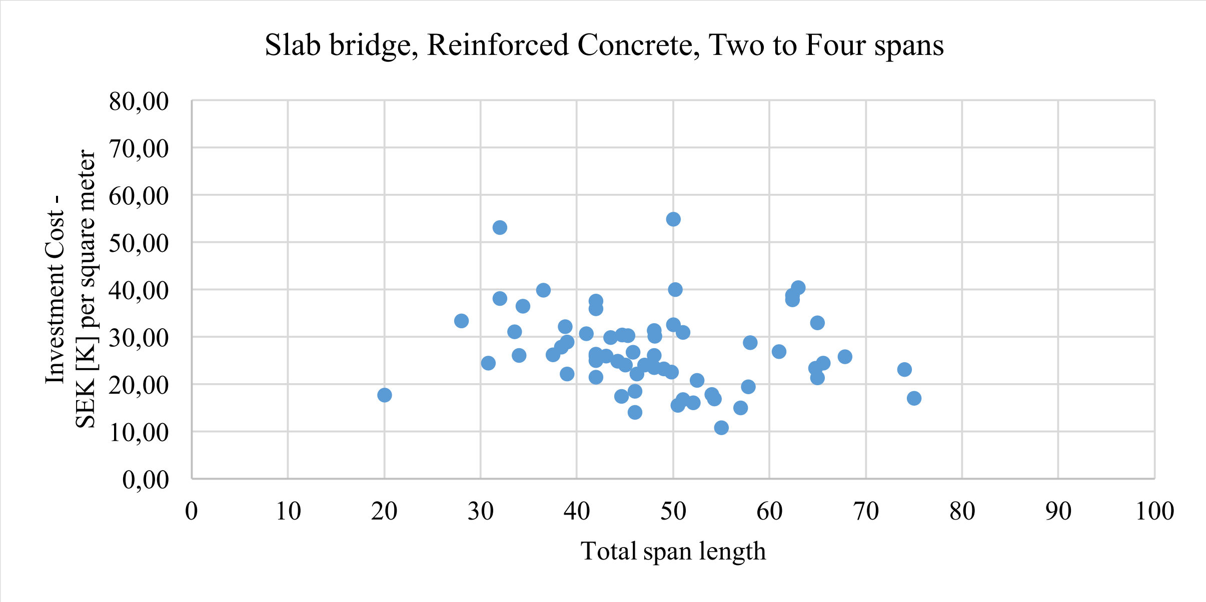


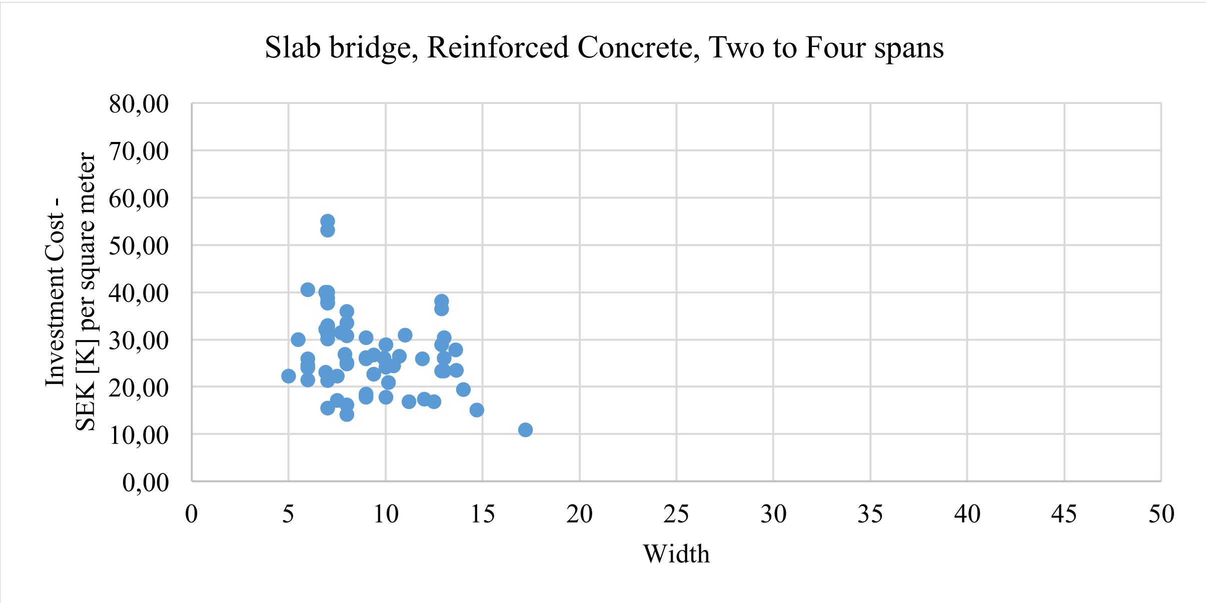


A.6 Slab bridge, Reinforced Concrete

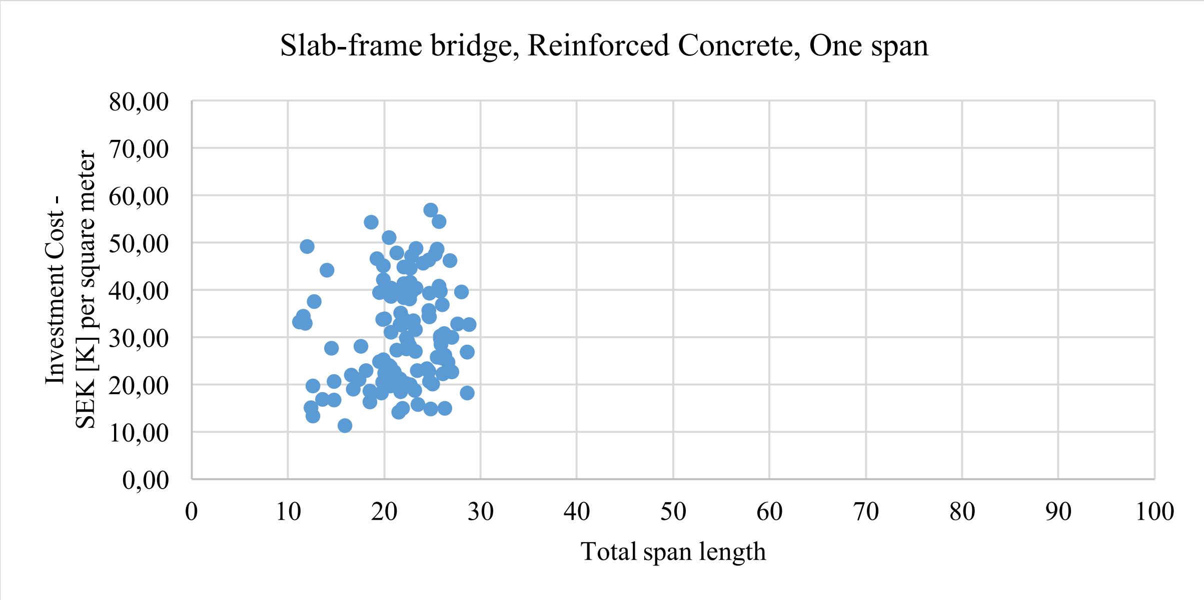


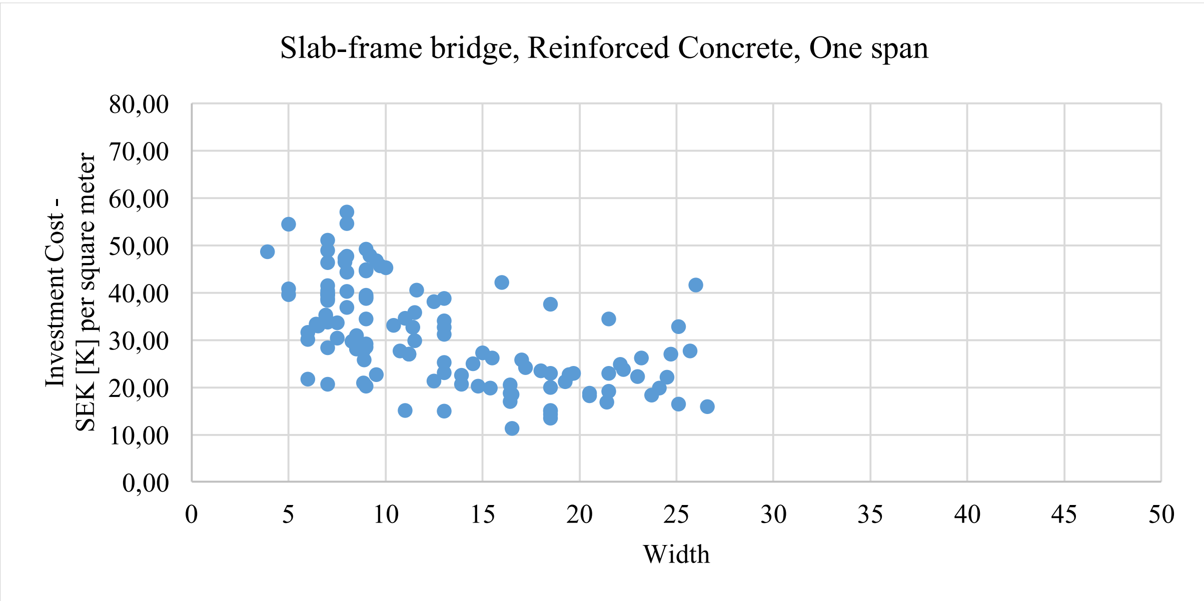


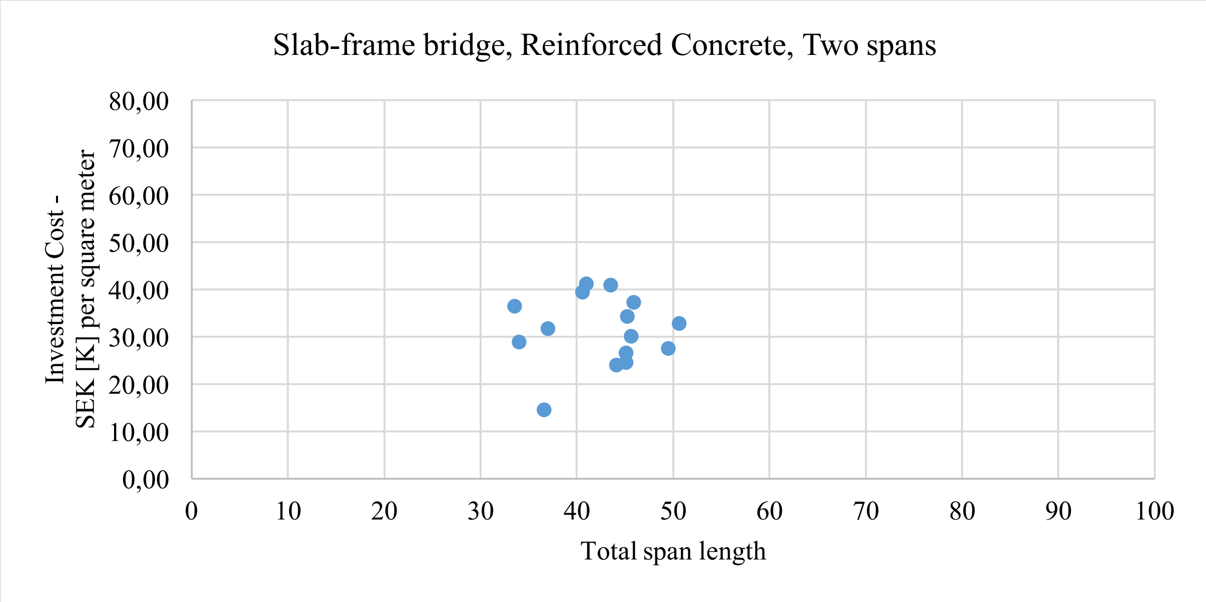

Slab bridge, Reinforced Concrete, Two to Four spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length

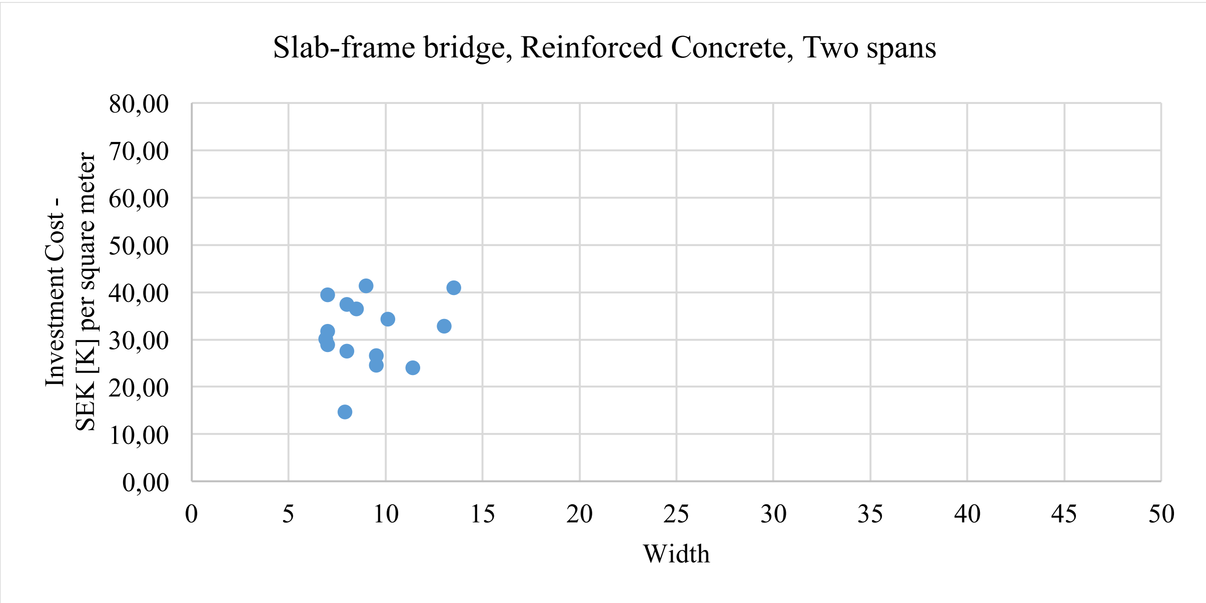

Slab bridge, Reinforced Concrete, Two to Four spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

A.7 Slab-frame bridge, Reinforced Concrete






Slab-frame bridge, Reinforced Concrete, Two spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
10
20
30
40
50
60
70
80
90
100
Total span length


Slab-frame bridge, Reinforced Concrete, Two spans
Investment Cost - SEK [K] per square meter
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0
5
10
15
20
25
30
35
40
45
50
Width

Appendix B – Validation of Regression Analysis

Bridge Type	Cost vs:	Coefficient of Determination (R^2)
Beam Bridge, Reinforced Concrete, One Span	Length	0,2014
	Width	0,3892
Beam Bridge, Reinforced Concrete, Two Spans	Length	0,0144
	Width	0,203
Beam Bridge, Reinforced Concrete, Three Spans	Length	0,0091
	Width	0,006
Beam Bridge, Prestressed Concrete, One Span	Length	0,1237
	Width	0,1614
Beam Bridge, Prestressed Concrete, Two Spans	Length	0,0564
	Width	0,0766
Beam Bridge, Prestressed Concrete, Three Spans	Length	0,0013
	Width	0,0329
Beam Bridge, Composite, One Span	Length	0,0033
	Width	0,027
Beam Bridge, Composite, Two and Three Spans	Length	0,015
	Width	0,1697
Beam-Frame, Reinforced Concrete, One Span	Length	0,1106
	Width	0,187
Beam-Frame, Prestressed Concrete, One Span	Length	0,0002
	Width	0,0368
Slab Bridge, Reinforced Concrete, One Span	Length	0,0054
	Width	0,3094

Slab Bridge, Reinforced Concrete, Two, Three and Four Spans	Length	0,0057
	Width	0,0583
Slab-Frame, Reinforced Concrete, One Span	Length	0,0176
	Width	0,3166
Slab-Frame, Reinforced Concrete, Two Spans	Length	0,0007
	Width	0,0222

Appendix C – Unit Prices Bridge Measures (BaTMan)

Bridge Part	Measure	Unit	Unit price (SEK)
Edge Beam	Impregnation	m	400
	Replacement	m	13 000
Railing	Replacement	m	1 600
Bearings	Paint Improvement	Pcs	9 565
Drainage system	Basic drain - Completion	Pcs	1 800
	Basic drain - Replacement	Pcs	2 200
	Downpipes - Replacement	Pcs	14 500
	Surface drainage - Completion	Pcs	14 000
Superstructure - Steel	Paint Improvement (0-99 m^2)	m^2	2 500
	Paint Improvement (99,1 - m^2)	m^2	1 900
Superstructure - Concrete	Concrete Repair (0-49 m^2)	m^2	3 055
	Concrete Repair (49,1-199 m^2)	m^2	2 015
	Concrete Repair (199,1- m^2)	m^2	1 603
Waterproofing	Replacement (0-100 m^2)	m^2	3 200
	Replacement (100,1-400 m^2)	m^2	2 350
	Replacement (400,1- m^2)	m^2	1 650
Wearing course	Replacement (0-299 m^2)	m^2	1 000
	Replacement (299,1-2999 m^2)	m^2	700
	Replacement (2999,1- m^2)	m^2	500
Pier	Impregnation	m^2	480
	Concrete Repair (0-5 m^2)	m^2	7 860
	Concrete Repair (5,1-19 m^2)	m^2	6 560
	Concrete Repair (19,1 - m^2)	m^2	5 640
Abutment	Impregnation	m^2	480
	Concrete Repair (0-5 m^2)	m^2	7 550
	Concrete Repair (5,1-19 m^2)	m^2	6 300
	Concrete Repair (19,1 - m^2)	m^2	5 400
Expansion Joint	Replacement	m	36 000
	Maintenance	m	800
Demolition	Demolition	m^2	750

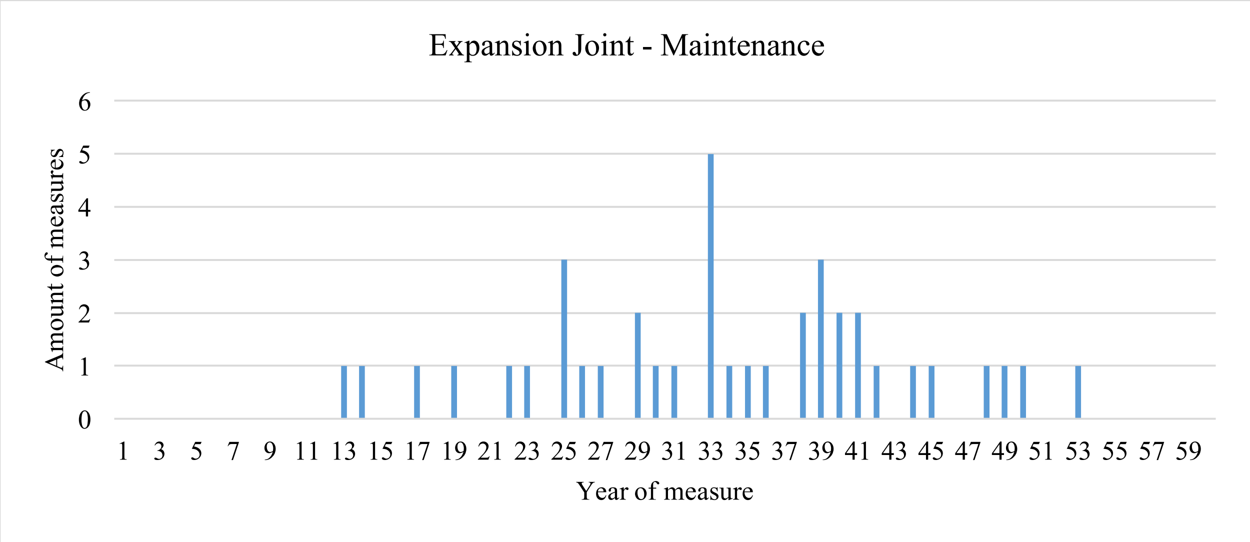
Inspection	Continuous Inspection (1 year intervals)	Years	4
	General Inspection (3 year intervals)	Years	4
	Main Inspection (6 year intervals)	Years	7

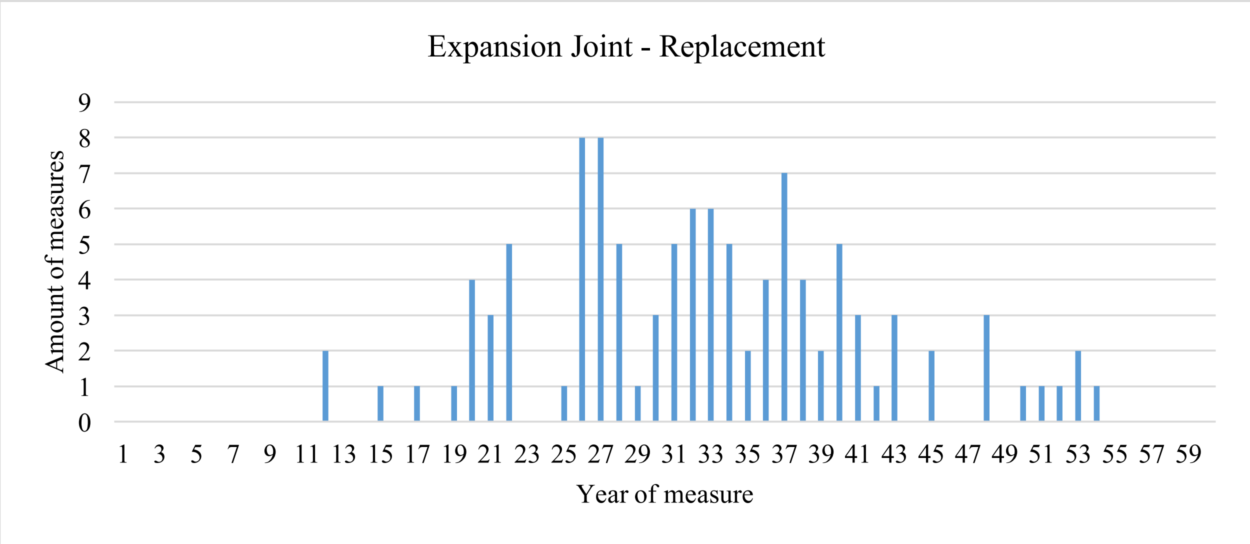
Appendix D – Validation of Maintenance Intervals

D.1 Comparison of intervals

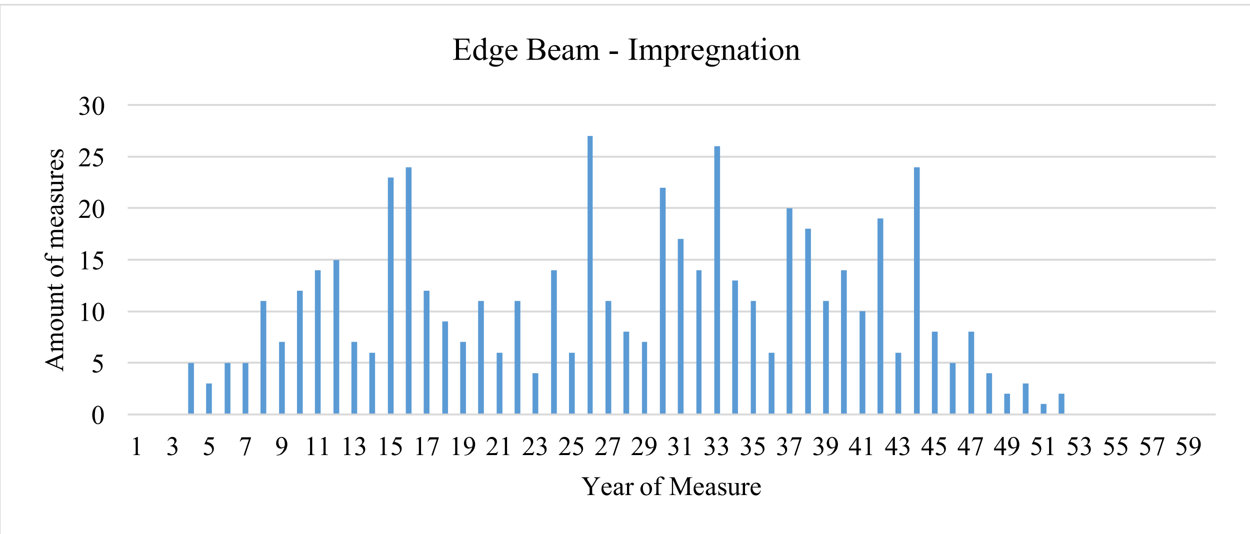
Bridge Part	Measure	Interval (years) according to the experience at the Swedish Transport Administration	Interval (years) according to BaTMan study
Expansion Joint	Maintenance	1	35
	Replacement	30-40	32
Edge Beam	Impregnation	15	15
	Replacement	30-40	40
Railing	Replacement	30-40	37
Bearing	Paint Improvement	30-40	32
Drainage system	Supplementation	30-40	35
	Replacement	30-40	35
Superstructure - Steel	Paint Improvement	40	15
Superstructure - Concrete	Concrete Repair	30-40	35
Waterproofing	Replacement	30-40	30
Wearing course	Replacement	15	15
Pier	Impregnation	15	15
	Concrete Repair	30-40	35
Abutment	Impregnation	15	15
	Concrete Repair	30-40	35

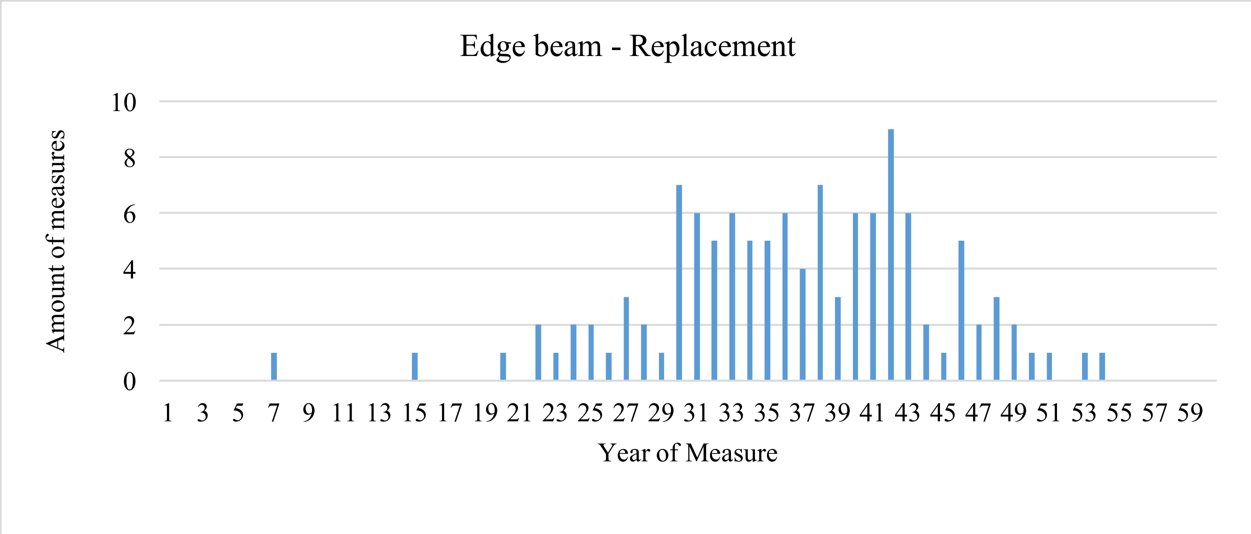
D.2 Expansion Joint



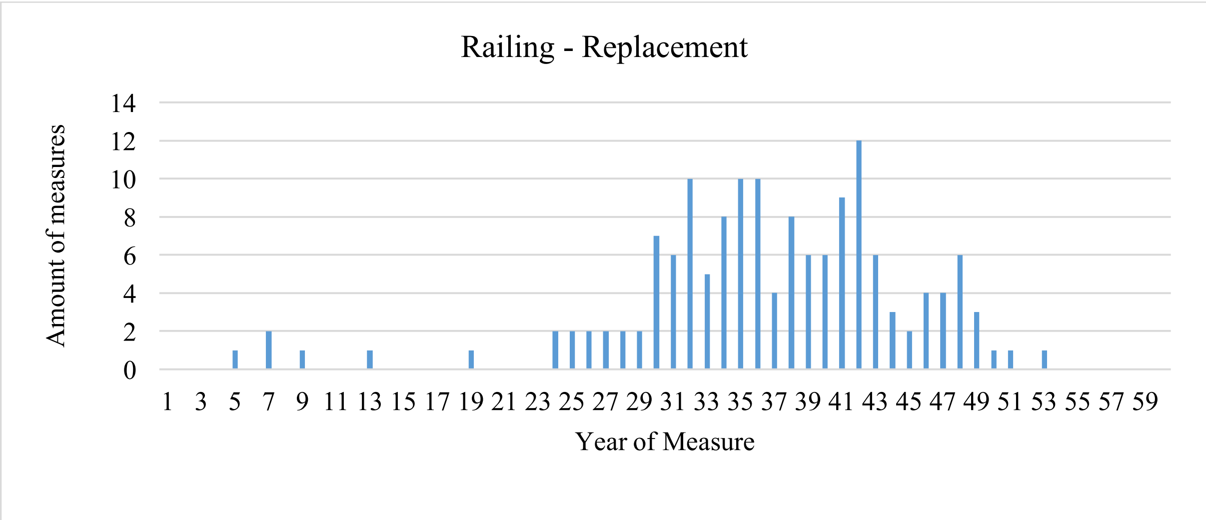


D.3 Edge Beam

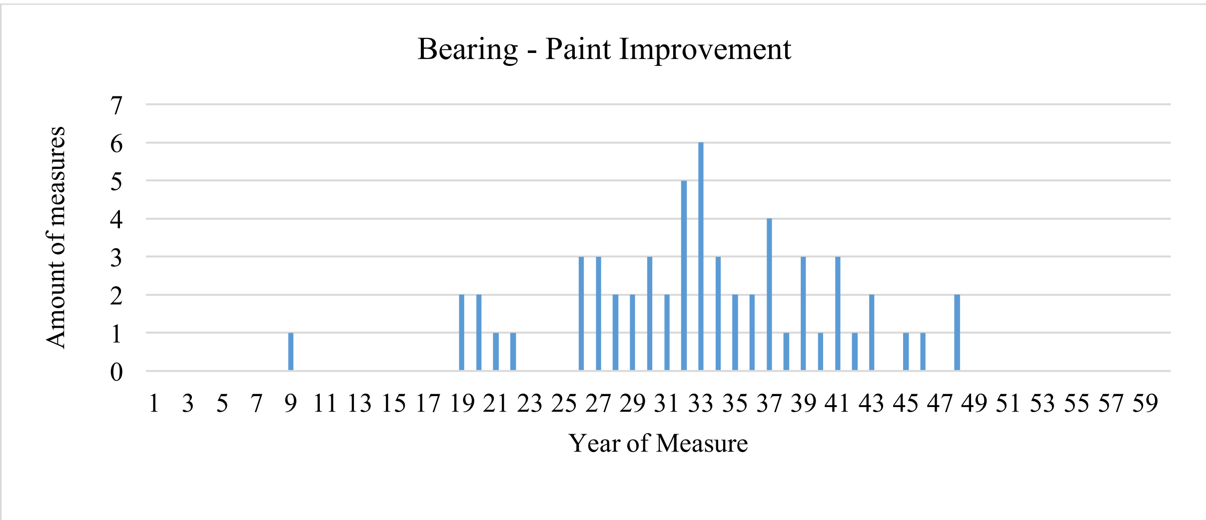




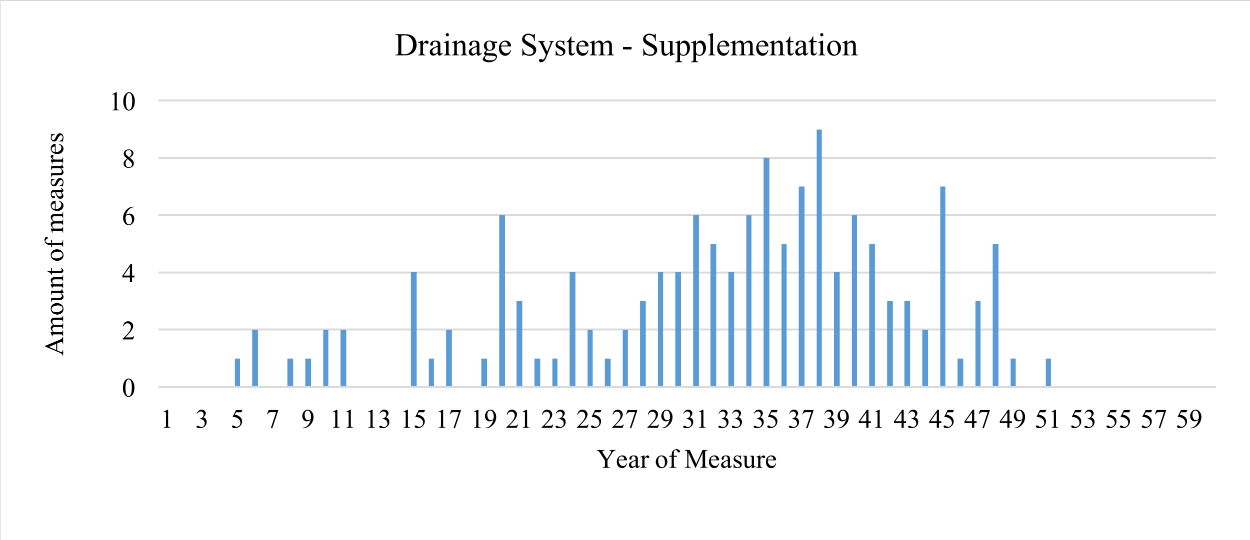
D.4 Railing

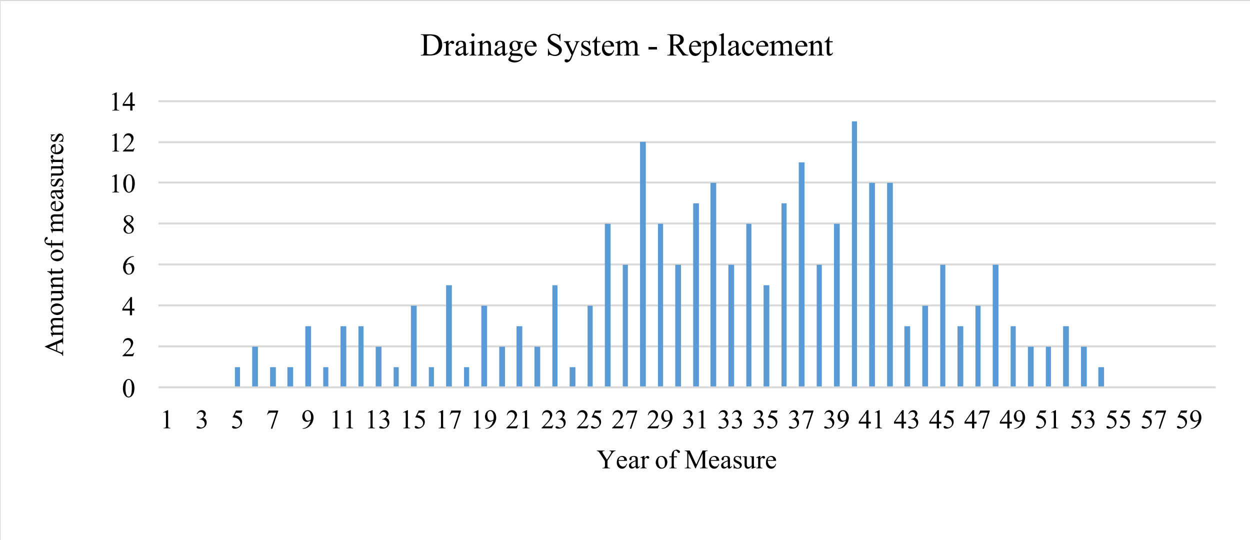


D.5 Bearing

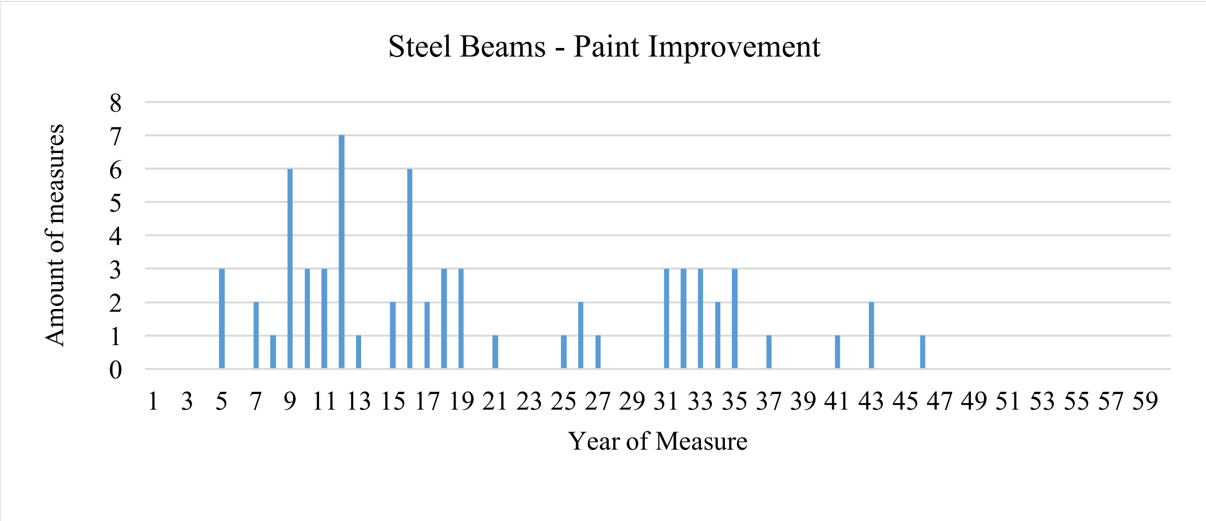


D.6 Drainage System

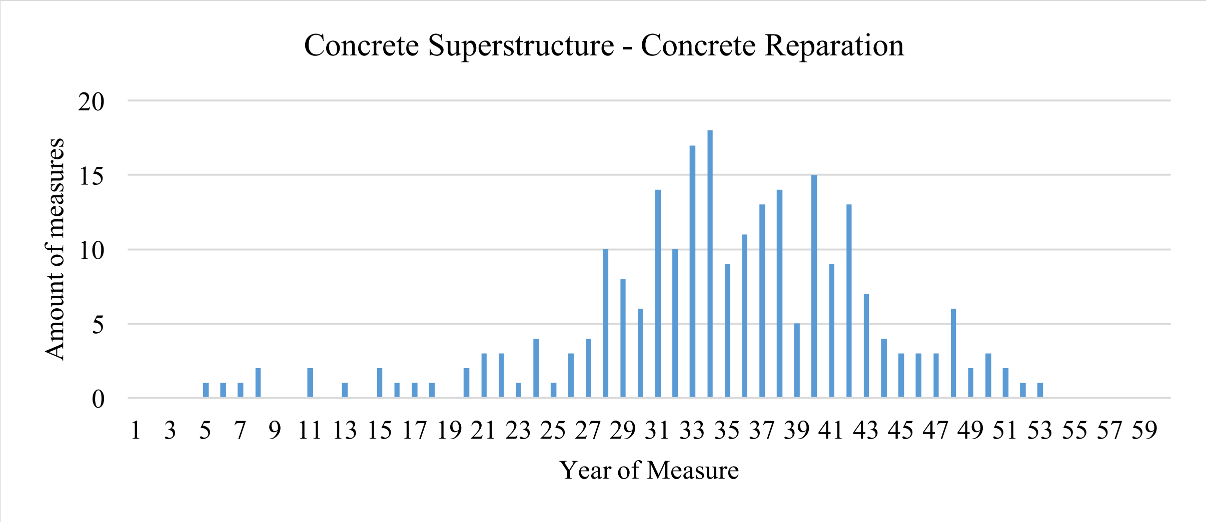




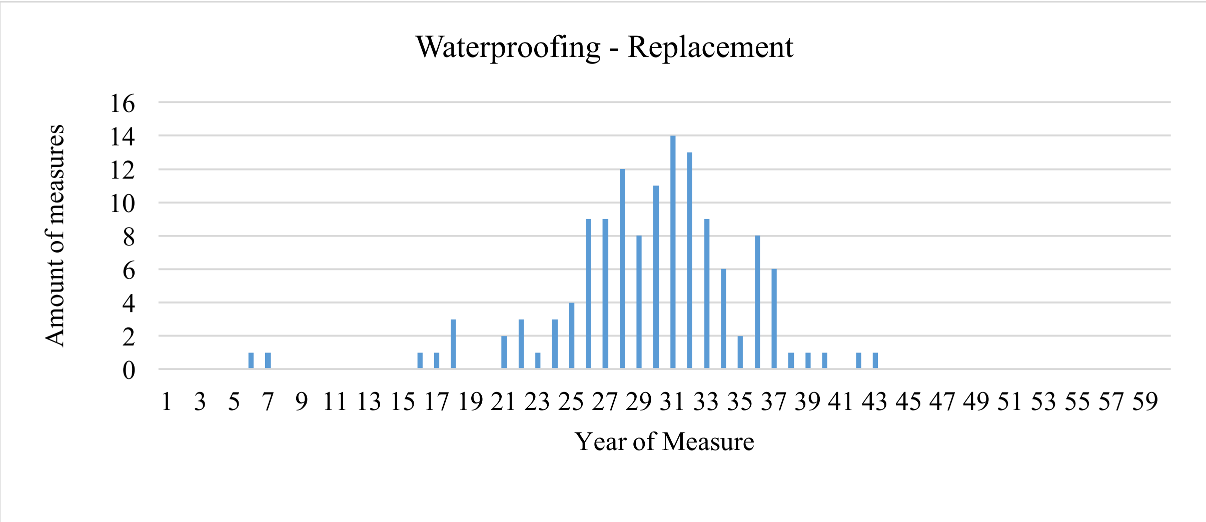
D.7 Steel Beams



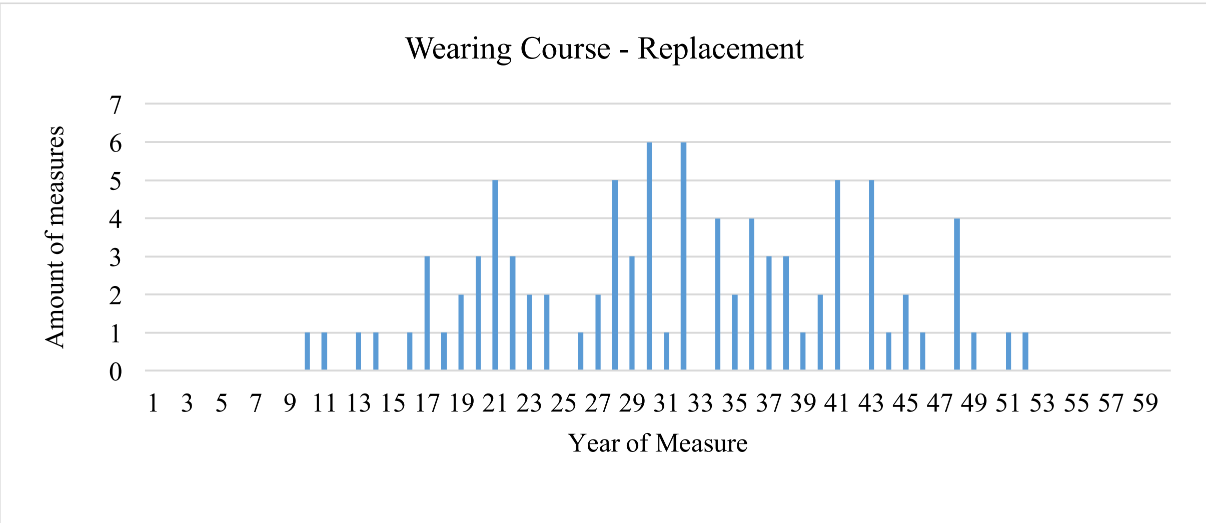
D.8 Concrete Superstructure



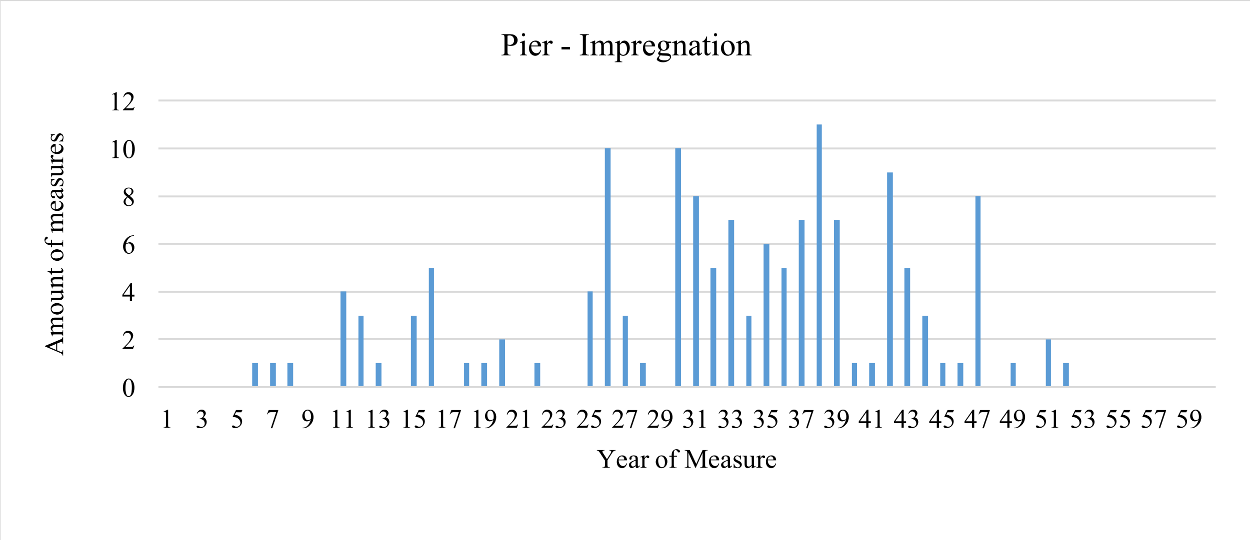
D.9 Waterproofing

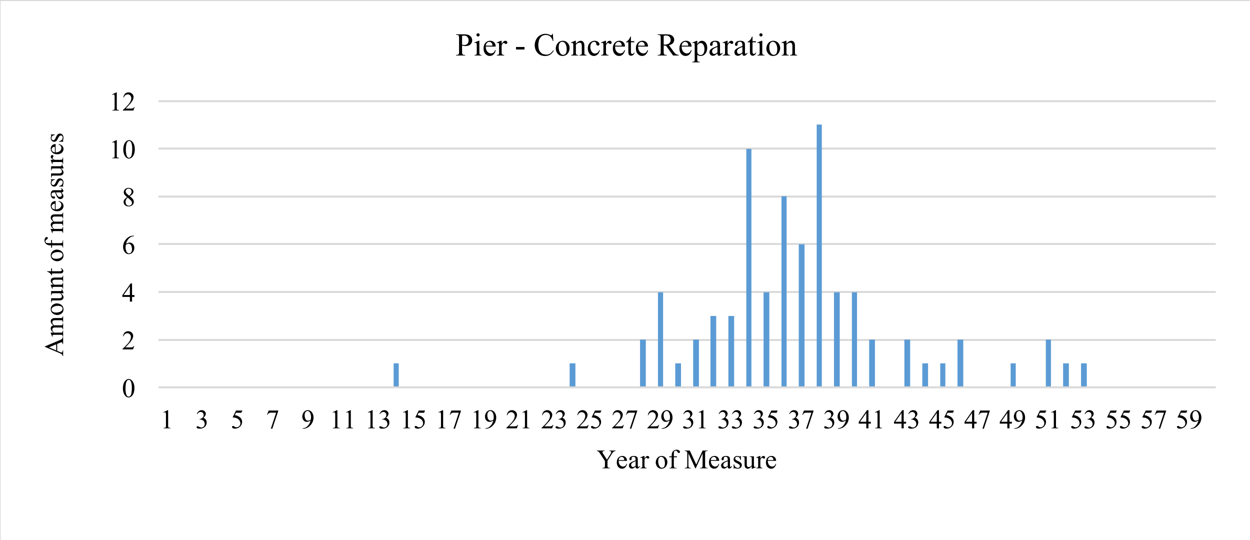


D.10 Wearing Course

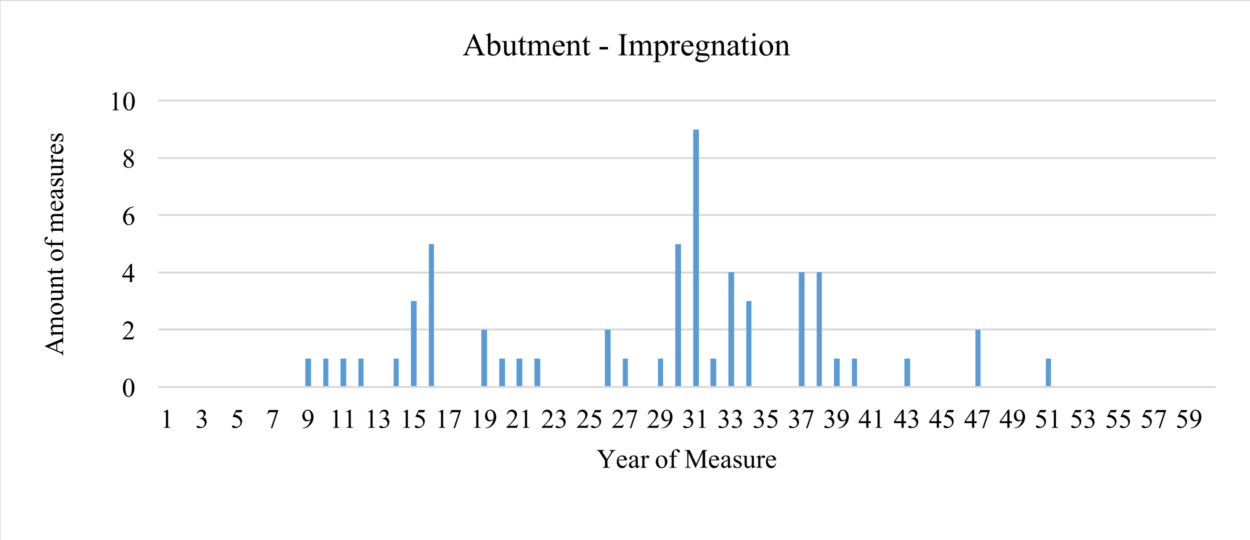


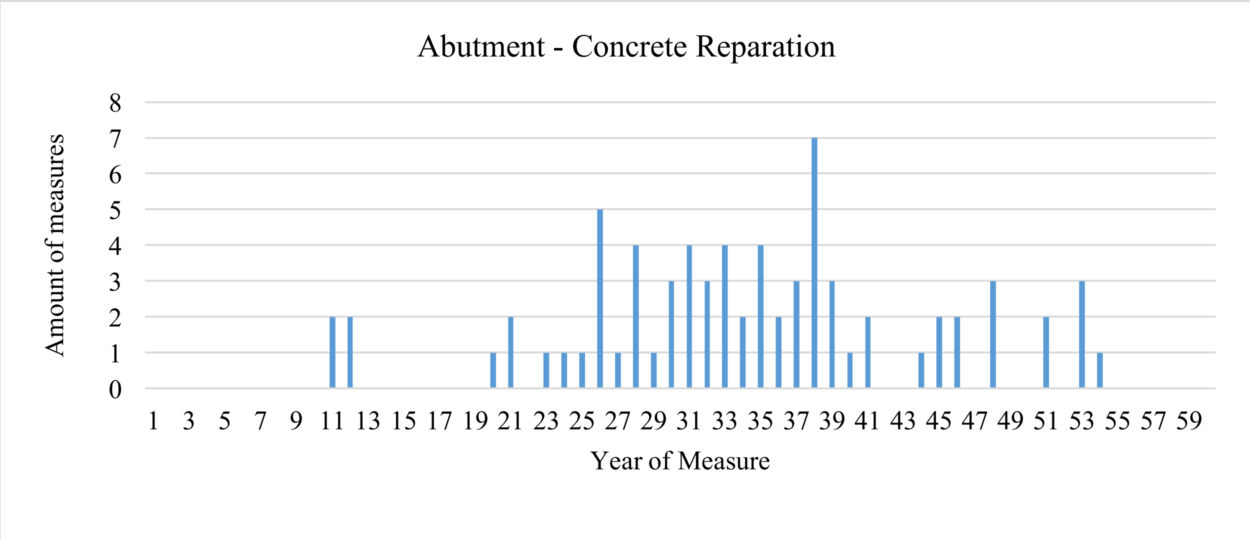
D.11 Piers


Pier - Impregnation
Amount of measures
0
2
4
6
8
10
12
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
Year of Measure


Pier - Concrete Reparation
Amount of measures
0
2
4
6
8
10
12
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
Year of Measure

D.12 Abutments





Appendix E – Weighting of maintenance activities

Bridge Part	Measure	Assumptions made according to price list from BaTMan	Exposure degree – Percentage of area repaired
Expansion Joint	Maintenance		
	Replacement		
Edge Beam	Impregnation	< 99 m	
	Replacement	< 99 m	
Railing	Replacement	<99 m	
Bearing	Paint Improvement	< 10 pcs 85% Repainting 15% Improvement	
Drainage system	Supplementation	< 29 pcs	
	Replacement	< 29 pcs	
Superstructure - Steel	Paint Improvement		
Superstructure - Concrete	Concrete Repair	65% (0-30mm) 35% (30-70mm)	Low – 10%
Waterproofing	Replacement		
Wearing course	Replacement		
Pier	Impregnation		
	Concrete Repair	40% (0-30mm) 60% (30-70mm)	High – 100% Average – 50% Low – 10 %
Abutment	Impregnation		
	Concrete Repair	50% (0-30mm) 50% (30-70mm)	High – 100% Average – 50% Low – 10 %