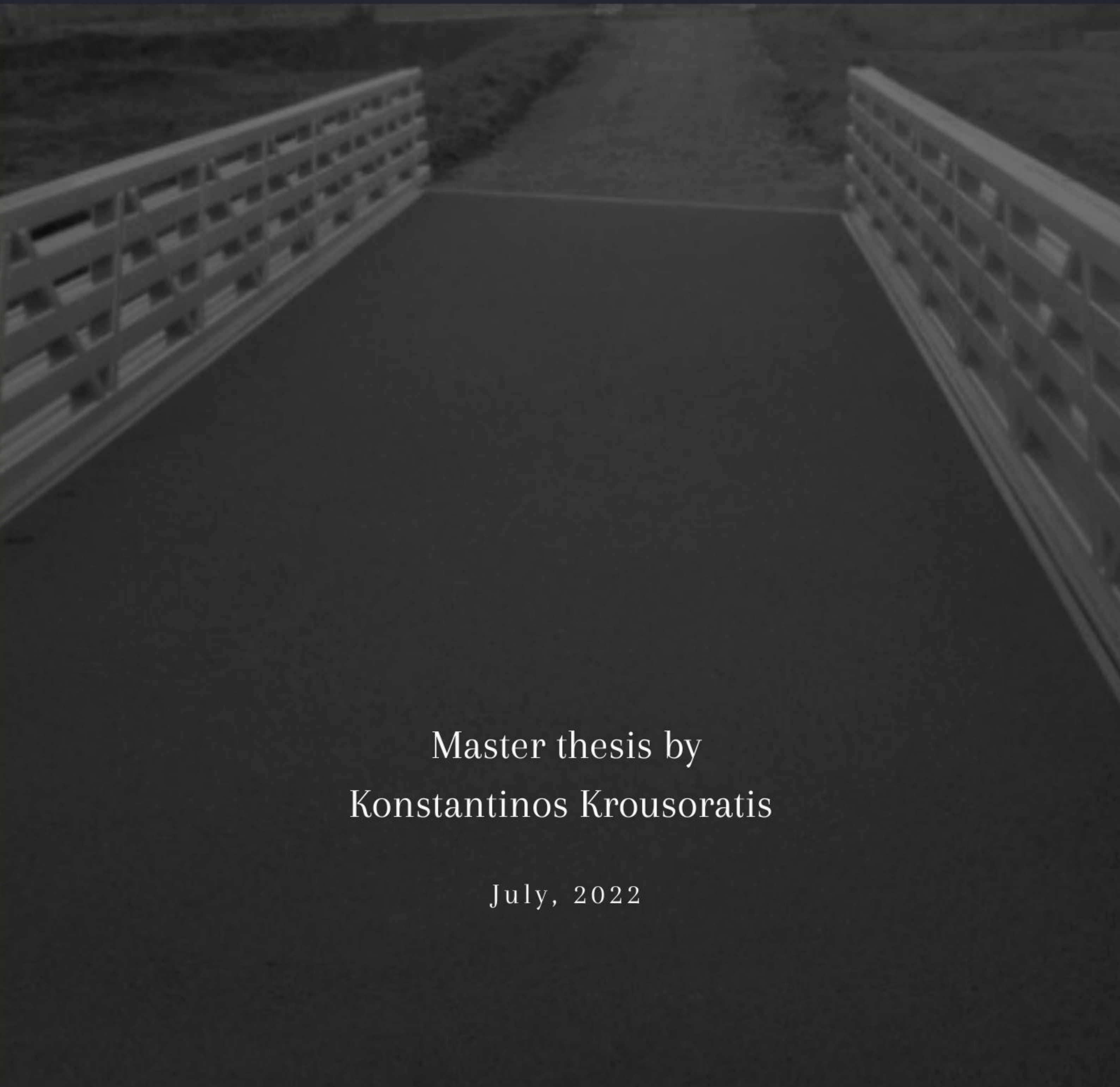
Towards more reliable cost estimations for asset replacement projects

Incorporating probabilistic models and the price uncertainty in the preliminary cost estimates for asset replacement projects



Master thesis by

Konstantinos Krousoratis

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TU Delft

SWECO

Toward more reliable cost estimations for asset replacement projects

Incorporating probabilistic models and the price uncertainty in the preliminary cost estimates for asset replacement projects

By

Konstantinos Krousoratis

in partial fulfilment of the requirements for the degree of

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Thesis committee:

Prof.dr. G.P. (Bert) van Wee TU Delft

Dr. ir Martine van den Boomen TU Delft

Dr. J.A. (Jan Anne) Annema TU Delft

Company Supervisor:

Ben Visser, Project leader, Sweco Nederland B.V.

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Preface

This particular graduation thesis is in partial fulfilment of my master’s studies in Construction Management and Engineering at TU Delft and signifies the conclusion of a remarkable two-year journey. This research was conducted in collaboration with Sweco Netherlands, which, together with TU Delft, provided me with valuable information necessary for effectively carrying out this challenging endeavour.

Having been raised in Greece during an extended economic crisis, I was very interested in understanding the various factors that led to this adverse situation. Many people consider that a single event served as a catalyst for Greece’s economic demise – the 2004 Athens Olympics. The state initially estimated this cost at 4.5 billion; Greece eventually ended up spending around 8.6 billion. Most of these financial resources were intended for infrastructure projects meaning that the allocated budget for these projects had been significantly underestimated. Moving to TU Delft to pursue my master I witnessed throughout the curriculum courses that the cost overrun issue is more the rule rather than the exception in infrastructure projects and that the problem has actually no national borders. This instantly sparked my interest to delve further into this topic. In that direction, the present research constitutes my undertaking to understand the issue and contribute to reducing the existing knowledge gap in the particular section of asset replacement projects.

Completing this six-month undertaking would never have been feasible without the significant contribution of certain people, to which I would like to express my deepest gratitude. I want to thank the members of my graduation committee, Prof. dr. Bert van Wee, Dr Ir. Martine van den Boomen and Dr Jan Anne Annema for the time they devoted in order to guide me throughout the whole endeavor. First of all, I would thank my committee chairman Professor Bert van Wee whose expertise in this particular topic enlightened every detailed aspect I had to consider when approaching my topic. His comments enriched my thesis with the academic flavor required and made my work far more professional. Also, I would like to express my deepest gratitude to my first supervisor, Martine van den Boomen who was the very first person onboard to guide and encourage me throughout the entire process. Without her precise scientific comments and contribution, I would have never overcome the impediments I faced during this scientific journey. Finally, I would like to thank my second supervisor Jan Anne Annema for navigating me and continuously enhancing the quality of my research. His willingness to hear and discuss my ideas and concerns, as well as his accurate remarks, constituted a key factor in successfully completing my thesis.

In addition, I would like to thank my company supervisor in Sweco, Ben Visser, for many reasons. First of all, for being the one who trusted me from the very beginning and provided me with the opportunity to work in one of the largest consultancies in Europe. Then I would like to personally thank him for guiding me throughout the process and providing me with his fruitful advice both regarding my thesis and my future professional life.

Last but most essential, I would like to thank my people. I am really privileged to have a family who made sacrifices in order for me to pursue my study goals and obtain a master's degree abroad. I would like to sincerely thank them for their unconditional love and support. Then I would like to thank all my friends for supporting and making this journey unforgettable. Apart from the knowledge, the most important takeaway from this journey is the people I met and the special moments we lived together.

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Executive Summary

Introduction and Research Approach

The majority of existing infrastructure assets are ageing, and sooner or later, they will have reached the end of their service life. As a result, many asset owners are confronted with large-scale replacement projects in the coming decades. These investments require allocating a significant amount of capital, which is lacking in most cases. Keeping in mind that cost overruns are more the rule than the exemption in construction projects, the planning and financing of replacement projects have become an issue of great concern for asset owners.

The present research investigates the various factors that can lead to budget overruns in replacement projects and provides a model intended to deal with them. More specifically, this dissertation demarcates and investigates the technical factors connected with how replacement costs are estimated in practice. The overall scope of this research is reflected in the main research question, which needs to be answered in order to achieve the defined goals and has been formulated as follows:

How can the current practices of estimating replacement costs be improved?

The whole approach of this research is divided into two main sections. In the first one, there is a twofold analysis to further understand the budget exceedance issue observed in replacement projects. The theoretical analysis contains a literature review which helps identify the various factors that can lead to budget overruns and theoretically describes the problem. Then the multiple factors identified in the conceptual part of the analysis are tested on a practical level by examining multiple case studies concerning past replacement projects. The second section of the research resembles an effort to deal with the problem described in the first part of the research. It contains the process of developing and validating a conceptual model capable of dealing with the problem and providing an answer to the main research question.

Results, Validation and Conclusion

All the findings from both sections represent the core contribution of this research both in the industry and the scientific community. In the first section, which includes the research analysis, useful findings were extracted related to the factors that can lead to budget overruns in replacement projects and the level of their contribution. The results in total were used to develop a conceptual framework capable of explaining the observed issue to a certain extent. More specifically, the research indicates that there are two essential characteristics of replacement projects that influence the accuracy of their cost assessment.

The first one is in connection with the fact that usually replacement budgets are determined with imperfect preliminary cost assessments conducted when little information about the project is available. The examination of the case studies revealed that the deficiencies related to the techniques and inputs used for preliminary estimating costs as well as the limited information which is used as input for the estimation highly contribute to the observed cost overruns. More particularly for the specific asset type of bridges that were examined, it was observed that the unit prices used for roughly estimating the costs provide relatively reliable results for longer bridges (width≪length) however, for wider ones (width≈length) the cost assessment with such inputs results in extreme overruns.

The second characteristic identified in the analysis is associated with the fact that replacement budgets are usually structured in the long-term asset planning process. This implies that the cost assessment is conducted many years before the actual execution of replacement works, and, in that long timeframe, many changes can occur. The examination of the bridge replacement case studies showed that the ignorance of price escalation in the cost assessment could lead to an escalation of the estimated costs by 1.81% annually for that particular type of asset.

All the respective information about the factors that can lead to budget overruns in replacement projects derived from the first section of this research was used in the second section as an input for developing the proposed model to deal with them. The proposed model consists of two building blocks, and each of them is structured in such a way to target the factors associated with the two essential characteristics of replacement projects that contribute to the limited accuracy of their cost assessments. More particularly, the model's first building block aims to improve the current practices of preliminary estimating replacement costs by incorporating probabilistic methods. The probabilistic assessment is conducted by using available cost data referring to the contribution of the various work packages to the total budget for a specific asset type together with their respective best-fit distributions. Also, for the analysis, a Monte Carlo Simulation is performed. The second building block aims to provide an indication of the evolution of replacement costs in the future years by using historical prices and a stochastic model. The historical prices used are extracted from open databases and the stochastic model that is used is the Geometric Brownian motion. The first part of the model's validation which included the application of the model in a single case study showed that in the case study examined; the model was capable of providing better results than the current practices. More particularly, the probabilistic cost assessment indicated by the model resulted in a cost indication closer to the actual one than the one estimated with the common industry's practices. The deviation between the actual cost and the one estimated with the current practices for that particular case study was around 34%. With the proposed probabilistic model, this deviation was reduced to 27%. Also, it provided the opportunity to get a particular confidence range for the estimated replacement costs. This was done by offering the option to have a high and low value of the estimated costs, a feature that is currently missing from the current practices and can potentially increase the assessment's transparency. In addition, by incorporating historical prices and a stochastic model, the model was able to indicate how the initially estimated replacement costs could evolve over the years. The latter can enable project promoters and planners to incorporate the price (de) escalation effect into the estimations and provide them with more confidence when determining replacement costs in the long–term asset planning process.

All in all, the present research constitutes an endeavour to fill the knowledge gap both in the scientific community and the construction industry by explaining the cost overrun issue in replacement projects, the potential factors that contribute to it and eventually by providing a tool to deal with the identified causes.

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List of Abbreviations

AACE	American Association of Civil Engineers
ASCE	American Society of Civil Engineers
BO	Bestek Ontwerp
CBS	Cost Breakdown Structure
DO	Definitief Ontwerp
ITEP	Institute of Taxiation and Economic Policy
GBM	Geometric Brownian Motion
LCC	Life-Cycle Costs
MCS	Monte Carlo Simulation
NASA	National Aeronautics and Space Administration
NIC	National Infrastructure Comission
PMI	Project Management Institute
SO	Schetsontwerp
VO	Voor Ontwerp
WBS	Work Breakdown Structure

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1. Introduction

1.1. Problem description

Asset owners across the world, including public entities, are struggling in order to reassure that their asset's condition is the best possible in terms of safety, functionality, and appearance (Frangopol 2011). For that reason, the maintenance and replacement of their assets have been one of their primary concerns (AWWA, 2019; Stewart 2001, Klatter et al. 2009, Orcesi 2016; Chou, 2009; Lind & Muyingo, 2012). Annually, they allocate a significant number of resources, but these budgets are never adequate for executing all maintenance and replacement activities for their respective assets (Chong & Hopkins, 2016). Based on a report from ASCE (2021) in recent years, all levels of government in the US have prioritized road and bridge repairs and replacements through investments. For these investments to be feasible, 37 states have either increased or reformed their gas tax since 2013.

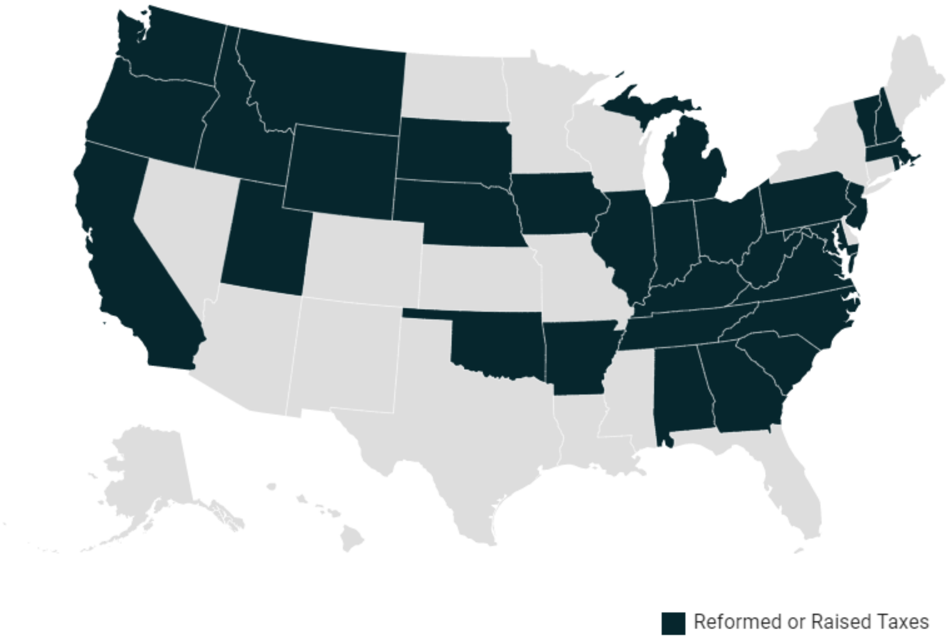


Figure 1: Gas tax increases in the US since 2013. Source: ITEP (2019)

However, despite states' increased investments, overall spending in the country's bridges remains insufficient. A recent Conditions and Performance Report from the Federal Highway Administration (U.S. Department of Transportation, 2020) indicates that the road bulk of backlog for repairing and replacing existing roads is estimated around $435 billion. Respectively for repairing and replacing existing bridges this amount is estimated at $125 billion. In the same report it is mentioned that there is an additional need to increase spending for road maintenance and replacement by 41billion for the next 20 years to improve their condition. For bridge rehabilitation this projection is evaluated to be 58% from $14.4 billion annually to $22.7 billion.

Based on similar data around the world (NIC, 2021; Infrastructure Australia, 2021) it can be said that the budgets allocated for maintaining and replacing existing assets are never adequate and the same pattern of consequent cost overruns and budget exceedance that is observed in new infrastructure projects over the years also exists for life-cycle budgets. In new infrastructure projects the inadequacy of financial resources and the exceedance of allocated budgets have been struggling the scientists and construction companies for years (Morris & Hough, 1987; Flyvbjerg et al., 2003; van Wee, 2007; Cantarelli et al., 2010). The most commonly attributed term for this issue is the one of "cost overrun", and various definitions have been given by different scholars. Flyvbjerg et al. (2003) consider cost overrun as the difference between the actual costs and the costs at the time of the decision. Love et al. (2013) define cost overrun as the difference between actual costs and the costs stated in the contracts. Following Flyvbjerg, in this dissertation which examines the issue of cost overruns in replacement projects, the first definition is adopted. It is used in order to describe the deviation between the actual costs and the costs at the particular point of time in which the decision to replace an asset is taken.

Although cost overruns mainly appear in the construction phase, their causes could be spotted in the pre-construction phase (Cantarelli & van Wee, 2013). Flyvbjerg et al. (2003) support that inaccurate cost estimations are one of the main factors that can lead to a misallocation of limited resources for new infrastructure projects, and this research observes that this is the case for replacement projects too. Based on this dissertation, the life-cycle budgets, especially those allocated to replace municipal assets, have two essential characteristics that affect their accurate forecast.

First, replacement budgets are usually constructed based on preliminary estimations, containing a high error range and low reliability (Christensen et al., 2005; AbouRizk & Mohamed, 2002). The limited accuracy of these estimates can be attributed to the differences in engineering experiences, perspectives, viewpoints, knowledge, agencies involved, estimation methods used, reliability of the collected information, and time of estimation (Wibowo & Wuryanti, 2007). Asset life-cycle budgets contain allocated funds for the required maintenance activities during their service life and their replacement at its end. For estimating the costs of regular/cyclic maintenance activities, these preliminary methods can be considered slightly accurate as few uncertainties exist, and a lot of information is available due to their repetitive character and inspections. Thus, their contribution to life-cycle budget overruns may be assumed low if a well-structured maintenance plan exists. However, this is not the case for the allocated financial resources intended for replacing an asset. For replacement projects, little is known about their degree of uncertainty due to their one-off nature. Consequently, roughly estimating these costs contains a high risk of ignoring these uncertainties and underestimating their budget.

There is also a second unique characteristic of replacement projects that increases the possibility of exceeding the initially estimated budget forecast. This second characteristic is linked to the fact that replacement budget estimations are usually conducted years before the initiation of the construction works. In the long-term asset planning process, the life-cycle budgets, including the amount attributed for the asset's replacement, can be constructed for more than 50 years based on the particularly designed lifetime (Klatter et al., 2003). During this long-time frame, many changes can occur. Long-term planning is binned with many uncertainties, such as price escalation, which this research proves can significantly affect the initial estimated costs. Even though discount rates are used in forecasts to deal with this time parameter, the low discount rates that public entities use do not cover the price escalation that is usually observed.

Figure 2 illustrates how the total cost of replacing an asset can evolve based on how it has been estimated. For very rough Class 5 estimates (see Chapter 3), the cost overrun can be very high due to the multiple uncertainties that exist in the phases in which they are conducted and due to the escalation of prices over the years. In contrast, this cost overrun for highly detailed Class 1 estimates is reduced as many of the previously mentioned uncertainties have disappeared in the phase when the detailed forecast is conducted. The factor that still exists and has a high contribution to the detailed estimates is mainly the price escalation inherent to the long-term asset planning process.

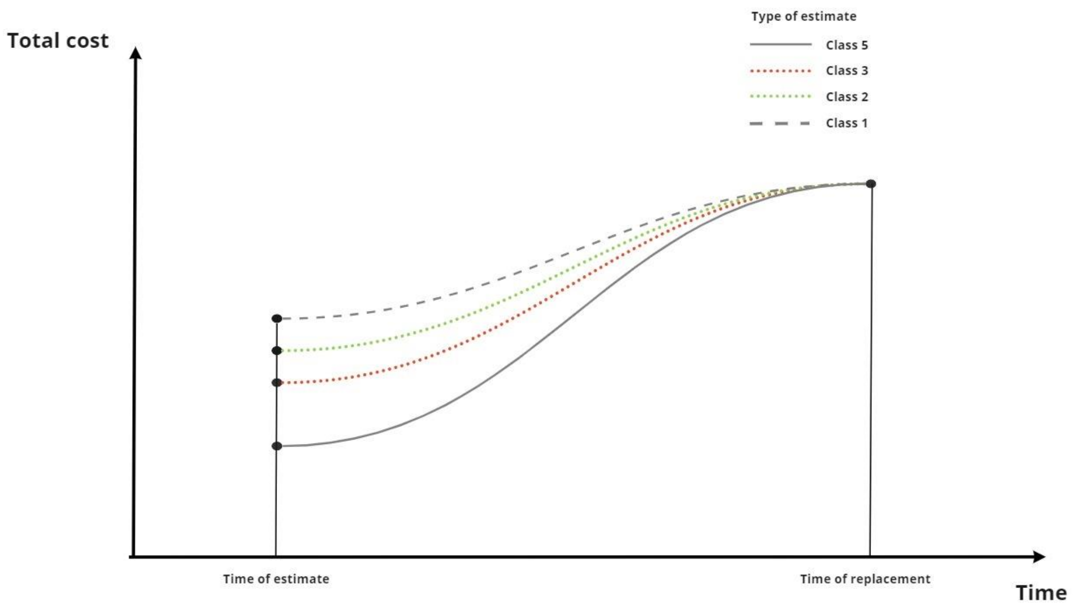


Figure 2: Evolvement of replacement budget over the years (own illustration)

Based on the above, public clients and engineering companies fail to forecast the replacement budgets accurately.

Although the problem of budget overruns in replacement projects highly exists in the construction industry, little or no literature is available about this specific topic. It is observed that most of the scholars are mainly trying to deal with cost estimations and cost overruns only for new infrastructure projects, and little attention has been given to the replacement ones. All of the available literature on cost estimations for new infrastructure projects focuses on three specific directions. The first direction concerns the scholars trying to develop new methods to improve the accuracy of estimates. The second direction is referred to authors who discuss the performance of estimated contingencies by comparing the estimated costs with the actual ones. A third direction that Hoseini et al. (2020) considered exists is the one that examines how the project cost estimates evolve in the early phases of a project. An overview of the available literature and the specific aspects are presented in Table 1.

Table 1:Different research directions about cost estimates in the literature

Category description	Scholars	Scope of the research
Development of new methods to improve cost and cost contingency estimates for new infrastructure projects	Mak and Picken (2000), Thal et al. (2010), Lee et al. (2017), Panthi et al. (2009), Lhee et al. (2011), Khamooshi and Cioffi (2009),	Developing quantitative methods to estimate cost contingency in the preconstruction phase
	Xie et al. (2011),	Developing quantitative methods to manage cost contingency throughout the project execution phase
	Hammad et al. (2016)	Developing methods to estimate and manage the cost contingency in both preconstruction and execution phases of a project

Investigating the cost performance in the projects	Flyvbjerg et al. (2002), Cantarelli et al. (2012), Baccarini (2004), and Hollmann (2012)	Comparing the realized and estimated costs and discussing the reasons for deviation
Cost contingency and cost evolvement of construction projects in the preconstruction phase	Hoseini et al. (2020)	The evolvement of the total project cost (contingency) estimates and the relation between "known unknowns" and "unknown unknowns" contingencies in the preconstruction phase of construction projects.

As presented in this table, there is quite some literature about cost overruns (Wachs, 1989; Cantarelli et al., 2012; Flyvbjerg et al., 2002) for new infrastructure projects, however; little for the replacement ones. This might be due to the assumption that replacement projects contain more minor uncertainties because they are not planned on blank paper. Another reason for the lack of literature is that replacement projects are usually planned way before their execution and documents related to the forecasts, and limited information on cost forecasts is publicly available because of their generally confidential nature. A probable third reason pertaining to the lack of literature is that replacement projects are not part of the political decision process. Consequently, they fly below the radar of the scientific community.

For many years, scholars have been dealing with cost overruns in new infrastructure projects (Flyvbjerg et al., 2002; Cantarelli et al., 2012; Baccarini, 2004; Hollmann, 2012). Along with describing the problem, they also illustrate the different factors that can lead to this phenomenon (Love et al., 2014; Cantarelli et al., 2012). Nevertheless, there is no clear evidence that all these factors referring cost overruns in new infrastructure projects are also applicable to the case of cost overruns in replacement projects. This research tries to investigate that by analyzing many of the relevant factors theoretically and practically and providing a conceptual framework that explains the cost overrun phenomenon in replacement projects. Once all these factors are identified, the next step is to develop a framework that can deal with them. With respect to that, in Chapter 5, a model is developed which is consisted of two building blocks. The first one is designed in such a way that it can target the factors related to the preliminary estimations used for structuring replacement budgets. The second building block is intended to deal with the uncertainties associated with the long-term asset planning process and specifically with the effect of price escalation. The ultimate goal of developing the respective framework is to improve the current practices of estimating the preliminary costs for replacement projects and contribute to reducing the number of budget overruns in the asset management sector.

1.2. Research objectives

The problem described before, both in the industry and the scientific community, can be translated into two main objectives that will guide this research. The first and fundamental objective of this research is to get a further understanding of the context of the problem and, more particularly, to identify all the causes that contribute to cost overruns in replacement projects. Once all factors that can lead to budget overruns have been identified, a comprehensive view of the problem would have been structured. This can facilitate meeting the second objective of this research, which is developing a framework that contributes to reducing the extent to which budget exceedance occurs in reconstruction projects.

1.3. Research questions

The process that will be followed to meet the research objectives contains various stages, and in each step, multiple questions need to be answered. Regarding the first objective related to identifying the causes of the problem, this will be achieved by answering four sub-research questions. The answer to the main research question will lead to meeting the second objective of this research. All the sub research questions and the main one is formulated as follows:

Main research question:

"How can the current practices of estimating the replacement budget for an engineering asset become better with respect to the accuracy of the cost indication they provide? "

Sub-research questions:

SQ1: *"What are the different phases in which cost estimations for replacement projects are conducted, the expected levels of accuracy per phase, and the position of preliminary estimates in these phases?"*

SQ2: *"How can the construction costs for replacing a specific asset be decomposed, and what is the contribution of each general component to the total construction costs?"*

SQ3: "*What are the different methods used for estimating replacement costs in each preliminary phase, and what is the actual accuracy observed in each phase?"*

SQ4: *"What are the most dominant factors contributing to budget overruns for replacement projects? "*

For this research, the term "accuracy" mentioned in the main research question refers to the degree to which a measurement or calculation varies from its actual value (Dysert, 2017). Therefore, the term "improved accuracy" means that in a particular situation, the deviation between the estimated costs and the actual ones becomes lower than the one provided with the current practices.

Based on what has been mentioned so far, the structure of the thesis is presented in Figure 3:

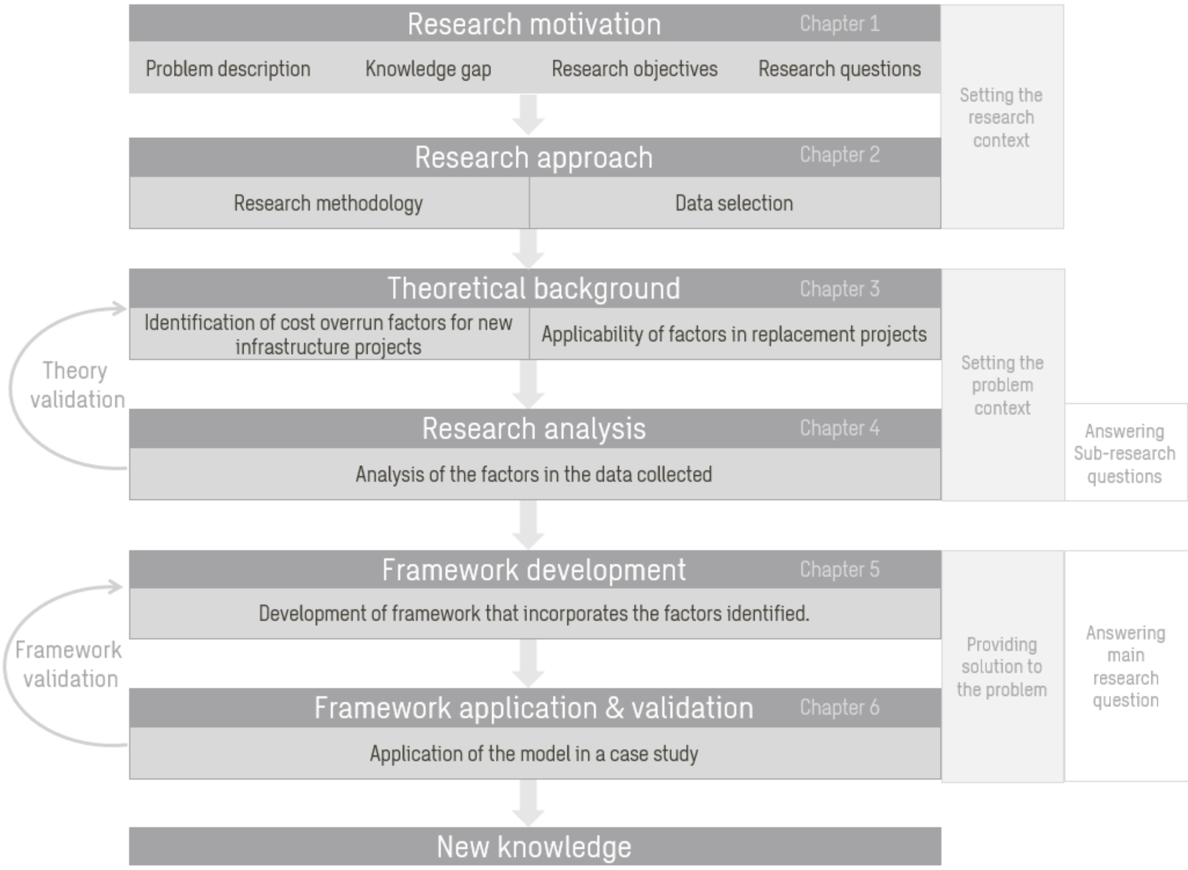


Figure 3: Structure of the thesis (own illustration)

2. Research design

As described before, different objectives are aimed to be achieved through this research, and this will be done by answering several questions. The specific procedures or techniques that will be used to identify, select, process, analyze the relevant information about the topic and eventually fulfil this research's objectives are described in the research methodology. This Chapter initially describes this research methodology in its first part, while in the second part, a more detailed description of the data selection process is described.

2.1. Research methodology

The first step in every research is the definition of the research methodology or strategy, which indicates how the study is about to be undertaken. The research methodology is considered an integral part of the thesis. It helps to ensure consistency between the different techniques, tools used, and the underlying philosophy (Melnikovas, 2018). There are many ways to construct the research methodology, and in this research, the “research onion” concept is adopted for that purpose. The research onion was proposed by Saunders et al. (2016). According to Raithatha (2017), it provides a description of the different stages that need to be accomplished to structure an effective research methodology. These various stages are illustrated in the concept as separate layers, as presented in Figure 4. This concept includes six layers/steps: the research philosophy, approach to theory development, methodological choice, strategy, time horizons, techniques, and procedures. In this chapter, every stage is described and analyzed for this research's specific context to structure a solid plan that will be followed to address the problem described in the previous chapter.

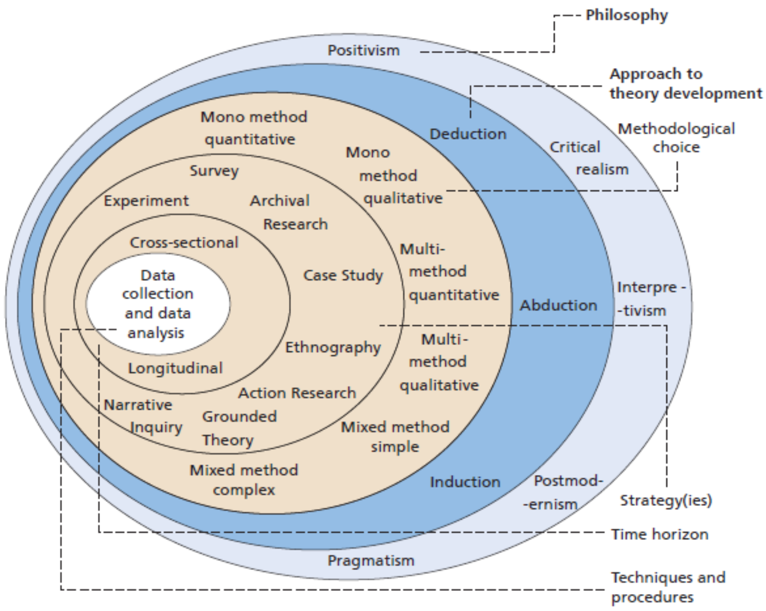


Figure 4: The research onion (Sander et al., 2016)

2.1.1. Research philosophy

The first stage of the methodology development is to define the research philosophy, which contains the system of beliefs and assumptions underlined in the research. This step is crucial for the thesis as all the assumptions made during it can inevitably shape the way of understanding the research questions, methods used, and finally, the practice of interpreting the findings (Crotty 2020). There are various research philosophies, as illustrated in the outer layer of the research onion; however, the pragmatism philosophy is adopted in this research. The main characteristic of this philosophy is that the research starts with a problem and aims to contribute a practical solution that can be used in the future. In order to achieve this goal, different theories, ideas, and concepts are used to explore any answers to the research questions that have not been studied in depth before. Thus, adopting a pragmatism philosophy means that instantly, the purpose of the research is defined as exploratory.

For the specific thesis context, the initial problem that needs to be addressed is the improvement of cost estimations for replacement projects that seems to trouble the asset management department of Sweco. The practical solution that will occur from a pragmatism point of view is developing new knowledge in the particular field both for the scientific community and Sweco and providing a probable approach that can be followed to deal with it.

2.1.2. Approach to theory development

According to Saunders et al. (2016), almost every research involves the use of theory, and whether there is a use or a building of a theory, this should be included in the research design. There are different approaches to theory development, and in this research, an inductive approach is followed. With this approach, the research starts with observations and data collection relevant to the specific problem, followed by a description and an analysis that helps develop a theory.

This research begins by providing the relevant theoretical background about the various factors that can lead to cost overruns for replacement projects. As little information is available in the research about this problem in replacement projects, the applicability of the available literature for new infrastructure is critically examined under the scope of replacement projects. After providing the theoretical background, all the theoretical knowledge is tested in practice by analyzing the various data collected from different sources, including the examination of case studies to get a more comprehensive view of the problem both on a theoretical and a practical level. Having clearly defined the problem and its causes, a new theory is added to the source by providing new knowledge about the causes of cost overruns in replacement projects and proposing a framework to deal with this problem.

2.1.3. Methodological choice

The third step in the methodology development is to determine the methodological choice of the research. Various methods can be used, such as quantitative or qualitative methods. In this research, a mixed methodology is adopted, meaning that both qualitative and quantitative data will be used to explore the problem of the budget overruns for replacement projects. The various sources from which qualitative and quantitative will be gathered are presented in the next layer of the research onion.

2.1.4. Strategy for collection and analysis of data

The fourth and one of the most important considerations when designing research is constructing the strategy used to collect and analyze data. As mentioned, both quantitative and qualitative data will be used in this research. According to Verschuren et al. (2010), for a combination of quantitative and qualitative research, the triangulation of methods can be considered a prominent strategy for gathering data. With this technique, the examined topic is analyzed using different forms of data collection.

At the beginning of this research, a thorough literature review is conducted to get the theoretical background needed for understanding the context of the topic examine and identify the various factors that can lead to budget exceedance in reconstruction projects. The literature review is conducted by using Scopus, which is an abstract and citation database. For identifying the most relevant literature, specific keywords related are used. A list of the keywords is presented in Table 2 bellow. Apart from the usage of the scientific database, also snowballing is used. This term implies that other relevant scientific papers were found from the most pertinent scientific papers already identified by using Scopus.

Table 2: Keywords used for relevant literature gathering

Keywords
Replacements; cost overruns; long-term asset planning.
Probabilistic; preliminary estimations; forecasting.
Price escalation; Geometric Brownian Motion.

Then all the aspects that have been mentioned on a conceptual level are tested in practice by analyzing the various data collected. More particularly, as in the theoretical chapter, it is described that the preliminary nature of estimations has an essential role in the undesired situation observed; the preliminary estimations are defined by examining the viewpoints from two perspectives, namely one of the clients and the engineering consultancies. On the one hand, to understand what clients consider preliminary estimations, various archival documents are gathered by seven public entities and are analyzed accordingly. On the other hand, to investigate the industry's perspective on preliminary estimations, an exploratory interview is conducted with a cost estimator who works at Sweco, and the findings occurring from the interview are analyzed. As only a single organization was examined, no different results would have been expected regarding the different phases and methods that are used in the current examined organization. Therefore, the number of interviewees has been limited to a single one. However, as it is mentioned in the limitations and recommendation's part, future research that could extract the perspectives of various organizations could certainly enrich the results of this empirical study.

Having clearly defined the context of preliminary estimations, the various factors contributing to the low accuracy of preliminary estimates spotted in the theoretical chapter are then scrutinized in practice. The analysis is conducted by analyzing the different case studies gathered for that purpose and are described in the following sub-chapter. Lastly, the factor of price escalation, which is linked with the second characteristic of replacement budgets and refers to the inherent uncertainty of forecasting a future situation, is examined. The effect of price escalation is again investigated through its application in the case studies. So, selecting the multiple case study approach will help validate the theory and generate insights from intensive and in-depth research into studying a phenomenon in its real-life context. This will lead to collecting detailed, empirical descriptions of the problem, it will help to develop theory and finally contribute to creating a framework and answering the research questions (Dubois & Gadde, 2002, p.554; Eisenhardt, 1989; Eisenhardt & Graebner, 2007; Ridder et al., 2014; Yin 2014).

2.1.5. Time horizon

This layer is referred to the time frame for the research. Research can be either a short-term cross-sectional study or a longitudinal one. Both refer to the process of gathering the data, which can be at a specific point of time or over a more extended period to compare data. In this research, a cross-sectional study is considered as past bridge replacement projects that have already been finished and will be used for the case study analysis. Also, past documents will be examined, and one-off interviews will be conducted

2.1.6. Techniques and procedures

This final layer concerns the data collection and analysis procedure followed during the research. Both primary and secondary data will be used for the purposes of this research, and the detailed procedure for data selection is described in the next Sub-chapter.

2.2. Data selection

After providing the theoretical background of the problem, in Chapter 4, all the conceptual findings will practically be examined by analyzing various data extracted from different sources. Initially, qualitative data will be gathered from archival documents and an exploratory interview, and then multiple case studies will be examined to collect both qualitative and quantitative data.

2.2.1. Archival research

In the problem description, it has been mentioned that the observed budget overruns in replacement projects can be happening because they are usually structured based on preliminary estimations. However, not everyone interprets preliminary estimates in the same way. For that reason, various documents are gathered from nine public entities in order to get an insight into their perspective. These documents describe the multiple phases in which they expect estimations and the respective accuracy for each estimate. Usually, these documents are provided to consultants within Sweco to communicate with them their demands. The documents are confidential with respect to clients; however, data is subtracted (anonymously) for the purpose of this research. The relevant references for accessing the respective governmental archival documents can be found in the Appendix B

2.2.2. Interviews

Besides clients' viewpoints about preliminary cost estimations, it is also valuable to get an insight into the current practices and perspectives inside the construction industry. For that purpose, an interview was conducted with a cost estimator within Sweco who has more than fifteen years of experience. The character of this interview is an exploratory one in which the different phases of cost estimations, the expected accuracy in each phase, the inputs, and the methods used are discovered. The results occurring from this interview are compared with those that occurred from the client's perspective and those provided in the theoretical Chapter. This comparison helps get a more comprehensive definition of preliminary cost estimations that can be used for this research. As no different input would be expected with regard to the way and phases in which cost estimations are conducted within a single organization there was no need for conducting more than one interview for that purpose. However, as further explained in Chapter 6, multiple interviews were used for validating the proposed framework of this research.

2.2.3. Case studies selection

The definitive source of data on which all the theoretical knowledge is tested is the multiple case studies gathered from the project inventory of Sweco. As this research deals with replacement projects, there was an effort to collect past replacement projects at a municipal level. More than any other country globally, a typical asset that Dutch municipalities have in their possession is the bridges. Various types of bridges can be found in a Dutch municipalitysuch as traffic, pedestrian, or bicycle bridges. The different municipal bridges are divided based on their type to reduce the variation between cost data. This research follows the categorization indicated by Van der Linde (Van der Linde et al., 2017), which distinguishes eight kinds of municipal bridges in the Netherlands.

1. Movable road bridges (drawbridges)
2. Concrete road bridges
3. Concrete bicycle/pedestrian bridges
4. Wooden road bridges
5. Wooden bicycle/pedestrian bridges
6. Steel road bridges
7. Steel bicycle/pedestrian bridges
8. Plastic bridges

This categorization of bridges based on their type is very well in line with the case studies examined from the archive of Sweco. The dataset contains municipal bridges that are not part of any provincial road or highway and mainly concern parts of the municipalities' secondary roads.

There are several criteria under which the case studies have been collected. The first criterion for selecting the case studies was that all projects selected should be municipal bridge replacement projects in the aforementioned categorization. A second criterion is related to their budget, which should not exceed the amount of 800.000€. The primary rationale for this second criterion is that even though the cost of these projects is relatively low, there are a lot of municipal bridges in terms of quantity that need to be replaced in the following years, and this research can contribute by improving the estimations for future projects. The third criterion concerns the available information about each selected replacement project. A detailed drawing should be in place for all case studies, and cost estimations should be available in at least two phases. This criterion is used to have enough data needed to facilitate any comparisons between projects and phases. Even though in most relevant studies, the most critical criterion for selecting the case studies is that the chosen case studies present a cost overrun, in this research, this is not the primary one. As it can be further seen in Chapter 6, where the model is developed, the quantity of the case studies is critical for determining the best-fit distribution for the various work packages included in the replacement budget assessment. Thus, it is more acute in this research not only to gather replacement projects with budget overruns but also, to have a sufficient sample of case studies that can facilitate in developing the proposed model.

2.2.3.1. Description of case studies

Nine case studies occurred based on the above criteria, referring to municipal bridge replacement projects from 2008 until 2015. An illustration of the selected case studies is presented in Table 3. Also, in Table 4, the different phases in which cost estimations are available for each project are shown. The distinction of phases is done based on the proposed and described classification in Chapter 3. A more detailed description of the case studies can be found in the Appendix A.

Table 3:Basic information about the case studies

Project	Width (m)	Length (m)	Deck area (m^2)	Province	Bridge type
Project 1	4.5	6.7	30.2	Friesland	Concrete road bridge
Project 2	4.5	12.3	55.4	Friesland	Concrete bicycle/pedestrian bridges
Project 3	5.5	13	71.5	Friesland	Concrete bicycle/pedestrian bridges
Project 4	5.2	6.7	34.8	Friesland	Concrete road bridge
Project 5	7.2	17.2	124.	Noord-Holland	Concrete bicycle/pedestrian bridges
Project 6	7.2	17.2	123	Noord-Holland	Concrete bicycle/pedestrian bridges
Project 7	7.6	17.2	130	Noord-Holland	Concrete bicycle/pedestrian bridges
Project 8	8	10.5	84	Friesland	Concrete movable road bridge
Project 9	3	7.1	21.3	Friesland	Steel movable road bridges

Table 4: Available estimates per case study

Project	Year of Estimates	Conceptual (Class 5)	Budgetary (Class 3)	Control (Class 2)	Bid/Tender (Class 1)
Project 1	2008	✓	✓		✓
Project 2	2013	✓		✓	✓
Project 3	2013	✓		✓	✓
Project 4	2016	✓	✓		✓
Project 5	2018	✓		✓	✓
Project 6	2018	✓		✓	✓
Project 7	2018	✓		✓	✓
Project 8	2015	✓	✓	✓	✓
Project 9	2015	✓	✓	✓	✓

3. Theoretical background

The introduction chapter of this research described a particular problem in the construction industry associated with the life-cycle budgets that are structured for maintaining and replacing public assets. Life-cycle costs concern expenses intended for preserving the asset in good condition in terms of safety, functionality, and appearance but also concern money allocated for replacing the asset when it reaches the end of its service life. Even though municipalities allocate a significant number of resources when structuring the life-cycle budgets, it seems that are never adequate. Thus, the same pattern of consequent cost overruns and budget exceedance observed for new infrastructure projects over the past years (Flyvbjerg et al., 2003; Cantarelli et al., 2010; Morris & Hough, 1987) is most likely to be happening for life-cycle budgets too. This research observes that replacement budgets that are subsets of the total life-cycle budgets significantly contribute to these overruns. There is an effort here to address the problem of life-cycle budget overruns by first addressing the issue of replacement budget overruns. Before seeking a solution to this problem, it is essential to provide the theoretical background needed to understand the reasons for this phenomenon. Thus, in this Chapter, a thorough literature review is conducted to get further insight into the factors that other scholars have observed and support that can lead to budget overruns. As little or no literature is available on budget overruns for replacement projects, all these factors identified in the literature for new infrastructure and maintenance are tested against their applicability to replacement budgets. The Chapter starts with an overview of typical factors identified in the literature, and then a more specific analysis is provided for replacement projects. The outcome of this Chapter is a conceptual model that presents the different factors contributing to cost underestimation in replacement projects.

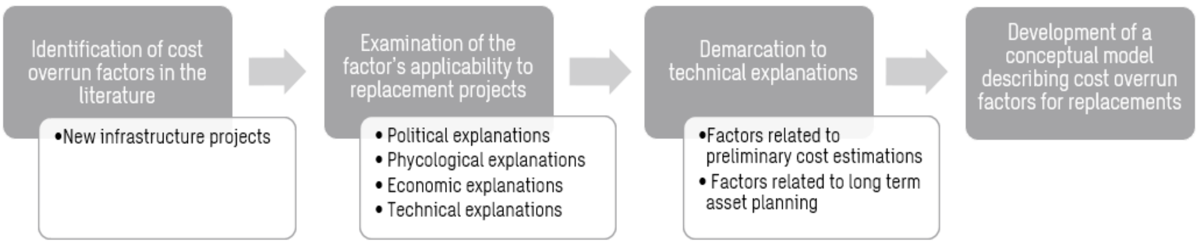


Figure 5: Chapter 3 overview

3.1. Cost overrun factors in the literature

Many scholars point out that cost overruns are more the rule than the exception in infrastructure projects (Wachs, 1989; Cantarelli et al., 2012). Almost 90% of projects fail to perform as forecasted in terms of costs (Flyvbjerg et al. 2002), and the average cost overruns for large-scale infrastructure projects can range from 20% to 45% (Flyvbjerg et al. 2004). Based on Bruzelius et al. (2002), there have been no systematic improvements in the particular issue for the last 70 years, and neither is a specific pattern that explains their occurrence (Lundman 2011). However, there is extensive literature about this topic that tries to identify, list, and analyze the various factors that can lead to cost overruns, especially for new infrastructure projects.

Love et al. (2013) support that the factors that contribute to cost overrun are price escalation, poor design and implementation, inadequate financial plans, administrative uncertainty, and the lack of coordination between enterprises. Herrera et al. (2020) tried to map out all the cost overrun causative factors for road infrastructure projects. After a thorough literature review, the authors identified the top-10 cost overrun factors presented in Table 5.

Table 5:Cost overrun factors and number of documents that report the factor. (Herrera et al., 2020)

Factors	Number of Documents that report the factor (n = 45)
Failures in design	35
Price variation of materials	30
Inadequate project planning	29
Project scope changes	26
Design changes	25
Inadequate bidding method	25
Poor site management and supervision	23
Political situation	18
Legal issues	18
Unrealistic contract duration	17

In another recent research, Annamalaisami and Kuppuswamy (2019) surveyed to identify the causes of cost overruns for non-infrastructural construction projects in India. Sixty-eight (68) factors were identified and categorized into seven elements: quantity, price, scope, resource utilization, quality nonacceptance, delay in the construction activities, and other external factors. Another related research in which 258 large infrastructure projects were examined was conducted by Flyvbjerg et al. (2002). In that research, they support that there are various reasons for cost underestimations which all can be summed into four general explanation types, namely, political, economic, phycological, and technical. As this categorization is quite broad and includes most of the factors identified by the other scholars, it is used in this dissertation for analyzing the cost overrun causative factors in replacement projects. However, before testing the applicability of the various factors identified for new infrastructure projects to the replacement ones, a description of every explanation type based on Flyvbjerg et al. (2002) is provided.

3.1.1. Political explanations

The first explanation type of cost overruns described in the research is the political one. Based on the scholars, it is very likely that decision-makers can intentionally bias the forecasts to promote their interests and get a specific project started. These factors are hard to trace for legal, economic, moral, and other reasons. If decision-makers and forecasters have intentionally underestimated a cost assessment for getting it started, they are unlikely to admit that this is the case (Wachs, 1989). However, for new infrastructure projects, the initiation of a significant undertaking, which improves the lives of citizens, can be potentially an event that increases a person's popularity and facilitate their re-election. Thus, there is an apparent political gain for promoting a project and underestimating its costs can be a possible way to achieve this.

3.1.2. Economic explanations

Besides political, economic explanations are described as being responsible for budget overruns for new infrastructure projects. Under these explanations, a deliberate underestimation of costs and an overestimation of benefits is done because it can facilitate the project initiation from which the various parties involved can economically benefit. When a project starts, many parties can be benefited, such as suppliers, contractors, engineering consultancies etc. Some of these parties can also be present in forecasting the costs, and a deliberate underestimation cannot be excluded from their side.

3.1.3. Psychological explanations

The third type of explanation identified by Flyvbjerg et al. (2002) is the psychological one. According to the authors, the most common phycological explanation is the "appraisal optimism." Under this explanation, project promoters and forecasters can be over-optimistic about the benefits of a project in the appraisal phase when the project is planned (Fouracre et al., 1990). The scientific term for this phenomenon is called "planning fallacy" and is widely mentioned in the literature as being responsible for cost overruns (Lovallo and Kahneman, 2003).

3.1.4. Technical explanations

The last type of explanation for cost overruns identified in the research is the technical one. This broader category contains all the factors related to errors in the forecast itself and can be attributed to imperfect techniques, lack of data, lack of experience, or inherent problems associated with predicting the future (Wachs, 1990). The researchers claim that for new infrastructure projects if the technical reasons were mainly responsible for cost overruns, this would have led to a de-escalation of the problem over time. However, they observe that the issue has not yet been resolved, and for that reason, they question whether technical explanations are the most dominant for cost overruns in new infrastructure projects.

3.2. Analysis of cost overrun factors for replacement budgets

Based on what has been mentioned so far, many researchers have investigated the causative factors of cost overruns in new infrastructural and non-infrastructural projects. However, as little or no research is available for cost overruns in replacement projects, this sub-chapter is valuable for investigating the applicability of the factors identified in the literature. For that purpose, the four explanation types indicated by Flyvbjerg et al. (2002) are examined and analyzed under the scope of replacement projects. This analysis helps to develop a conceptual model that explains to some extent the factors that can potentially contribute to cost overruns in projects related to existing infrastructures.

The first type of cost overrun explanation described is the political one. The approval of a new infrastructure project occurs only after a political process, especially for those requiring significant financial resources. As described in this process, project promoters can deliberately underestimate the costs and overestimate the benefits to convince political parties about the project's viability and contribution. However, the approval for allocating funds intended for replacing existing infrastructures is usually not the result of any political process. In fact, these projects do not constitute something new and tangible that adds further value to the citizens and project promoters can see them as "zero-value expenses." This term implies that the resources allocated for replacing assets do not add any new value to the citizens. Still, in contrast, they derive money that could be given to other aspects such as healthcare, education, etc. Also, as replacement planning is happening many years before the project's initiation, it is most likely that the people involved in the long-term asset planning process are no longer politically active. This means that there is no clear link between a potential political gain on the one hand and a deliberate underestimation of costs on the other, as is the case for new infrastructure projects. Based on these two arguments, it is assumed that the political explanations may contribute less to cost overruns in replacement projects than for new infrastructure, as described by Flyvbjerg et al. (2002) and (Cantarelli et al. 2012).

Apart from political explanations also, the economic ones were mentioned by Flyvbjerg. It was described that parties involved in the project promotion and forecast deliberately underestimated the costs because they can be benefited from its initiation. In terms of replacement projects, this explanation can also be the case. As Engineering companies are the ones who are structuring replacement budgets and can also be involved in the construction phase, this means that they can benefit from the initiation of the project. So, they can intentionally prepare low forecasts to get a replacement project started.

The third type of explanation was the phycological one, with the most important one being the appraisal optimism. Considering this explanation for replacement projects, this factor can be also important when determining the expected endpoint of the service life for an existing asset. Both promoters and planners can be very optimistic about the service life of an asset. Still, literature has shown that the poor maintenance of public assets can dramatically decrease the expected life of an asset. Also, the over-optimism can be related to the prices that are determined in the estimate. The following chapter points out that price escalation can significantly impact the initial assessment, but this is often ignored in practice. A possible explanation for this can be a phycological one under which cost estimators underestimate the effect of price escalation because they consider that the contingencies, they use can cover any price increases.

The last type of cost overrun explanation is related to the technical ones and contains all the factors associated with the cost forecast itself. Probable factors can be imperfect techniques, unreliable benchmarks used as inputs, limited project information, etc. In addition, it was described that replacement budgets have two specific characteristics linked with the phenomenon of their respective budget overruns. First, most replacement budgets are constructed based on preliminary cost estimations. This characteristic includes the uncertainty in the assessment when little information is available due to the early phase in which they are conducted, and the uncertainty associated with the low expected accuracy techniques used. The second characteristic is that long-term asset planning and the respective estimates are usually performed years before the project's initiation; thus, any effort to predict the future is inherently bound to certain risks. Based on these two characteristics related to how replacement budgets are estimated, it can be said that technical explanations can also be potentially responsible for their budget overrun.

So far, it has been described that based on Flyvbjerg et al. (2002) and Cantarelli et al. (2012), there are four types of explanations for cost overruns in new infrastructure projects. All these types were examined under the scope of replacement projects. It was underlined that there is a shred of clear evidence for the economic, phycological, and technical ones that might contribute to the phenomenon of replacement projects. For the political explanations, based on the line of reasoning of this research, it is assumed that the contribution of this category might be lower compared to new infrastructure projects. This is mainly because the approval of a new project usually occurs after a political process, while this is not the case for replacements. Even though it is assumed that phycological and economic factors contribute equally to the issue in replacement projects, these are left out for two reasons. First of all, the time frame of this research is quite limited, and the investigation of these would not be feasible. Though as it is discussed in the Discussion chapter, it would be an essential contribution to the knowledge of this particular field to investigate their effect on the issue in another study. The second argument for leaving out of the scope the psychological and economic explanations is because it is assumed that their impact on the issue is more or less similar both for new infrastructure and replacement projects. This implies that some literature is available that underpins their impact and suggests potential solutions. However, technical explanations are more specific and relate to the particular project type and the respective forecasting process. This means that the various technical factors can be specific and differ for replacement projects. As little or no research has been conducted about the cost overrun explanations in replacement projects, it is worth examining the potential effect of technical factors on the industry's specific.

Thus, the technical factors linked to the two characteristics of replacement projects are presented in the following sub-chapters. First, the technical factors related to the preliminary estimations for structuring replacement budgets are examined. Then, there is an analysis of the price escalation factor inherent to the long-term asset planning process.

3.2.1. Factors related to preliminary cost estimations

Any cost estimating process aims to generate the most accurate reflection of the total project's budget based on the given quantity and the quality of information at a specific time. It is clear that there is quite an uncertainty in the estimation at the early stages of a project due to the limited available information, and a high error range is expected. As the project progresses, more and better information about the project's scope becomes available, and the expected error of the cost estimate decreases (Jensen, 2002).

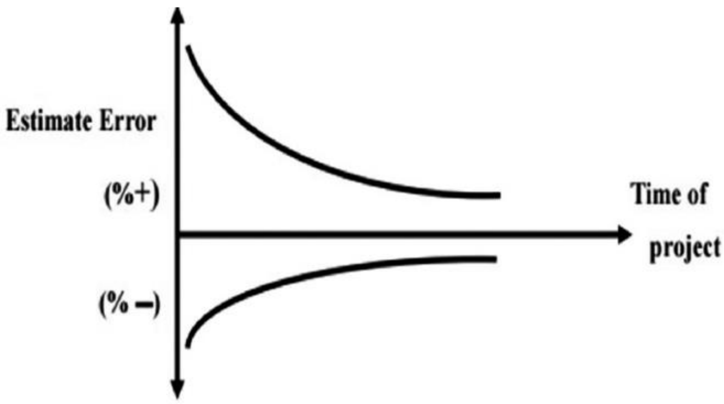


Figure 6: Relationship between cost estimation accuracy and time (Dandan et al., 2019)

Although the amount and quality of information about the project vary from phase to phase, the cost estimation process itself remains significantly essential in every stage conducted. In the preliminary stages, it can provide interested parties with vital information to be used in the decision-making process (Serpell, 2014). In the case of replacement projects, municipalities often use preliminary cost appraisals for structuring the total life-cycle costs (including replacement) for an asset, thus, allocating the necessary resources. Therefore, it is evident that preliminary cost assessments have an equally important role in the planning phase of a project.

What is usually not obvious is what project promoters and planners consider preliminary cost estimations and the different levels of accuracy they expect. The accuracy of a cost estimate is defined as the deviation of the forecasted cost from the project's actual cost (Dysert, 2006). According to Flyvbjerg et al. (2002), inaccurate cost estimations can misallocate limited resources. For that reason, it is first essential for the people involved in the forecasting process to understand the level of accuracy of their estimations and then to communicate this to the clients for whom the estimate is prepared.

Therefore, the first step is to define where preliminary cost appraisals are positioned in the pre-construction phase. Necessary guidance for that is using the estimates classification that various scholars have done. Samphaongoen (2010) categorized cost assessments based on the expected accuracy as conceptual, semi-detailed, and detailed. He suggested that an error of 20% can be expected in conceptual appraisals, while this should be minimized by 5% for detailed ones. The American Association of Civil Engineers (AACE) established five cost estimate classes based on several characteristics. The primary one is the degree of project definition, while for secondary characteristics, the purpose of the estimate, the methodology, the expected accuracy, and the preparation effort are considered. Table 6 illustrates this cost estimate classification matrix by AACE.

Table 6: AACE- Cost estimate classification system

Estimate class	**Level of project definition** Expressed as % of complete definition	**End usage** Typical purpose of the estimate	**Methodology** Typical estimating method	**Expected accuracy range**
Class 5	0% to 2%	Concept Screening	Probabilistic or Judgment	**L:** -20% to -50% **H:** +30% to +100%
Class 4	1% to 15%	Study or Feasibility	Primarily Probabilistic	**L:** -15% to -30% **H:** +20% to +50%
Class 3	10% to 40%	Budget, Authorization, or Control	Mixed, but Primarily Probabilistic	**L:** -10% to -20% **H:** +10% to +30%
Class 2	30% to 75%	Control or Bid/ Tender	Primarily Deterministic	**L:** -5% to -15% **H:** +5% to +20%
Class 1	65% to 100%	Check Estimate or Bid/Tender	Deterministic	**L:** -3% to -10% **H:** +3% to +15%

According to this classification, a Class 5 estimate is based on the lowest level of project definition, while Class 1 estimates indicate almost a full project definition and maturity. Based on the data analysis presented in Chapter 4 and the classification provided in Table 6, this research considers the Class 5, Class 4, and Class 3 estimates as preliminary cost estimations.

Now that preliminary cost estimations have been determined, the next step is to identify technical factors that explain why these early forecasts present a low accuracy. Based on the classification shown in Table 6, the level of project definition, the preparation effort, and the methodology used are three critical parameters that characterize an estimate in all phases, including the preliminary ones.

3.2.1.1. Level of the project definition

According to Hoseini et al. (2020), a cost estimate is a quantitative assessment based on the available information at a given point regarding the resources required to execute a particular project. Little information is available in the early phases, in which preliminary cost estimations are conducted; as the project progresses, more and better information becomes available, and the accuracy of cost estimates is improved (Fragkakis et al., 2010). The amount of data used for conducting an assessment can be derived from observations, available drawings, and other sources such as the Work Breakdown Structure (WBS) of a project. Most of the literature, including NASA guidelines (NASA, 2015), indicates that building or obtaining a WBS can be critical in identifying the budget components for a project. A WBS is a consistent structure that includes all project elements that the cost estimate will cover. A WBS aims to divide the project into manageable work packages that can facilitate the planning and control of cost and schedule. It can also be used as a basis for constructing the Cost Breakdown Structure (CBS), in which each element represents the cost to do that work (PMI, 2017). An illustration of a typical decomposition of construction costs based on the WBS is presented in Figure 7.

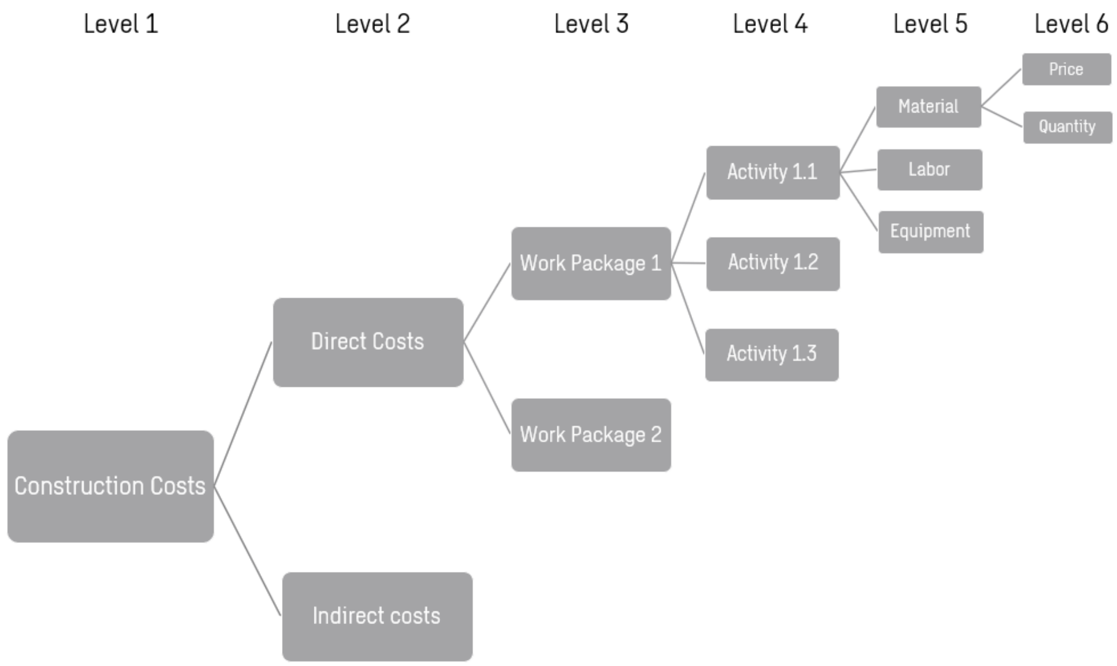


Figure 7: Construction costs decomposition (Own illustration)

In the Netherlands, the detailed construction costs are estimated by interested parties based on the CROW specifications (CROW, 2018). These guidelines indicate that the construction costs are the summation of both direct and indirect costs. Direct costs are directly associated with the physical replacement of the bridge. They can be seen as the various resources' costs to execute the project. Thus, these costs are strongly related to the needed work scope and can be divided based on their respective work packages. The direct costs (Level 2) are initially decomposed into several broad work packages (Level 3). The cost of each work package is considered the summation of all activities' costs (Level 4) included in the specific work package. Then, respectively, each activity cost depends on the resources (Level 5) required to execute this activity. The resources can be material, labor, equipment, etc. and their cost occur by multiplying the quantity of the specific resource by their respective price (Level 6). On the other hand, the indirect costs concern expenses that do not directly connect with the construction project. They can be seen as costs necessary for running the project, but they generally do not vary or only indirectly with the scope of the work. The most common indirect costs in the construction industry are; one-off costs, execution costs, general costs, profit and risk, 'provisional items, and 'contributions well described in the RAW provisions.

In preliminary estimates (Class 5, 4, 3), the replacement budgets cannot be decomposed at a high level due to the limited available information, usually extracted from sketch designs and expert judgment. For that reason, preliminary estimations are conducted based on information derived from the first three or four levels of decomposition (Level 1 – Level 4). Structuring a replacement budget based on these limited decomposition levels contains at least two critical risks. The first one is related to the quantities of the various cost components used in the assessment. When little information and no detailed design is in place as in the early estimations, the exact volume of activities, materials, personnel, and equipment cannot be estimated precisely, leading to a significant deviation from the ones required during execution. The other substantial uncertainty refers to the prices used. When a detailed design and WBS exist, the pricing of the materials, equipment, etc., can be done with higher reliability as their type and quantities have been predetermined. In contrast, when the information about the project is limited, some prices are determined based on previous experience and available data, and their reliability might be questionable.

These two uncertainty types about the estimated quantities and the various prices used in the assessment are the same elements identified by Annamalaisami and Kuppuswamy (2019) in their survey. Also, both of these uncertainties, linked to the low level of project definition, are very well in line with Love et al. (2013b), who identified that the poor design and its implementation are responsible for cost overruns.

With respect to the level of project definition, it is imperative here to mention that many scholars (Herrera et al., 2020; Love et al., 2013b; Annamalaisami and Kuppuswamy, 2019) point out that one of the most critical factors leading to cost overruns in new infrastructure projects is the changes of the project's scope. For that reason, it is argued that when changes in scope occur, the degree of cost overrun for a particular project should be measured after the addition of the new scope and not during the initial decision. In the case of replacement projects and even more when small municipal assets are replaced (scope of this research), the factor related to scope changes is considered to have less influence to the issue rather than in new infrastructure projects. This is mainly because scope changes are usually applied to improving or adjusting the existing design. In the case of small municipal assets, it is considered that in most cases, there is not so much space for upgrades and the current asset is replaced with another one which includes none or minor design variations. Therefore, the influence of scope changes with regard to the cost overruns happening in replacement is considered to have less impact than for new infrastructure projects, as indicated by the scientific community.

3.2.1.2. Estimating methods

Apart from the low level of project definition in preliminary estimations also, the methods used during these assessments can potentially be responsible for the cost overruns in replacement budgets. Various cost estimation methods are used in the construction sector, and their accuracy varies between different projects and phases. The selection of the most appropriate method depends on multiple factors such as expected accuracy, effort, the time needed, and general information available. However, all the available techniques can be classified into two main categories, namely deterministic and probabilistic methods.

Deterministic methods

Deterministic methods are based on preparing single-point estimates and treating all input parameters as constants. They are strongly dependent on the level of the project's scope definition, project design phase, available historical data, contractor rates, and preliminary quotes from sub-contractors and other vendors (Gregory, 2012; Yeo, K. T. 1990). In this cost estimating method, the cost contingency part is represented by a certain percentage of the total project cost added to the base cost to account for uncertainty in the calculations. According to the Australian transport and infrastructure council, rigorous deterministic project costing is appropriate for smaller projects where a probabilistic estimate which requires much more effort cannot be employed. The criticism of this method lies in the fact that this technique requires access to reliable benchmark data to estimate the contingency allowance

(BITRE 2014). Another criticism pointed out in the literature is related to the fact that with this method, a strong dependency on the estimator exists when trying to determine the contingency (Mak and Picken 2000).

The most commonly used deterministic methods are:

- Parametric cost estimating (Top-down estimating)
- Detailed cost estimating (Bottom-up estimating)
- Comparative cost estimating

Probabilistic methods

The probabilistic cost estimating approaches are a form of quantitative risk analysis which attempts to quantify the project cost variability based on one or more parameters. Contrary to deterministic approaches, which are based on point-estimate values, these approaches use probabilistic values that can better incorporate uncertainties in a mathematical way (Xenidis and Stavrakas 2013). Using probabilistic values, the uncertainties and risks included in a cost estimation can be modelled using the best fit probability distribution. In that way, helpful information can be extracted, for example, about: the chance of exceeding a particular cost, the range of possible costs, the potential amount of the cost overrun, information about the different types of uncertainties involved, and how they can drive the cost.

In the Netherlands, Rijkswaterstaat and Prorail were the first who point out the importance of having a systematic approach to estimating costs. This resulted in developing the standard systemic method (SSK) for estimating costs by considering risks and uncertainties in a probabilistic manner. Sweco, one of the largest consultancies in the Netherlands, employs probabilistic cost estimating methods based on Dutch standards (CROW, 2013), especially in the first design phases when little information about the project is available. In the last few years, Sweco also started using the probabilistic estimating methods for life-cycle costing when the respective guidelines were added to the new Dutch standards (CROW, 2018b). These are very well in line with international standards such as those provided by the Commonwealth of Australia (2018), NASA (2015), UK Department for Transport (2017).

The most common practice employed when using probabilistic estimating approaches is the Monte Carlo simulation which generates a sample of all possible cost outcomes and the likelihood of each occurrence. The result of a Monte Carlo simulation also includes the confidence levels that can be assigned to the generated outcome value of the total cost. In that way, it can support decision making processes by providing an insight into the quantitative values of the involved risks and their impact (Humphreys, 2005b). Dutch standards suggest that a triangular distribution can quantify the volume and price uncertainty, and then a Monte Carlo simulation approach should be employed to reach a final estimate.

Most scholars and institutions indicate that probabilistic methods are the most prominent ones, and their use is recommended wherever possible, as the associated process provides the opportunity to discuss and document the risks with relevant stakeholders and agree on the appropriate quantum and probability for each risk item thus, it increases the transparency of the cost estimation process. However, there are also some drawbacks associated with the method. The first one is the extensive time and effort required to conduct the probabilistic assessment, as it is considered more complex and sometimes is not well understood by the practitioners (Geberemariam, 2018). Therefore, proper training might need before using these methods (Jørgensen et al., 2021). Another significant drawback is the questionable accuracy of the method when little quantitative information is available (Panthi et al., 2009). The last drawback is also supported in recent research by van den Boomen et al. (2020), who points out that in the absence of data supporting distributions of uncertainty variables, the result of Monte Carlo Simulations should be viewed with extreme care as it suggests a level of accuracy which does not exist.

Based on Table 6, the ACCE indicates that for preliminary estimations, primarily probabilistic methods should be used to capture the uncertainty in these early phases better. However, as shown in Chapter 4, in practice, only deterministic methods are employed to estimate the costs of replacing an existing asset in all cost estimation phases. This is done because little preparation is required due to the over-optimism of estimators who claim that their deterministic estimations are reliable. However, as mentioned in such deterministic computations, reliable benchmark data (inputs) are needed to conduct an estimate, and the reliability of the used unit prices might be questionable. In the following chapter, in which the case studies are examined, the reliability of the inputs used (unit prices) for the estimation is reviewed to confirm whether these inputs and methods used for the estimates are reliable.

3.2.2. Factors related to the uncertainty of predicting the future

In the previous sub-chapter, it was described that the preliminary nature of the estimations used is the first technical parameter that defines the accuracy of these estimates. The second characteristic mentioned here is the inherent uncertainty when forecasting a future situation. Long-term asset planning is a process in which all the maintenance and replacement activities for an asset are determined and planned beforehand. In some cases, this process can occur even when a particular asset is first constructed and can contain a forecast for more than 30 years in advance, based on the asset's service life. Through the years, many changes can occur, which can significantly affect the initial estimated budget. Such a significant change can be considered the gradual increase in the prices of materials and labor, which is very common in the construction industry and has been proved a crucial factor for the viability of many construction companies worldwide (Cobouw, 2019). A few researchers have pointed out the importance of considering the changes in prices over the years. Among them, Love et al. (2013) and Annamalaisami and Kuppuswamy (2019) supported that price escalation is an essential factor that, if it is ignored, can lead to cost overruns. Also, Swei et al. (2015) and Swei et al. (2017) underlined a lack of attention to price uncertainty in the construction and engineering industry. In the same line of reasoning, Ilbeigi et al. (2017) and Faghih Sayed Amir and Kashani (2018) observed a knowledge gap in predicting the uncertainty of asphalt prices and steel prices in the USA, respectively. Younis et al. (2016) investigated the impact of inflation and its uncertainty on (waste) water mains capital works, and they stressed the impact on the cost estimates. Anastasia et al. (2018) investigated the effect of price uncertainty modelling of electricity on the profitability of offshore wind parks. They concluded that as electricity prices are known to be volatile, adequate predictions are essential for investors. Another recent research that stressed the importance of price escalation is the one conducted by van den Boomen et al. (2020). Their exploration examined the effect of price escalation in the long-term planning of maintenance activities, and they proposed an approach to incorporate price uncertainty in the estimations.

Under the same line of reasoning, this dissertation suggests that apart from the planning of maintenance activities, also the planning of asset replacement can be part of the long-term asset planning process. This means that the effect of price escalation can be significantly important for the respective estimated costs. In Chapter 4, in which the case studies are examined, there is a practical illustration of the contribution of this factor to the initially estimated replacement budgets.

Nevertheless, although many scholars point out the importance of price – (de) escalation for infrastructure and maintenance projects, this specific factor is not incorporated in the estimates. In probabilistic approaches and the SSK method used in the Netherlands, the price uncertainty is quantified by using a triangular distribution that sets an upper, a mean, and a lower value for the price of a particular activity. Typically, the upper and lower bounds are selected based on expert judgment. As van den Boomen (2020) indicates, there are currently no standards for setting upper and lower bounds of unit prices. They observe that for estimating life-cycle costs, usually, ± 15% are typical values for estimating the upper and lower bounds. Figure 8 visualizes an example of a triangular distribution with mean costs of 100 and upper and lower bounds of ±15%.

The next step in the probabilistic approach after obtaining the distribution is to run a Monte Carlo Analysis, which provides the numerous scenarios which are discounted, counted and presented as a frequency distribution graph. Even though this approach can cover the uncertainty to a certain extent, it cannot incorporate the time-variant uncertainties such as the price – (de) escalation. The triangular distribution presented in Figure 8 accounts for the uncertainty in the price, but the mean value and the standard deviation remain constant over time. In order to make this more tangible, consider the cost of constructing a concrete beam with steel reinforcement. Three parameters need to be considered in the estimation.

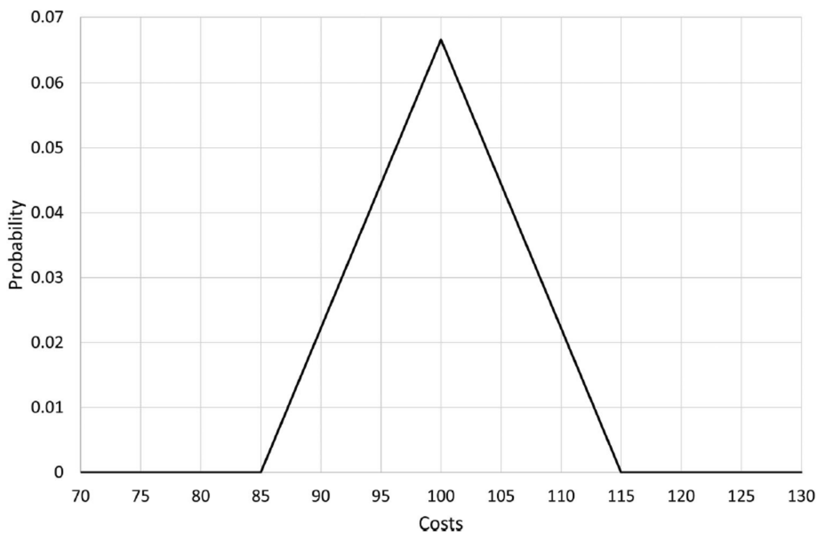


Figure 8: Illustration of triangular distribution (van den Boomen et al., 2020)

The first one is the required quantity of concrete and steel and the uncertainty regarding this quantity. Then a second parameter is a deviation from the price determined by the estimator for the amount of steel and concrete and the actual price that the sub-contractor will eventually supply these amounts. These two uncertainties (parameters) can be very well quantified and modelled using probabilistic methods by using a triangular distribution and running a Monte Carlo Analysis. What cannot be quantified with the existing methods is the evolvement of the prices for the quantities of steel and concrete over the beam's service life.

With the high volatility of prices observed in the construction industry in recent years, forecasting a future situation becomes a challenge. As replacement costs are usually estimated years before the actual execution of works, the price escalation that forecasters ignore can significantly affect the initially estimated budget. This research aims to address this factor by incorporating price uncertainty into the preliminary cost estimations.

3.3. Chapter Summary

As it can be clear from this Chapter, cost overruns are very common in the construction industry, and a lot of research has been conducted on this topic. Most scholars have attempted to deal with the issue by first identifying the factors contributing to this. All the available literature was presented in this chapter. However, it is observed that it mainly concerns the problem related to new infrastructure projects. For replacements, most scholars have ignored this phenomenon for various reasons. One of the main objectives of this research is to examine the specific topic under a particular scope. Under this consideration, initially, in this chapter, there was a process in which the various factors identified by the other scholars for new infrastructure projects were gathered. Due to the variety of factors, the categorization by Flyvberg et al. (2002) was adopted under which all the possible explanations are positioned into four broader explanation types, namely, political, economic, phycological and technical. Based on this categorization, there was a theoretical analysis in which the applicability of the various factors was examined for replacement projects. It was assumed that as replacement projects are not part of the political process and there is no evidence that a political gain occurs from their initiation, the contribution of political factors to the cost overruns is assumed to be lower for replacement projects than for new infrastructure projects. As far as phycological and economic explanations, their contribution is assumed to be equally high to the issue as for new infrastructure projects. In fact, the various factors in these two broader categories seem to have many similarities for new infrastructure projects and replacements. For that reason, and as the scientific community has extensively investigated these explanation types, there is a demarcation to the technical factors that are very specific and related to the specific characteristics of replacement projects. Therefore, and due to the limited time frame of this research they were intentionally left out of scope but, it worth investigating in future research the contribution of these two categories in the issue applicable to replacements.

This thesis supports that there are two specific characteristics of replacement budgets that can potentially be linked with the respective technical explanations leading to their cost overruns. The first characteristic is associated with the preliminary nature of the estimations used, while the second one is related to the difficulty in forecasting replacement costs for a project that may be imitated many years after.

To identify why preliminary estimations significantly affect their accuracy, it is essential to determine how preliminary estimates are determined. It was described that preliminary estimations are not interpreted in the same way by all people involved in the construction industry, and for that reason, the classification system proposed by the American Association of Civil Engineers was adopted to obtain a certain point of reference for this research. It was underlined that Class 5, Class 4, and Class 3 are considered preliminary estimates in this research.

After defining the preliminary estimations, the next step was to identify the factors contributing to their limited accuracy. It was mentioned that the degree of a project definition linked to the level of budget decomposition and done via the WBS could be an essential factor for replacement cost overruns. Poor WBS decomposition due to limited information can increase the uncertainties related to the number of estimated quantities and their respective prices, leading to low accuracy budget forecasts.

Apart from the level of project definition, the methods used in practice for estimating replacement costs were mentioned to affect the accuracy of the assessments. Even though probabilistic approaches are suggested in the literature as they can better capture most of the uncertainties mentioned, only deterministic approaches are used to estimate the costs for small replacement projects. These methods usually require reliable benchmark data as inputs for the estimate, and as presented in Chapter 4, the ones that are used in practice are not capable of capturing all different types of replacement projects. Except for the inputs used, it was mentioned that both probabilistic and deterministic techniques contain various deficiencies that can potentially affect the accuracy of cost assessments. Multiple criteria exist for selecting the most appropriate technique per project type and appraisal. So, the reliability of each technique should be viewed with extreme care.

Finally, it was mentioned that the second characteristic of replacement projects that contributes to their limited estimation accuracy is that usually, a forecast of a future situation is conducted when determining replacement costs. The most important factor related to this characteristic is the price – (de) escalation inherent in any future forecast. Material, equipment, and labor prices can dramatically increase over the years, affecting the initial estimate. Current methods, both in most of the literature and in practice, fail to address this problem, and this research lies in the direction of providing a solution to that.

It is evident that many technical or any other factors can potentially be responsible for the cost overrun phenomenon observed in replacement projects. However, due to the limited time frame of this research, only the above mentioned are further examined both on a theoretical (Chapter 3) and a practical level (Chapter 4). An overview of the various problem explanations is presented in the following conceptual framework in Figure 9.

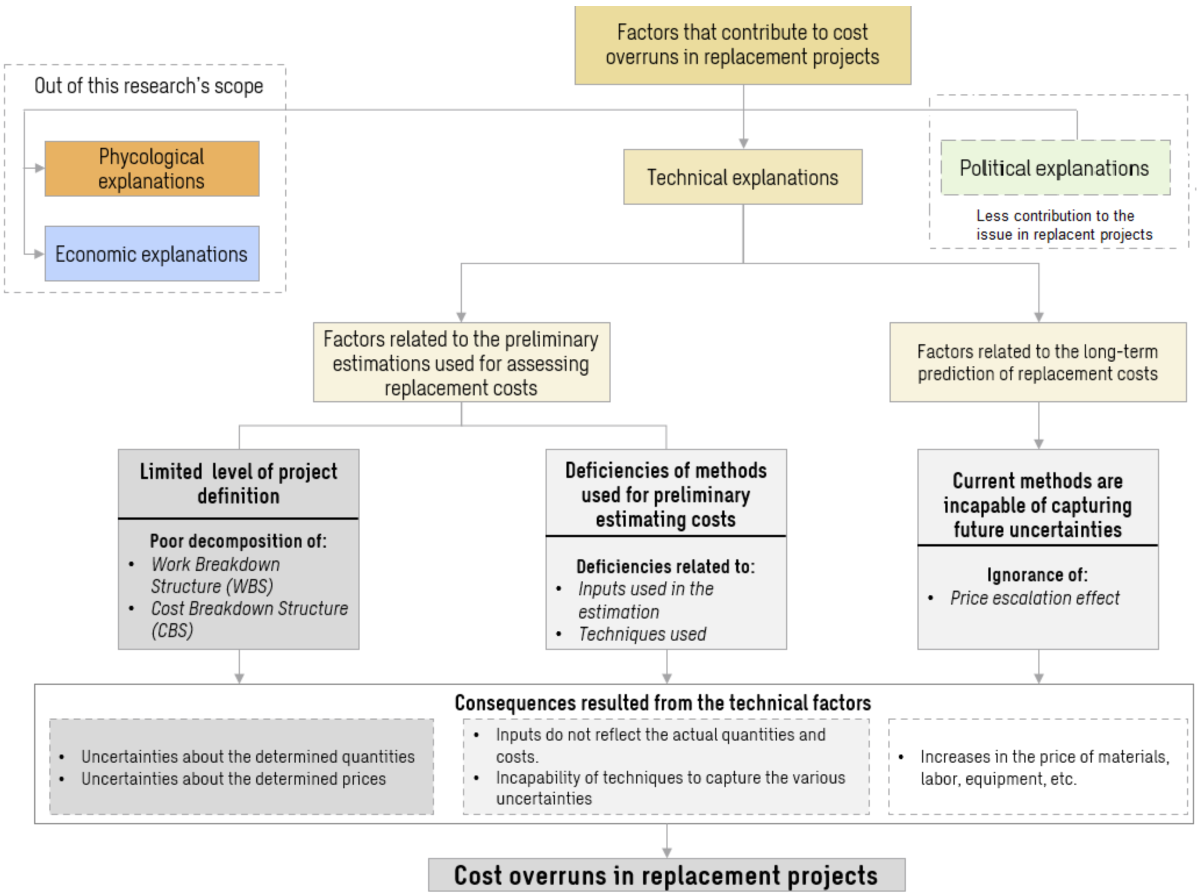


Figure 9: Conceptual model describing cost overrun factors in replacement projects (Own illustration).

4. Analysis of collected data

In Chapter 2, it is mentioned that the problem is determined both on a theoretical and a practical level in this research. There was a literature review and a short analysis to theoretically describe the problem's context in the previous chapter. The outcome was a conceptual framework describing potential factors that can lead to budget overruns in replacement projects. In this Chapter, all the aspects mentioned before on a theoretical level are tested in practice by analyzing the various data gathered through this research. This twofold analysis can help obtain a more comprehensive view of the problem and eventually answer the research questions that have been defined. The chapter starts with examining the different perspectives on preliminary cost estimations from municipalities and consultancies' points of view. This examination analyses data collected from governmental archival documents and conducts an exploratory interview. Understanding the various perspectives on this aspect can help determine the preliminary estimations and validate the previous chapter's theory. After defining preliminary estimates, the multiple factors that can lead to budget overruns for replacement projects and presented in the theoretical framework are examined practically via the analysis of various case studies. First, the factors related to the level of project definition are examined by getting an insight into the extent to which the object and cost decomposition can affect the estimates. Then the second factor related to the methods used for preliminary estimating the replacement costs are analyzed, and various conclusions are extracted. Lastly, the effect of price escalation associated with the second characteristic of replacement projects is investigated by conducting a case studies analysis.

4.1. Definition of preliminary estimates

As has been extensively described before, the early project phases in which cost estimations are conducted for structuring replacement budgets is considered a potentially important reason that contributes to the observed budget overruns. It was also mentioned that to identify why preliminary cost estimations present limited accuracy, it is crucial first to determine where preliminary estimates are positioned in the pre-construction phase. The classification system by AACE shown in Table 6 was adopted for that purpose. Even though this classification is widely used, it might be that it declines a lot from what is observed in practice. For that reason, various archival documents were gathered from public authorities to examine whether this classification corresponds to the different phases in which public authorities expect cost estimations. Secondly, an interview with a cost estimator was conducted, and also the case studies were examined to get a further understanding of the current practices in engineering consultancies.

4.1.1. Preliminary estimations from the perspective of municipalities

Under this consideration, documents from seven public authorities were gathered, containing information about the different phases in which they usually ask for cost estimations from engineering firms and contractors. These documents are generally provided to cost estimators as guidelines to clearly define the clients' expectations. The classification of estimates indicated by various public entities is presented in Table 18 in the Appendix B according to their position in the classification system of AACE. It can be seen that most public entities usually distinguish between five cost estimation phases, while a few distinguish between four. Only one public entity uses the classification of estimates in three stages.

Except for the description of the phases in which they expect estimates, these documents also contain information about their expectation of accuracy for the estimation. The level of accuracy is defined as a coefficient variation represented in a percentage of the total deviation between the estimated cost in that phase and the actual one. The different expectations from public entities per phase/estimate are presented in Table 19 in the Appendix B. It can be seen that the percentages of deviation between estimated and actual costs that the municipal or national organizations suggest are, in general, very well in line with the classification adopted by the AACE, as all of them lie between the recommended ranges.

Thus, based on the analysis of data obtained from the public entities, the definition of the preliminary estimations as Class 5, Class 4, and Class 3 estimates seems reasonable as it is pretty aligned with the expectations these organisations have.

4.1.2. Preliminary estimations conducted by engineering consultancies.

However, apart from the viewpoint of public authorities, which usually act as the clients, it is also essential to get an insight into the different phases in which engineering consultancies and contractors conduct estimates. For that purpose, an interview was conducted with a cost estimator from Sweco, who has more than 15 years of experience. Based on this interview, of which the full transcript can be found in the Appendix, the different phases, level of project's definition, inputs needed, methods, and expected accuracy from the viewpoint of Sweco are identified.

From the interview occurs that Sweco, as an Engineering consultancy, is highly involved in cost estimation processes for all kinds of projects, including the replacement ones. Their clients, especially the municipalities, ask the company to conduct various cost estimations in different project phases. These can either be at the beginning of the project, during the design, the tender, or even for project control purposes. More particularly, there are four different phases in which cost estimations are conducted within Sweco; the SO-Schetsontwerp (Sketch design) phase, VO-Voorontwerp (preliminary design) phase, DO- Definitiefontwerp (Final design) phase, and BO-Bestek ontwerp (Specification design) phase. The level of detail and the estimates' accuracy are at their lowest level in the SO phase, while more detailed cost estimations are conducted in the BO phase. Primarily, cost estimations in all stages are conducted in a deterministic way, and only when the client requires it, probabilistic cost estimations are provided. This happens to be the case in more complex projects or when the client is either the Dutch organization Rijkswaterstaat (RWS) or the Dutch railway operator ProRail. These two organizations require that all cost estimations should be conducted probabilistically.

For the asset management department in Sweco, preliminary cost estimations are the ones that are considered most important. Usually, they are responsible for estimating the total life-cycle costs for a certain amount of assets, including the replacement of the assets. As the replacement process is conducted years after estimating the life-cycle costs, municipalities are unwilling to spend a lot of resources on Sweco beforehand to provide them with detailed replacement cost estimations. Thus, the asset managers provide cost estimations in the SO phase. Their methods are limited to expert judgment estimations based on previous replacement projects, historical data, and unit costs per m^2 for the entire object extracted from databases. The supporting information for the conceptual estimations generally includes only a general description of the project, such as the function, location, size, schematic layout, and intended use (Manfredonia et al., 2016).

Based on the classification by the American Association of Civil Engineers illustrated in Table 6 and the information derived from the interviews, it can be concluded that both classifications contain a lot of similarities. In the SO-Schetsontwerp phase, the estimations can be related to Class 5 and Class 4 estimates, while in the VO-Voorontwerp phase, Class 3 estimates resemble most of the current practices. Finally, in DO- Definitiefontwerp and BO-Bestek ontwerp phase, Class 2 and Class 1 estimates can be considered more closely related.

Based on what has been mentioned so far, both in the theoretical chapter and in this subchapter, the first sub-research question can be answered, which has been formulated as:

What are the different phases in which cost estimations for replacement projects are conducted, the different levels of accuracy per phase, and where preliminary cost estimations are positioned between these phases?

It is clear that even within the same country, there are different perceptions about the cost estimation phases, the level of accuracy in each phase, and the various methods used. In this sub-chapter, documents from seven public entities were examined, and the results related to the different phases and the accuracy levels in each phase were presented. Also, the current practices in one of the largest Engineering firms in the Netherlands were examined through an interview. An important finding from this first analysis of data is that, even though there are a lot of similarities between the different phases and levels of accuracy from both sides, there is no specific and global classification system that all clients can use in order to determine the cost estimation phases. In practice, it is observed that each client determines their preferences and engineering companies follow the different indications. Thus, there is a need for a more global and specific point of reference or a classification system that all practitioners understand and accept. Having it in place can facilitate their communication and the mutual realization of both sides' expectations. The classification proposed by the American Association of Civil Engineers (AACE) seems to be such a system that can be used to define the different cost estimation phases, methods used, and the expected accuracy per phase. Thus, in this research is adopted as it proves to be very well in line with the scientific community's perspectives, public clients, and the construction industry. Based on this classification presented in Table 6, there are five different phases in which cost estimations are conducted, and every phase contains a specific range of accuracy for the estimation. From the data, it seems that preliminary assessments dealt in this research are more similar to Class 5, Class 4, and Class 3 estimates which practically refer to SO and VO estimates conducted by Engineering and Construction companies in the Netherlands.

4.2. Factors related to the preliminary nature of estimates

Based on what has been mentioned at the end of the theoretical chapter, there are different types of explanations related to the budget overruns for replacement projects; however, due to the limited time frame of this dissertation, there is a distinction only on the technical ones. One important characteristic of replacement projects that can be linked to technical explanations is the preliminary nature of the estimations used. Based on the conceptual framework presented in Figure 9, two critical factors are associated with this characteristic. The first is the degree of project definition, which is described to influence the accuracy of preliminary estimations, and the second is associated with the methods used for preliminary estimating costs. In this sub-chapter, these two factors are examined in a practical way supplementary to the conceptual one in order to get a comprehensive insight into their contribution to cost overruns. The practical examination is done by examining nine case studies related to bridge replacement projects from the project inventory of Sweco.

4.2.1. Factors related to the level of project definition in preliminary estimates

In each of the different pre-construction phases, the level of project definition strongly varies in accordance with the available information at that specific point in time. An essential source of information in each phase is provided by the project's Work Breakdown Structure (WBS). In the early phases, the decomposition of the WBS is considered very limited due to the finite information. As more information about the project becomes available in its later stages, the further it can be decomposed, resulting in a more precise project overview. As the WBS is an essential input used for structuring the CBS, this means that a poor decomposition of works will result in a low definition of the various costs for executing them. In order to ascertain the extent to which the level of project definition affects the accuracy of the estimates, it is essential to get the first insight into the different cost components included in the estimation. For that reason, the process of determining the different cost components for past bridge replacement projects is described. The first step in this process is to identify the various works during the project execution, which is done by decomposing the examined object to the highest possible extent based on the available information. For the specific asset type of bridges, the Object Breakdown Structure (OBS) can be constructed based on the four-level breakdown structure presented by Du Bois et al. (2017) and is done as follows:

- Level 1: Object-level
- Level 2: Rate build up level
- Level 3: Item level
- Level 4: Heading level
- Level 5: Elemental level

In the first level of the Object Breakdown Structure, the least detail is provided as the total end product is positioned. The entire object is decomposed into different components while moving from Level 1 to Level 5. The whole structure is decomposed into three distinct areas on the second level: the foundation, substructure, and superstructure. In Level 3, the different components included in the previous three areas are positioned. For example, the foundation area contains items such as Piles, pile cups, etc., while in the substructure, abutments, wing walls, and other items are included. An illustration of the typical components included in the first three decomposition levels is provided in Figures 10 and 11.

It is clear that at the beginning of the project, the estimations are usually done on an object unit price basis, meaning that the total costs are estimated based on the highest level of decomposition with the respective lower detail. However, as long as the project progress, the cost estimation is conducted based on the cost of the activities required to construct the very detailed sub-components of a bridge.

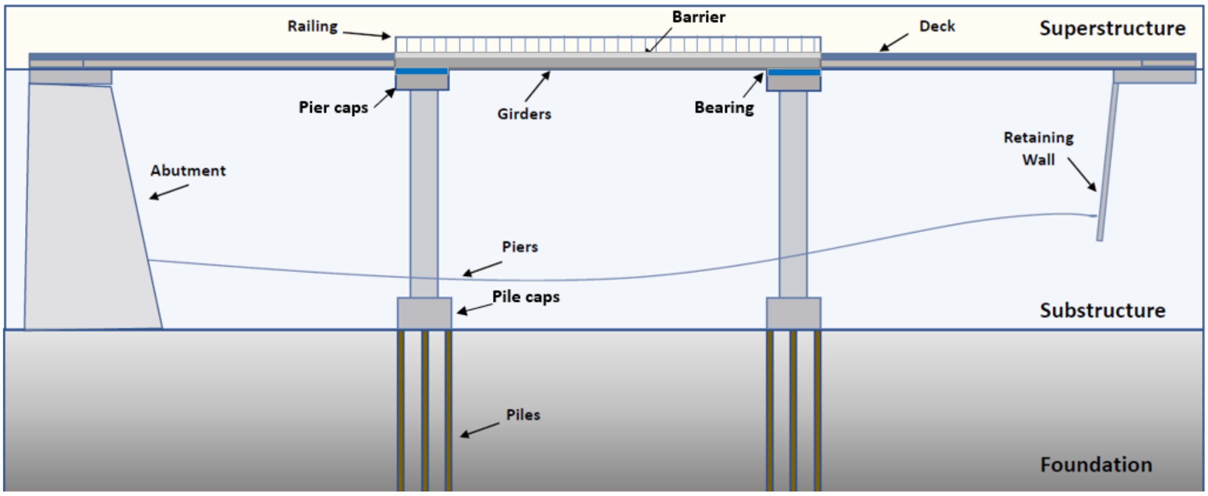


Figure 10: Bridge areas and typical components (Own illustration)

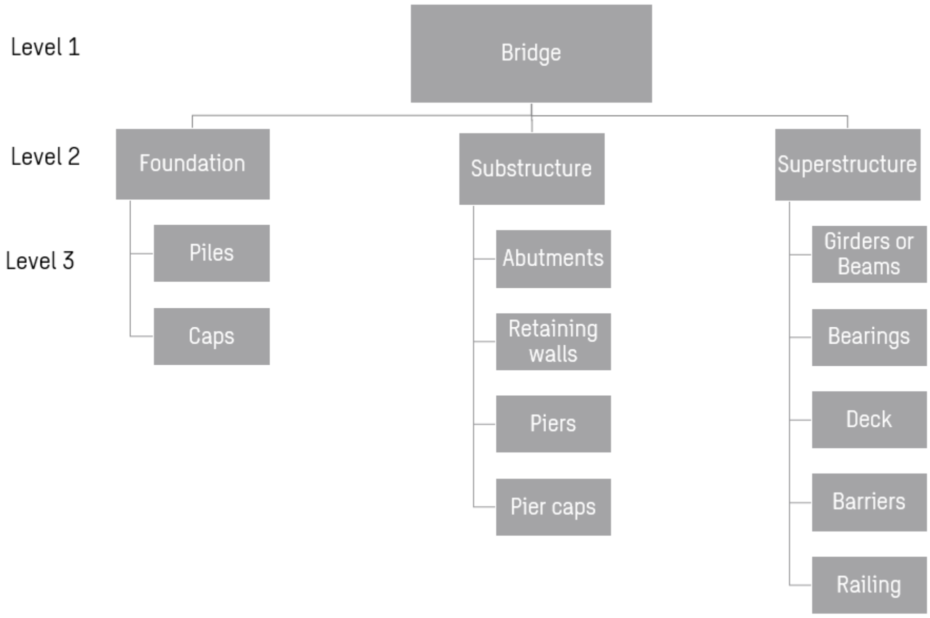


Figure 11: 3-Level decomposition of a bridge (Own illustration)

Certain activities and respective costs are associated with constructing each part of the bridge. All these costs constitute the total construction expenses for replacing the examined asset. The process of identifying the different cost components has been theoretically described in Figure 7; however, here is tested in practice by exploring its application to the case studies. The first part of the second sub-research question can be answered with both the theoretical and practical description of the cost decomposition process. This has been formulated as:

"How can the construction costs for replacing a specific asset be decomposed, and what is the contribution of each general component to the total construction costs?"

A guideline for decomposing construction costs for replacement projects that this research suggests is the six-level Cost Breakdown Structure illustrated in Figure 7. Based on that, the total replacement costs are positioned at the highest level, and the various costs of work packages, activities, or even more detailed equipment, material, and labor costs are set at the lower levels.

In the case of bridge replacement projects, the construction costs are positioned in Level 1 and then divided into direct and indirect costs. Then both direct and indirect costs are decomposed into work packages in Level 3. It was observed that the first three levels of cost decomposition were the same for all replacement projects; however, for the last two levels, variations were observed from project to project. This is since, in Levels 4 and 5, the cost of the various activities and their resources are positioned respectively. These costs are very specific and can vary based on each project's characteristics. An illustration of the second and third levels of cost decomposition observed in the past bridge replacement projects is presented in Figure 12. The direct costs (Level 2) are the aggregate of nine different work packages, which become ten in the case of moveable bridges. Respectively, the indirect cost is the summation of costs for six work packages and is estimated as a percentage of the total costs in practice.

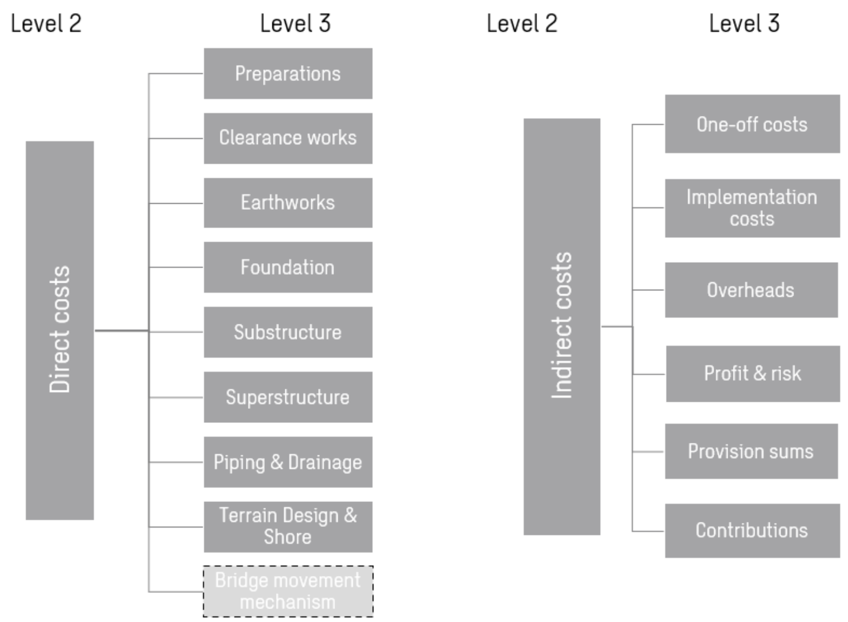


Figure 12: Decomposition of Direct & Indirect costs (Own illustration)

Having an indication of how replacement costs are decomposed based on the level of project definition, in this stage, it is essential to get an insight into how the preliminary cost estimations, which by their nature present low levels of project definition, can affect the estimates. In order to achieve this, the costs of the various work packages are assessed in two different phases. The comparisons can be facilitated if at least one estimate is available in the preliminary phase and at least one in later project phases when a detailed design is in place. Based on the data selection process description presented in Chapter 2, Class 5 and Class 1 estimates are available for all case studies. Also, for five out of nine projects, Class 3 estimates are present. As in Class 5 estimates, the decomposition of costs is very limited, and no cost data exists for the various work packages (Level 3), only the five case studies that include both Class 3 and Class 1 estimates can be used. In Class 3 estimates, there is a decomposition of costs on an activity basis (Level 4), while for Class 1 estimates, there is a decomposition of costs to the highest possible extent (Level 6).

According to the available estimations, the cost of each work package is calculated as the aggregate of the cost of all activities included in that specific work package. Then, for a better illustration of the results, the contribution of each work package to the total costs is expressed as a percentage of the total budget for the different forecasts and projects. Finally, in order to realize how the costs of different cost packages vary from Class 3 to Class 1 estimates, the deviation is calculated based on the equation below:

$$Deviation = \frac{Initial\ cost - Final\ cost}{Intitial\ cost}$$

And for the specific case:

$$Deviation = \frac{Class\ 3 - Class\ 1}{Class\ 3}$$

The total contribution of each work package and the respective deviation between the two phases for all projects is presented the Table 21 in the Appendix D:1.1.

From the results, it is evident that there is a noticeable deviation between the cost of each work package in the two different estimation phases for all projects. This is happening because, for Class 3 estimates, there is a limited degree of project definition, and any information used for conducting the forecast is derived from sketch designs and low decomposed OBS and WBS. Also, in these estimates, the forecaster uses a lot of expert judgment as there is no clear overview of the project. Thus, there are many uncertainties about the determined quantities and prices, and overall, there is limited reliability of the cost assessment. In contrast, as more information about the project becomes available and a detailed design is in place, the cost of each work package can be determined more accurately based on the exact cost of each activity and the respective resources. This results in a more reliable estimation with fewer uncertainties.

Based on the case studies examined, the level of project definition, which varies from phase to phase, can significantly contribute to the estimated replacement budgets. The effect of the level of project definition can be depicted in the cost estimation process via decomposing the construction costs in replacement projects. An essential guideline for decomposing the construction costs can be the six-level CBS presented in Figure 7. This CBS was theoretically described in the previous chapter, and in this one, a practical illustration was provided by examining its application to the case studies. From this, it is extracted that, in early project phases, the construction costs cannot be decomposed thoroughly due to the limited information. At the same time, for later design stages, the presence of detailed documents can lead to the complete decomposition of costs. As most replacement budgets are calculated based on preliminary assessments with a limited degree of project definition, it is evident that the decomposition of costs is quite limited in most of these assessments, as observed in the case studies. This eventually results in low-reliability forecasts and, consequently, cost overruns.

4.2.2. Factors related to methods used in preliminary estimations

Except for the level of project definition, another critical parameter associated with the preliminary nature of the estimations is the methods used to conduct the estimate. The theoretical chapter described two general categories in which most of the typical cost estimating methods are positioned: the deterministic and probabilistic approaches. Both have pros and cons and choosing the most appropriate one depends on various factors. It is imperative in this sub-chapter to get an insight into the different methods used in practice for conducting preliminary estimations and assess whether the techniques and their inputs contribute to the low accuracy of the estimates. For that reason, the various case studies are again examined under this scope.

Preliminary cost estimation methods

In the cost estimation classification system of Table 6, there is a suggestion for the methods that can be used for every Class estimate. There is a recommendation for using probabilistic approaches for the first three classes (Class 5, Class 4, and Class 3) as they can better capture the uncertainty in these early phases. For the last two classes, a deterministic approach is suggested as it is assumed that there is a high degree of project definition, less uncertainty, and reliable benchmark data available for estimating the exact activities' costs. Based on the documents examined, most public entities also recommend probabilistic approaches for estimating preliminary costs; however, this is not a binding condition for engineering companies. In practice, both based on the interview and the case studies, it is observed that only deterministic methods are used in all cost estimation phases for small replacement projects such as those of replacing municipal bridges. This is mainly done because probabilistic methods usually require more effort, and cost estimators do not fully understand some principles, especially those with less experience.

Although deterministic methods are used for all preliminary estimations (Class 5, Class 4, and Class 3), the techniques and inputs used vary between the different estimate classes. The asset management department in Sweco, which is usually responsible for communicating and monitoring the condition of municipal assets, provides only Class 5 estimates when the clients require an appraisal. This is generally done because municipalities are not willing to spend a lot of financial resources to get an indication of how much a possible replacement will cost. Thus, very rough Class 5 estimates are provided mainly by Sweco to determine replacement costs in the long-term asset planning process. Based on this research, these estimates contain many deficiencies concerning the inputs used to conduct the assessment.

The past bridge replacement projects are examined to get an overview of the reliability of inputs used for conducting Class 5 preliminary estimates. Based on these, it is observed that the methods used are only deterministic, and the information for the estimation are unit prices that some experts have proposed based on their experience. These unit prices are expressed in prices per deck area (price/deck area m^2), and there are different indications for different types of bridges. The first question that arises from this observation is why unit prices per deck area are used for the estimation?

To answer this question, the contribution of each work package to the total costs mentioned in the previous sub-chapters is used. More specifically, as Class 1 estimates resemble the actual costs of each work package, these are the ones used here for the analysis. The contribution of each work package to the total cost for all projects is presented in Table 22 in the Appendix D1.2. Also, a visualization of the respective graphs is shown in Figures 18 -26 in the Appendix D.1.2.

Estimating in the same table the mean values for every work package and all projects helps also answer the second part of the second sub-research question, which has been formulated as follows:

"How can the construction costs for replacing a specific asset be decomposed, and what is the contribution of each general component to the total construction costs?"

The table shows that the superstructure is the most dominant cost category in seven out of nine projects, accounting for 17.8% to 54.8% of the case studies examined. This is very well in line with Konstantinidis and Maravas (2003), which underline that for modern concrete bridges, the superstructure cost ranges from 35% to 53%. This high contribution to the total construction costs justifies using unit prices per deck area to estimate the preliminary costs for bridge replacement projects.

However, the level of accuracy of these unit prices is not yet known, and to get this insight, it is valuable to compare how the costs estimated with Class 5 assessments deviate from the more actual costs. Since no actual costs are available, it is assumed that the estimated expenses with Class 1 estimates are close to the actual costs. This assumption is based on the fact that cost overruns are almost always happening in construction projects, and there is a small probability that the cost estimated with Class 1 estimates will be significantly higher than the actual one. Thus, the estimated deviations between Class 5 and Class 1 estimates can be close to or even higher than those between Class 5 estimates and actual costs.

The deviations between the two estimates are conducted by using the equation of Flyvberg et al. (2012) presented before; however, it is adjusted for Class 5 estimates as below:

$$Deviation = \frac{Class\ 5 - Class\ 1}{Class\ 5}$$

The different estimated costs and the deviations are presented in Table 7.

Table 7: Estimated costs (Class 5, Class 1) and their deviation in the case studies

Project	Conceptual (Class 5)	Bid/Tender (Class 1)	Deviation
Project 1	€ 105,525	€ 195,000	-85%
Project 2	€ 166,050	€ 202,703	-22%
Project 3	€ 214,500	€ 142,006	+34%
Project 4	€ 135,000	€ 242,400	-80%
Project 5	€ 371,520	€ 321,801	+14%
Project 6	€ 372,384	€ 324,651	+13%
Project 7	€ 390,000	€ 332,061	+16%
Project 8	€ 294,000	€ 515,605	-75%
Project 9	€ 213,000	€ 297,043	-39%

To have a reference for comparison and identify the level of accuracy of the estimations, the coefficient variation limits from the classification adopted are used. Based on the AACE for Class 5 estimates, the range of cost overrun percentage can be between the range of (**-50%, -20%)** while the cost underrun can be in the field of **(+30%, +100%).** The results show that six out of nine projects lie within these limits; however, in Project 1, Project 4, and Project 8, there is a slight declination from these limits. As the only input used for estimating these costs are the unit prices and the area of the deck in m^2, this means that the explanation for this phenomenon has its roots within these two parameters. By examining the basic dimensions of the bridges presented in Table 8, it is observed that for the six projects whose deviation is within limits, the length is significantly higher than the width (two times or more). In contrast, the estimated variations are out of the proposed boundaries for projects 1, 4, and 8, of which the two fundamental dimensions are close to one another.

Table 8: Basic dimensions of the bridges

Project	Width (m)	Length (m)	Deck area (m^2)
Project 1	4.5	6.7	30.2
Project 2	4.5	12.3	55.4
Project 3	5.5	13	71.5
Project 4	5.2	6.7	34.8
Project 5	7.2	17.2	124.
Project 6	7.2	17.2	123
Project 7	7.6	17.2	130
Project 8	8	10.5	84
Project 9	3	7.1	21.3

So, the unit prices that Sweco uses for conducting Class 5 estimates present a noticeable accuracy for long bridges, so it is advisable to use them. In contrast, these unit prices should not be used for wide bridges due to their probable limited accuracy.

In addition, the theoretical chapter described that except from Class 5 estimates, the Class 4 and Class 3 estimates are also considered preliminary estimates. However, as these are conducted in later project stages, different techniques and inputs are used in the estimation. No data was available for Class 4 estimates in the case studies examined, so only the techniques and inputs for Class 3 estimates are analyzed. Based on the projects, the total replacement costs are estimated by determining the costs of the different activities (Level 4 of decomposition) identified by the cost estimators. These activities are usually sub-sets of the work packages mentioned before (Level 3), and their costs are determined based on the quantity of the activities and their respective price. The cost of these activities is derived from online databases such as the GWW Kosten, and the experts assume the quantities. As in that phase of the estimate, there is no final design in place, and the level of project definition is limited; the uncertainties that exist regarding the assumed quantities can be multiple. Even if the prices (inputs) of the activities extracted from online databases are considered valid, the deterministic techniques used can affect the accuracy of the estimation due to their incapability to capture the above-mentioned uncertainty.

In order to get a more practical understanding of the accuracy of Class 3 estimates used in practice, the different case studies are again examined. However, as mentioned, Class 3 estimates were available only for five out of nine projects. Again here, the deviations from Class 1 estimates are estimated in the same way as described before, and the results are presented in Table 9.

Table 9: Estimated costs (Class 3, Class 1) and their deviation in the case studies

Project	Feasibility (Class 3)	Bid/Tender (Class 1)	Deviation
Project 1	€ 205,000	€ 195,000	+5%
Project 2	€266,262	€ 202,703	+24%
Project 3	-	€ 142,006	-
Project 4	€182,067	€ 243,400	-34%
Project 5	-	€ 321,801	-
Project 6	-	€ 324,651	-
Project 7	-	€ 332,061	-
Project 8	€792,476	€ 515,605	+35%
Project 9	€199,851	€ 297,043	-49%

To define the level of deviation in that case, again, the limits indicated by the classification adopted are used, which suggest that for Class 3 estimates, the cost overrun can be positioned in the range of (-20%, -10%) while the range of underrun can be in the field of (+10%, +30%). Based on the results, it seems that there is a declination from the limits proposed and a significant cost overrun in three out of five projects. This is because the quantities and prices assessed in Class 3 estimates are slightly different from those in Class 1 estimates. Also, it means that the contingencies added in the deterministic estimation for covering these uncertainties were not adequate for most of the projects examined.

Based on all the above, the third sub-research question can be answered. This has been formulated as follows:

"What are the different methods used for estimating replacement costs in preliminary phases, and what is their observed accuracy?"

It is observed that even though probabilistic methods are proposed for preliminary estimating costs both from public entities and from the AACE classification system in practice, only deterministic methods are used for preliminary estimating the costs for small replacement projects. For Class 5 estimates, these are done quite roughly based on unit prices per total object, while for Class 3, this is done on an activity or work package level. It was observed that the inputs used for estimating the costs in Class 5 assessments could be considered valid for long bridges ($L \gg w$) as they lead to relatively accurate forecasts. However, when applied to wider bridges ($L \approx w$), these result in low accuracy estimations for longer bridges, and it is not advisable to use them. This validates the assumption made in the theoretical chapter, under which it was described that deficiencies in the inputs used for preliminary estimating the costs could lead to budget overruns. In terms of Class 3 estimates, it was also observed that there was also a significant deviation from the Class 1 forecasts in more than half of the projects examined. The explanation is very much related to the previous sub-chapter, which described that quantities and prices could be underestimated due to the limited information. However, in this sub-chapter, it is also pointed out that the deterministic methods also contribute to their incapability to capture these uncertainties. The literature has shown that probabilistic methods can better capture uncertainties regarding the quantities and prices, but these are ignored for various reasons in the current practices.

Thus, it is concluded that both for Class 5 and Class 3 preliminary estimates, there are cost overruns observed, and the techniques and inputs used can contribute to the replacement budget exceedance.

4.3. Factors related to long-term asset planning

Except for the preliminary nature, there is also a second characteristic that has been mentioned in the theoretical Chapter and is considered to have a significant contribution to the low accuracy of replacement budget estimates. This one is associated with the inherent uncertainty that exists when trying to predict the cost of a project which is actually initiated years after the cost estimation process. This initial estimation is usually done in the long-term asset planning process for replacement projects, which can occur at the beginning of the asset's service life. This means that the respective replacement of the asset can be initiated at the end of its service life, which is usually expected 30 years or more after the construction of the asset. Many things can change during this extensive time frame, with the most common one being the prices attributed to each cost component in the cost assessment phase. Many scholars have underlined the importance of the price escalation factor in these situations; however, the problem still exists in the industry. In order to practically identify the effect of price escalation on replacement budgets, the different case studies are examined in this sub-chapter. For conducting this analysis, multiple inputs are needed. First, in order to determine the effect of price escalation over the year for replacement projects, it is essential to have the initial estimated costs and the year on which these costs have been estimated. Then, time series are needed to get an insight into the probable evolution of the initially estimated cost through the years. This input is derived from statistical data available in open data sources. In the Netherlands, the Dutch Central Bureau of Statistics (CBS) provides this kind of data in the form of indices. The indices or index numbers summarize the changes in price and quantities for a group of products into a single number (Balk, 2008). There are multiple kinds of data available from the CBS database; however, as bridge replacement projects are examined, the most suitable indices available are the ones that indicate the evolvement of bridge construction costs from the year 2000 until 2021. An overview of these indices is presented in Table 23 in the Appendix E1.1. Using the indices and the initially estimated costs as inputs, the evolution of costs through the years due to price escalation can be estimated. The initial and final costs for all case studies can be seen in Table 10. In Figure 13, this evolvement of costs due to price escalation is presented graphically for all projects. However, a detailed presentation of all estimated costs through the years for all projects can be found in Table 24 located in the Appendix E: 1.2.

Table 10: Evolvement of replacement costs due to price escalation

Projects	Year of the initial estimate	Initial estimate (Class 5)	Estimated cost in 2021	Deviation
Project 1	2008	€ 105,525	€ 239,952	-23.1%
Project 2	2013	€ 166,050	€ 249,828	-23.2%
Project 3	2013	€ 214,500	€ 175,020	-23.2%
Project 4	2016	€ 135,000	€ 295,694	-22.0%
Project 5	2018	€ 371,520	€ 369,820	-14.9%
Project 6	2018	€ 372,384	€ 373,096	-14.9%
Project 7	2018	€ 390,000	€ 381,611	-14.9%
Project 8	2015	€ 294,000	€ 635,981	-23.3%
Project 9	2015	€ 213,000	€ 366,392	-23.3%
			Average increase in %	**-20%**

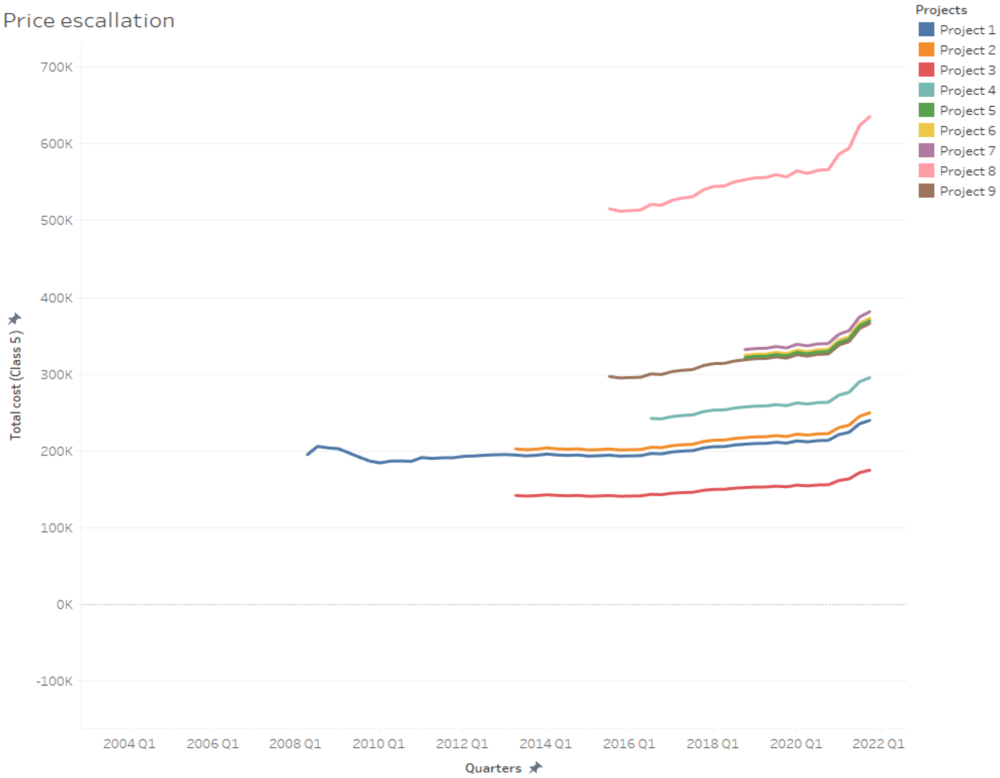


Figure 13: Evolvement of replacement costs due to price escalation

From the indices and the estimated costs, it is observed that if the costs had been evaluated in the specific year mentioned for every project, and the actual initiation of works had started in 2021, there would be a significant increase in the initial budget due to price escalation. More particularly, an average increase of 20% is observed in the projects examined between 2008 and 2015. This means that for the specific case studies, the cost had been estimated 15 to 8 years before the execution of the works, and such a percentage of increase in cost is observed. However, in the Netherlands, most public infrastructures are constructed with an expected service life of 40 years. Thus, conducting such a long-term forecast for their replacement significantly affects the initial estimated budget. To have an indication of that impact, the average escalation of the bridge construction costs per year is calculated based on the indices. This is estimated based on the equation below (Park, 2016).

$$f_T = \left(\frac{PPI_n}{PPI_0}\right)^{1/n} - 1 = \left(\frac{144.7}{99.3}\right)^{1/21} - 1 = 0.0181 = 1.81\% \qquad (1)$$

Where:

f_T= annual total escalation rate [per year]

PPI: Producer Price Index.

0 = base year of the period considered

n = the year at the end of the period considered = 2021-2000 = 21years

April 2000: PPI = 99.3 Bridge construction costs (see Table 22)

April 2021: PPI = 144.7 Bridge construction costs (see Table 22)

Based on this equation, it is calculated that there is total inflation of 0.018 or 1.8% for bridge construction costs per year over this selected period. This means that 40 years after the initial estimation, the cost would have been increased enormously, leading to extreme budget exceedance.

So, based on the price indices and the case studies, it is observed that price (de)-escalation can significantly affect the initial estimated costs for replacing an asset, mainly when this estimation is conducted years before the actual execution of the works.

4.4. Chapter summary

The primary purpose of this Chapter was to investigate whether all the theoretical context of the problem provided in Chapter 3 is applicable on a practical level. For that purpose, the various data collected for this research were analyzed and used to get a more comprehensive overview of the problem and answer the formulated sub-research questions. The first part of this Chapter contributed to the definition of the preliminary cost estimations and answered the first sub-research question. This was done by gathering and analyzing data from archival documents and interviews to examine the different points of view of both the clients and the engineering consultancies. The results suggested that the classification system proposed by AACE is very well in line with both two perspectives and can be used as a reference point for defining preliminary cost estimations and their respective accuracy. The preliminary estimations were defined as Class 5, Class 4, and Class 3 estimates based on this classification. After determining the preliminary estimations, the analysis of the various factors that can lead to budget exceedance was followed. Firstly, the factors related to the low accuracy of preliminary cost estimations were analyzed, followed by a further analysis of the price escalation factor, which usually exists in replacement budget estimations. In terms of preliminary estimations, the factors related to the level of project definition and the methods used in the estimations were practically examined by analyzing various case studies. From the results, it was observed that the decomposition of the object examined, and the total construction costs are highly associated with the level of the project definition. A thorough decomposition of both is complex in the preliminary phases due to the limited information. However, a possible decomposition of the construction costs and the object for bridge replacement projects was suggested. Based on this decomposition and the examination of case studies, interesting findings occur related to the contribution of each work package to the total costs. These findings were used to answer the first part of the second sub-research question and will also be used to develop the proposed framework. Regarding the second factor related to the methods used, after examining the various case studies, it was observed that although probabilistic estimates are suggested in these phases, only deterministic are used in practice. The multiple inputs and techniques used in the estimations were scrutinized in the case studies, and valuable conclusions were extracted about the accuracy of these estimations. It was observed that the inputs used for Class 5 estimates are relatively reliable for high span bridges; however, they present low accuracy for wider bridges based on the case studies examined. Also, it was proved that Class 3 estimates which in the case studies were conducted deterministically, might present low levels of accuracy in many cases. These conclusions were used to answer the second part of the second sub-research question. Finally, the effect of price escalation in the case studies was examined, and valuable information was extracted. A remarkable result from this analysis is that for the case studies reviewed, an average 20% increase in the initial estimate can occur if ignoring the price escalation factor. Based on all this information-theoretically and practically, the last sub-question can be answered, which can help develop a framework that can improve the preliminary estimations for replacement projects in the next chapter. This last question had been formulated as:

What are the different factors that can lead to budget overruns in replacement projects?

The answer to this question is a summary of all the information provided in these last two chapters and can be structured in the conceptual framework structured at the end of Chapter 3 and presented in Figure 9.

5. Framework development and validation

In the last two chapters, there was an extensive analysis both on a theoretical and a practical level of the problem associated with the observed budget exceedance in replacement projects. The takeover from this twofold analysis was a theoretical framework that helped meet the first objective of this research, which was to acquire a further understanding of the potential factors that can contribute to this phenomenon. After completing the first objective of this research in this chapter, there is an effort to achieve the second and last objective, which is to improve the current ways of preliminary estimating replacement budgets. Meeting this goal can help enhance the reliability of the current practices and reduce the level of budget overruns. To achieve this, a second framework is developed. Its utilization can contribute to dealing with the different factors associated with the two essential characteristics of replacement projects specified in the theoretical framework of Figure 9.

5.1. Framework development

The developed framework would consist of two building blocks. The first one is responsible for dealing with the factors related to the preliminary nature of the estimations and individually, it can be used for the short-term asset planning. The second one is designed to reduce the effect of factors associated with the long-term asset planning process. Combined these two building blocks together, they can function as an integrated approach for improving both the short and the long term asset planning process. In order to structure the proposed framework, it is imperative that all the findings from the theoretical and practical analysis of the previous chapters are used. Once the developed framework is created, it is validated through a single case study and expert judgment's review.

5.1.1. Building block for dealing with factors related to the preliminary nature of estimates

Based on the conceptual framework illustrated in Figure 9, two important factors related to the preliminary nature of the cost assessments contribute to their limited accuracy. The first one is in connection with the finite level of project definition in these phases, while the second one is associated with the methods used for preliminary estimating costs. Based on the findings resulting from the twofold analysis, it was observed that there is a specific connection between these two factors. On the one hand, the limited level of project definition would lead to a finite level of budget decomposition and consequently to multiple uncertainties in these early assessments. On the other hand, the unreliable inputs and the deterministic techniques used for conducting these early assessments seem incapable of capturing the multiple uncertainties in some instances.

In an effort to improve the current practices of preliminary estimating the costs for replacement projects, it is imperative that all these observations from the twofold analysis are used for constructing the respective framework. Thus, it is essential here to mention the ones related to the factors associated with the preliminary nature of the estimations. First of all, based on the multiple case study analysis, it was observed that in three out of nine projects which concern wide municipal bridges, the inputs used for conducting the Class 5 estimates led to unreliable forecasts. In contrast, the inputs used for conducting very rough Class 5 estimates for longer bridges proved to be reasonably reliable, leading to relatively accurate cost assessments. As Class 5 estimates are rapid, easy to use, and in some cases can lead to reliable outcomes, it is reasonable to use them when reliable benchmark data exist and can be used as inputs in the estimates. However, more detailed appraisals such as Class 4 and

Class 3 should be conducted when there is a lack of reliable benchmark data for such assessments. In accordance with that, in a second observation concerning Class 3 estimates, it was observed that for three out of five cases, the deterministic techniques used for assessing costs were incapable of leading to reliable results based on the expectation levels defined. This was mainly because the deterministic methods couldn't easily capture the uncertainties in these early estimations.

Based on what has been mentioned in the theoretical chapter of this dissertation, probabilistic techniques focus on the specific risks and uncertainties that exist in the estimations and try to quantify them (Anderson et al., 2007). Literature has shown that probabilistic techniques can lead to more reliable cost estimations as these techniques usually use probability distributions in order to reflect the different outcomes of the cost assessments (Garvey et al., 2000; Chou, 2016). Thus, they can be used to estimate the replacement budgets in Class 4 and Class 3 assessments as an alternative when no reliable data is available for estimating replacement costs with rough Class 5 estimates.

The probabilistic estimation of replacement costs can be done using the most common risk analysis technique, the Monte Carlo simulation, well described by Wang et al. (2012). There are at least two critical inputs needed when probabilistically estimating the costs. The first concerns a deterministic cost assessment part in which the base costs are calculated. For Class 3 estimates, this can be estimated on an activity or work package level based on the available information.

Then, for quantifying the various risks associated with the previously estimated costs, a certain distribution is needed to reflect their variations. Usually, a three-point estimate and a triangular distribution are used as inputs for running a Monte Carlo simulation. However, as Larsson et al. (2019) indicate, in the absence of data supporting distributions of uncertainty variables, the result of Monte Carlo Simulations should be viewed with extreme care as it suggests a level of accuracy that does not exist. For replacement projects, as the activities contained in the various budgets are very specific even, for the same asset category, the various distributions can be defined on a work package level (Level 3 based on Figure 7). This means that there is a need for a systematic gathering of cost data related to the cost of work packages for the various asset types. In the following chapter, there is an illustration of the process associated with identifying the various distributions for the work packages included in the budgets of bridge replacement projects.

Having both the basic cost information and the respective distribution, a Monte Carlo simulation can be conducted using computing power to explore all the possible outcomes of the cost assessment (Loosemore et al. 2005). The different scenarios (also called iterations) can be drawn from the full range of the selected distribution by using computer software such as Palisade @Risk or even Microsoft Excel. The number of iterations or different scenarios to be generated in order to reach an acceptable answer can vary; however, in this dissertation, the approach of Gladwin (2006) is adopted, which supports that for most models, one to five thousand iterations are considered sufficient.

Taking all the above mentioned into consideration, the first building block of the framework can be structured and presented in Figure 14. The framework starts with a request for a preliminary cost estimate regarding the replacement of a particular asset, and then the first building block is described. As mentioned, this building block aims to target the factors related to the preliminary nature of these estimations and affect their accuracy.

The first building block starts with a decision gate in which the user has to decide whether reliable benchmark data (unit replacement costs) exist for preliminary estimating the replacement costs with Class 5 estimates. For example, in the case of Sweco, it was proved that the benchmark data they possess could be quite reliable for long bridges, while for the wider ones, these do not reflect their actual costs. After the decision gate, different processes are described.

In the case of available data, the cost is estimated with a very rough Class 5 estimate on an object or item level. In that case, the only inputs needed are some basic asset information and the respective unit prices for estimating the replacement costs for particular items or the entire object. The methods used in that case are very rough and are conducted in a deterministic way.

When no reliable unit prices are available, a probabilistic cost estimation process needs to be followed. This starts with identifying various activities and work packages that need to be included in the estimation, followed by calculating their respective cost. The outcome of this process is a Class 4 or Class 3 deterministic base cost assessment that most cost calculators conduct and does not include any risk elements. Having an indication of the bare costs, the various risks included in the estimation of the above-mentioned costs can be quantified and incorporated into the estimation. This is done by conducting a probabilistic cost estimation with a Monte Carlo Simulation. As mentioned, for running a probabilistic cost assessment, it is imperative that the most suitable distribution is selected together with its parameters. In the absence of information regarding the distribution, a triangular one is usually adopted, with its distribution parameters being the most likely, minimum and maximum value of a certain attributed cost for an activity or work package. When data are available regarding the distributions of costs for each activity or work package, this can lead to far better results and more accurate forecasts. Finally, a Monte Carlo Simulation is conducted using computer software when the distribution and its parameters have been defined. The result from both processes described in the first building block of the framework represents an indication of the replacement cost for the particular moment in which the estimation is conducted and individually it can be used for improving the practices in the short-term asset planning process. However, as described in the analysis, it might be the case that replacement costs are estimated many years before the actual execution of works in the long-term asset planning process. So, there is a need to address the factors related to that second identified characteristic of replacement projects in the presented framework. This is done in the following sub-chapter.

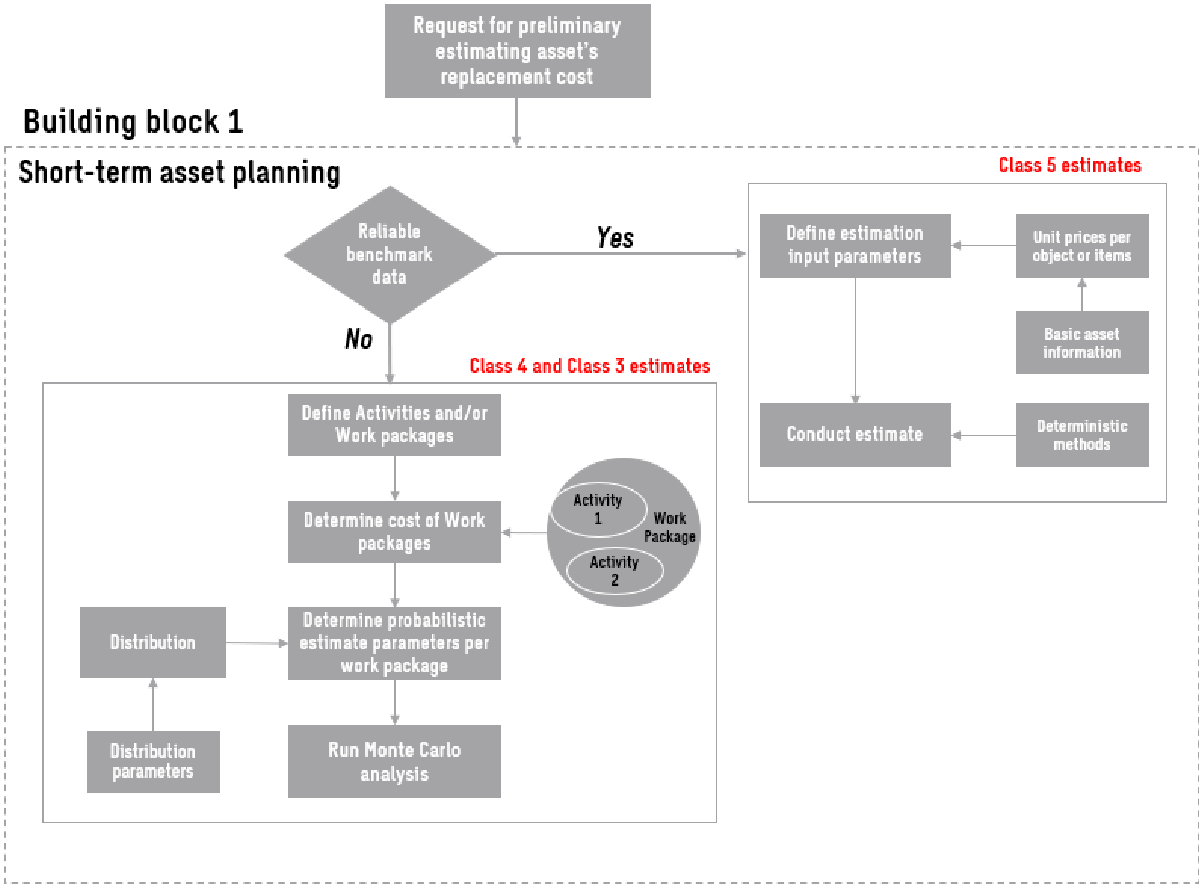


Figure 14: First building block; Approach for improved Short Term Asset Planning

5.1.2. Building block for dealing with the long-term cost forecast factors.

In the previous sub-chapter, the first building block of the framework for improving the current practices of estimating preliminary costs for replacement projects was described. As shown in Figure 14, the output from this first building block is an indication of costs at the specific point in which the forecast is conducted. However, replacement projects are initiated at the end of the asset's service life in some cases. At the same time, the actual estimation of costs is conducted in the long-term asset planning process when the asset is first constructed. Over the years, many changes can occur, such as increasing the cost of materials, equipment labor, etc. Even though the probabilistic models described in the first building block, try to quantify the various risks and provide a certain level of confidence in the estimates, such uncertainties related to the price (de)escalation over the years cannot be captured.

The literature review revealed that there are some scholars who have tried to incorporate the price uncertainties when forecasting the future value of various infrastructure assets. Ng et al. (2004) used time series analysis to predict the tender price indices for building constructions in Hong Kong. Younis et al. (2016) used unit prices developed by Rehan et al. (2016) and stochastic models to forecast how these unit prices will evolve at a future date. Van den Boomen et al. (2016) proposed that the price uncertainty can be incorporated into estimating life-cycle costs by using past indices and stochastic models.

Under the same line of reasoning as Van den Boomen, this research also supports that historical price indices and a stochastic model can incorporate the price uncertainty in estimating asset replacement costs. This practice has been widely applied in the financial domain to investigate the dynamics of stock prices and predict their future trends and can be easily used in the construction industry. A specific point of concern regarding this practice is that historic prices do not guarantee the validity of future predictions, but it gives some information about expected developments. The price data needed can be usually found in the form of time series and are generally provided by the various bureau for labor statistics and specialized agencies. As described in the previous chapter, in the Netherlands, the Dutch Central Bureau of Statistics (CBS) provides such data. Apart from the model, a forecasting method is also needed to predict the dynamic prices related to replacement costs. Different methods are available for such a purpose, but the Geometric Brownian motion (GBM) is selected in this research. The primary rationale for using the GBM is it uses only past prices as inputs for predicting the future value of replacement costs. Another reason is that this method is relatively straightforward as it is built upon basic statistical principles and can be used by cost estimators without needing very advanced background knowledge. Further to that, the results of a GBM are easily explainable contrary to more advanced methods, which are based on the principles of GBM but use regression analysis with more variables. In the discussion section of the dissertation, other financial forecasting methods are also reviewed.

A GBM describes a random walk defined by a drift and volatility. The price or cost changes in each time step based on a constant (drift) or growth rate and a random shock (volatility). Both the drift μ and the volatility σ are extracted from past prices/indices. The randomness of the volatility is incorporated by using a shock ε_j that follows a normal distribution $\varepsilon_j \sim N(0,1)$. Because returns on costs are compounded, a Geometric Brownian Motion uses its natural logarithm when describing an arbitrary walk according to:

$$\ln(C_j) - \ln(C_{j-1}) = \mu + \sigma\varepsilon_j \tag{2}$$

Where:

ln (P_j): natural logarithm of the replacement at time j

ln (P_{j-1}): natural logarithm of the replacement cost at time j-1

Rearranging a bit, the equation (2) the next cost can be obtained based on its previous forecast using equation (3).

$$C_j = C_{j-1}\, EXP(\mu + \sigma\varepsilon_j) \tag{3}$$

Also, an indication value of the cost in a certain year can be obtained using the initially estimated price in year zero. This can be done by using the equation (4).

$$C_j = C_0\, EXP\, \Big((j\mu) + \big(\sigma(\varepsilon_1 + \varepsilon_2 + \cdots + \varepsilon_j)\big)\Big) \tag{4}$$

As shown in Figure 14, the output of the framework's first building block indicates replacement costs at a particular point in time. Considering equation (4), this specific output accounts for the C_0 value or the initial replacement costs estimated in the long-term asset planning process. By having historical data regarding the evolution of costs over the years for a particular asset, and using the GBM, the Cj value representing the replacement costs at year j can be estimated. This can provide an indication of how the costs could have evolved over the year j, which is considered the year in which the execution of replacement works starts. Such an indication can help forecasters and estimators to structure more reliable replacement budgets that account for the (de)-escalation of prices from year 0 over year j. All the described processes of forecasting replacement costs using historical data and the GBM can be structured in the second building block of the framework, which is illustrated in Figure 15.

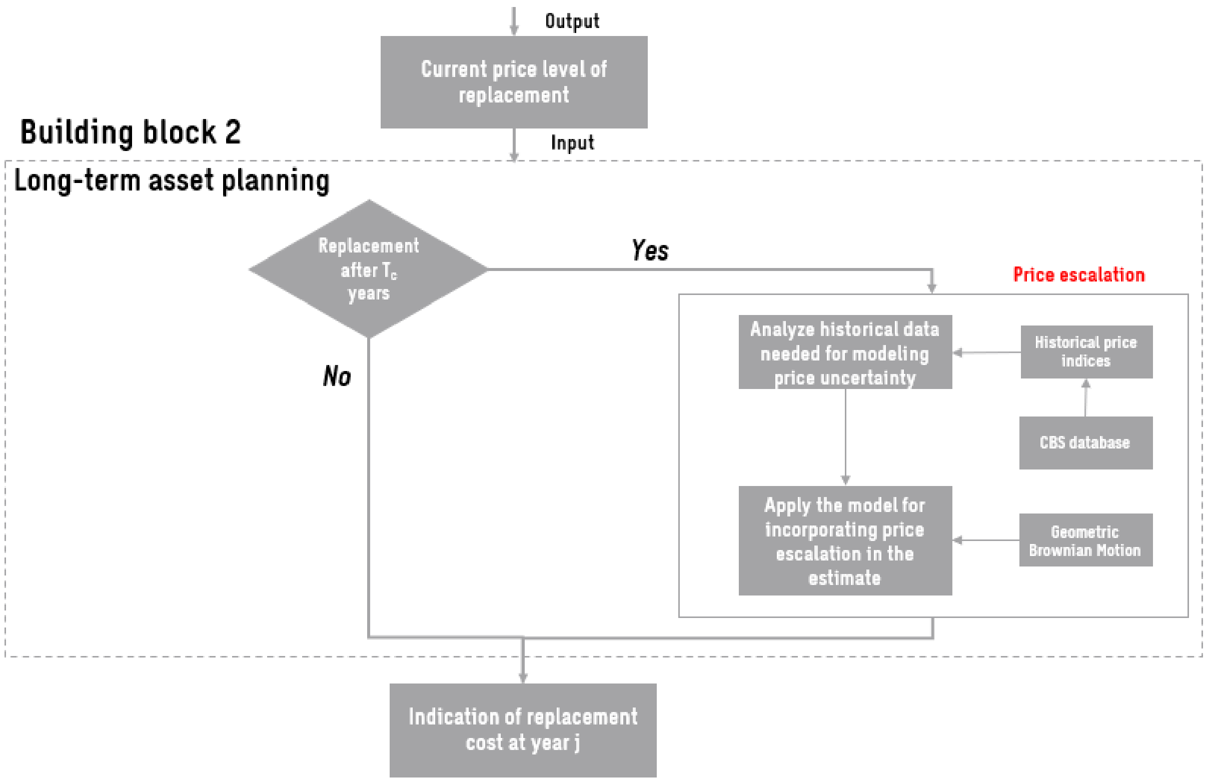


Figure 15: Second building block; Approach for improved Long Term Asset Planning

The output of the first part of the framework, which is the initial estimated cost (C_0), is used as an input for the second building block, which starts with defining the year in which the execution of the replacement works is expected to commence. Then by using the equation (1) described in chapter 4 and historical data related to the evolution of costs for a particular asset, the annual total escalation rate can be estimated. This can give a first indication of how the cost could evolve on a yearly basis and help the cost estimators assess the critical year T_c. In the framework, the critical year concerns the specific point of time (annually), after which the forecaster considers that the price escalation effect would have a significant impact on the initially estimated cost. After that point, the price escalation effect should be incorporated into the estimation. As the critical year, T_c is assessed based on the estimator's experience and is dependent on the total annual escalation rate; the definition of this parameter can be quite subjective and different from one asset type to the other. In the case of bridge replacement projects and based on the total annual escalation rate of 1.81% estimated in Chapter 4, the year T_c=5, refers to a 5.4% increase in replacement costs in five years, can be considered a reasonable value for using in the framework. Due to the limited time frame of this research, this aspect was not examined in depth; however, it is worth future research investigating how these values can be statistically better defined for the various types of assets.

Having defined the critical year T_c the next step in the framework contains a decision gate in which the expected year of replacement work's commencement is compared with the critical year defined in the previous step.

In the case in which the expected year of replacement is earlier than the critical year, then there is no need for incorporating price uncertainty, and the final replacement cost is the one defined in the first building block of the framework.

On the other hand, the price escalation should be incorporated into the estimation when the year of works' initiation is positioned later concerning the critical year. This is done using past historical data from open sources such as the CBS and the GBM, as described above. In that case, the ultimate output of the framework is the expected replacement cost in year j (C_j), which accounts for the uncertainties related to the preliminary nature of estimations and the uncertainties associated with the price escalation. A general overview of the framework consisting of the two building blocks is shown in Figure16.

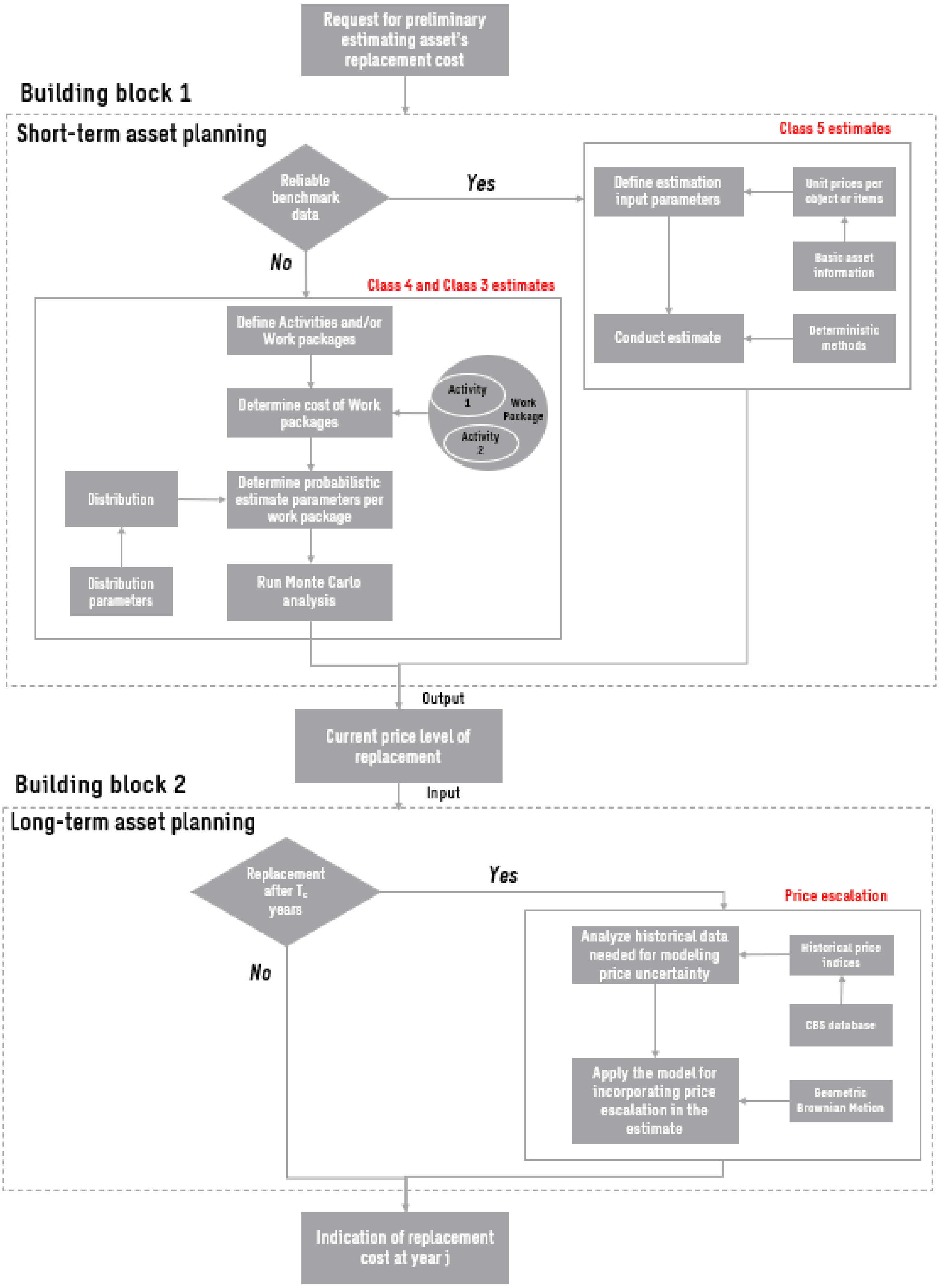


Figure 16: Framework for improving preliminary cost estimations in replacement projects

5.2. Framework validation

After developing a conceptual framework for improving the current ways of preliminary estimating the costs, the proposed framework needs to be validated. The validation process is conducted in two steps. In the first step, the framework is applied in two case studies to ascertain whether the developed framework provides better preliminary results than the ones occurring from the current practices. In the second step, the framework is validated through expert judgment. Due to the unavailability of other case studies for framework validation, the replacement projects used for the framework's verification concern bridge replacement projects from the sample used in the practical analysis of Chapter 4.

5.2.1. First building block

The case study used to validate the framework concerns the Project 4 of Table 3. The rationale behind the selection of this project is because it concerns a wide bridge which presented a high cost overrun when Sweco estimated it with preliminary estimates.

The process of validating the framework through the case studies is done by ascertaining whether the preliminary cost estimated using the proposed framework is closer to the results from the Class 1 estimate than those estimated by the cost experts from Sweco.

The estimated costs from the cost experts of Sweco in the different cost estimation phases are shown in Table 11.

Table 11: Estimated costs with the current practices

Class 5 estimate	Class 3 estimate	Class 1 estimate
€ 135,000	€ 182,067	€ 242,400

As described in the framework, the first building block starts with a decision gate related to the availability of reliable data for preliminary estimating costs with a Class 5 estimate. Based on the findings from the technical analysis, for wider bridges ($w \approx L$) as of the examined case study, the available unit prices are considered unreliable; therefore, a probabilistic assessment is needed. As described in the framework, the first step for conducting the probabilistic assessment is to define the various activities and the work packages included in the estimation. For bridge replacement projects, the work packages identified in the technical analysis are Preparations, Clearance works, Earthworks, Foundation, Substructure, Superstructure, Piping & drainage, Terrain design & Shore, General works, and Tail posts. The next step in the framework is to estimate the cost of the work packages. This is done deterministically, in the same way as is currently conducted by the cost estimators in Sweco.

After defining their cost, the probabilistic part of the estimate is commenced. That process includes the definition of the appropriate probability distribution for each work package and its respective distribution parameters. Usually, a triangular distribution is assumed by the estimators; however, due to the available case studies in this research, there is an effort to define the best-fit distribution for the respective work packages included in the replacement cost estimation. Generally, the best-fit probability distribution selection is made via the goodness of fit tests. The goodness of fit tests investigates observational data's consistency with certain probability distributions (Amirataee et al., 2014). There are various methods for identifying the best-fit probability distribution, such as chi-square, Kolmogorov-Smirnov, Standard Error Estimation, and Probability Plot Correlation Coefficient (PPCC) (Shin et al., 2012). Even though chi-square usually requires a lot of population to identify the best fit, in this research, it is adopted as it is easier to compute and makes no assumptions about the distribution of the population. Other tests can assume certain characteristics about the distribution of the population, such as normality, etc. As the number of case studies available for determining the distribution of the various work packages is limited to nine, Sweco should gather more relative information from past replacement projects and accurately determine the best-fit distributions. Nevertheless, it is valuable in this dissertation to present the process of determining the most suitable distribution.

The sample for which the probability distribution is investigated is the percentage that expresses the contribution for each respective work package in the total cost and all the available case studies. The entire sample is presented in Table 22, located in Appendix D1.2.

Once the sample has been defined, the goodness of fit test is conducted, and each distribution with its parameters for all work packages is presented in Table 12. Also, in the appendix, the respective graphs are shown.

Table 12: Best-fit distribution per work package and respective parameters

Work package	Distribution	Distribution parameters			
		P5	P95	μ	σ
Preparations	Triangular	1.20%	10.10%	5%	2.7%
Clearance works	Uniform	5.50%	7.49%	6.49%	0.71%
Earthworks	Triangular	1.40%	8.19%	3.99%	1.8%
Foundation	Uniform	3.30%	12.50%	7.9%	3.3%
Substructure	Normal	2.69%	23.04%	10%	6.1%
Superstructure	Triangular	17.81%	54.80%	40%	10%
Piping & Drainage	Lognormal	0.00%	2.69%	0.66%	0.96%
Terrain design & Shore	Triangular	0.18%	5.95%	2.9%	1.9%
General works	Triangular	1.53%	13.15%	5.00%	3.90%
Tail posts	Triangular	4.33%	19.02%	11%	4.7%

By using both the distribution parameters and the deterministic cost of each work package, the project's specific probabilistic parameters that are needed for running a Monte Carlo simulation can be determined. For project 4, these have been calculated and presented in Table 13. The values P5, P95, μ, and σ for each work package are estimated by multiplying the total deterministic cost estimated in the previous step by the values (percentages) in Table 12.

Table 13: Distribution parameters for each work package expressed in euros

Work package	Distribution	Distribution parameters				
		P5	Most likely	P95	μ	σ
Preparations	Triangular	€ 218.12	€ 12,750.00	€ 18,206.67	-	-
Clearance works	Uniform	€ 9,103.34	€ 20,950.00	€ 32,772.01	-	-
Earthworks	Triangular	€ 0	€ 8,000.00	€ 14,929.47	-	-
Foundation	Uniform	€ 2,421.49	€ 10,037.50	€ 22,758.34	-	-
Substructure	Normal	€ 2,403.28	€ 12,200.00	€ 41,875.34	€ 17,842.54	6.1%
Superstructure	Triangular	€ 32,407.88	€ 54,962.50	€ 99,772.56	-	-
Piping & Drainage	Lognormal	€ 0	€ 3,500.00	€ 4,879.39	€ 5,826.13	€ 4,187.53

Terrain design & Shore	Triangular	€ 327.72	€ 1,340.00	€ 10,741.94	-	-
General works	Triangular	€ 2,792.90	€ 16,789.14	€ 29,130.67	-	-
Tail posts	Triangular	€ 4,187.53	€ 41,537.58	€ 50,978.68	-	-

As all the project's specific inputs for conducting the probabilistic assessment have been defined, the next step in the proposed framework is to run a Monte Carlo Simulation. The number of iterations used for running the simulation is 1000, and the software is called @Risk, an extension of Microsoft Excel. All the results from the Monte Carlo Simulation are presented in Table 14.

Based on the analysis results shown both in Tables 14 and 15, the probabilistic estimation of replacement costs led to a more reliable forecast overall. In Class 3 assessment with the current practices, the deviation of the estimated costs from the more detailed estimates were- -34%. In contrast, a -27% cost overrun was observed with the proposed probabilistic assessment.

Table 14: Results of the probabilistic assessment for Project 4

Min. Replacement Cost	Most likely Replacement cost	Max. Replacement cost
€53,862	€190,220	€326,045
Distribution		

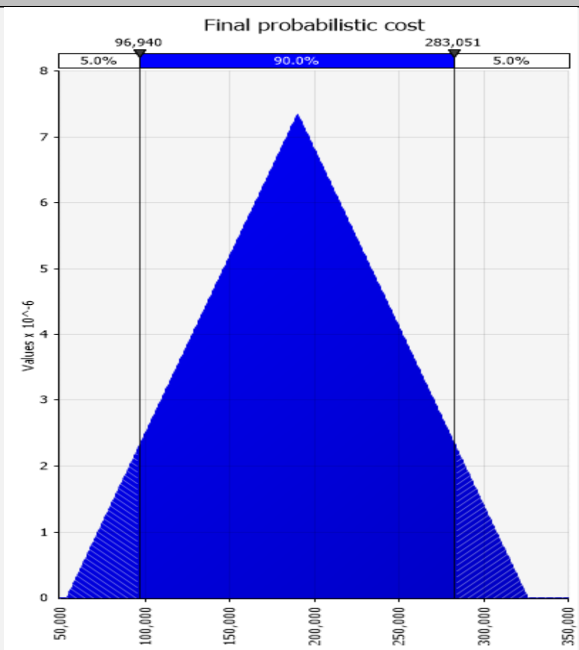


Table 15: Comparison between the accuracy of current practices and probabilistic assessment.

	Cost estimated with the current practices	Cost estimated with the proposed model	Actual cost (Class 1)
	€ 182,067	€ 190,220	€ 242,400
Deviation from the actual cost	-34%	**-27%**	

5.2.2. Second building block

In the proposed framework, the probabilistic replacement cost (€ 190,220.71) represents the output of the first building block. In the second building block, this output is used as an input to get an insight into the extent to which the price escalation affects the estimated costs. The second building block starts with a decision gate in which it is investigated whether the expected year of work initiation exceeds the defined critical year T_C. The year the estimate was conducted for the specific case study was 2016. As no information about the year of work's execution is available, the replacement would be executed in 2021. For bridge replacement projects, the annual escalation rate has been estimated in equation (1) and equals 1.81% per year. It is suggested that the critical year after which the price escalation effect would significantly impact the estimated costs is T_C= 5 years. This means that the commencement of replacement works (after six years) is later than the critical year (5 years). Therefore, the price escalation effect needs to be incorporated into the estimation.

Based on the proposed framework, the first step for incorporating the price escalation effect into the estimation is to determine the historical data used for forecasting the evolution of costs with the Geometric Brownian Motion. As the case study concerns a bridge replacement project, the historical data used are the ones that have already been presented in Table 23 in Appendix E1. 1. The usage of GBM for forecasting the costs requires obtaining the quarterly drifts and the volatilities from the historical data. The procedure for obtaining them is presented in Table 23 in Appendix E1.1. The ultimate parameters needed for using the GBM have been estimated based on the procedure described and are shown in Table 16.

Table 16: GBM input parameters

GBM parameters	
Initial bridge replacement cost (C_0)	€ 190,220
Year of estimation	2016
Year of replacement execution	2021
Drift per quarter	0.0053
Volatility per quarter	0.0139
Time step (quarterly)	3 months (quarterly)

By following the procedure described in the previous section and applying the equation (4). All the respective costs over the years can be estimated. As the model uses random shock to forecast the costs, multiple analysis of the stochastic model is conducted. In total for this case study, 10 iterations were executed, and all the respective graphs are presented in Table 25 in the Appendix F2. Also, an illustration of one analysis that indicates the evolution of costs over the years is shown in Figure 17.

From the results of all iterations which are presented in, the estimated costs of € 190,220.71 estimated on April 2016 would have been raised to € 330,143 in October 2021 and up to € 496,637 in July 2026. Table 24 located in Appendix E1.2 and structured in Chapter 4, is used to validate these results. This Tables illustrates the evolution of replacement costs for all case studies examined, and the costs were estimated based on the respective indices of each year. Based on that table, for Project 4, the replacement cost in 2021 has been forecasted to be €

295,694€. Comparing this with the € 330,143.00 provided by the application of GBM, it seems that the model provided a satisfactory indication.

Table 17: Different scenarios of replacement cost evolution through years 2021 & 2026

Iteration	Evolution of costs in 2021	Evolution of costs in 2026
First iteration	€ 339,062	€ 457,039
Second iteration	€ 343,787	€ 501,607
Third iteration	€ 340,176	€ 479,890
Fourth iteration	€ 316,447	€ 505,725
Fifth iteration	€ 329,913	€ 552,398
Sixth iteration	€ 342,325	€ 520,555
Seventh iteration	€ 328,868	€ 474,919
Eighth iteration	€ 320,019	€ 514,127
Ninth iteration	€ 311,425	€ 494,585
Tenth iteration	€ 274,054	€ 465,515
Average	**€ 330.143**	**€ 496,637**

For further validation, all these results provided by the proposed framework were assessed by two experts via semi-structured interviews. The interviewees are an Asset Manager with more than ten years of experience and a Cost expert with more than 15 years of experience. The full transcript of both interviews can be found in the Appendix F:3 however here the highlighted information is presented. Based on their viewpoint, the framework provided better results than the current practices and a future indication that is not incorporated in their practices. Also, they mentioned that even though probabilistic assessments require time, they can indeed provide more accurate results. Also, as the results are illustrated in the form of a range, they can be very well communicated with the client, providing more transparent information. However, they both pointed out that further validation is needed in two directions. First of all, the model needs to be tested to more bridge replacement projects in order to reassure its validity. Also, the model needs to be applied to other type of assets such as municipal roads, tunnels etc.

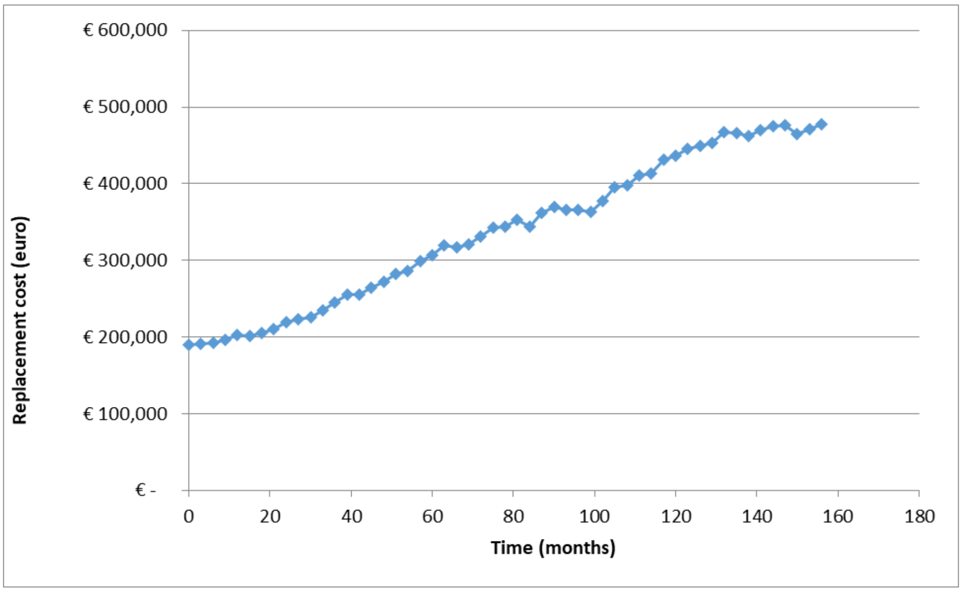


Figure 17: Forecast of the replacement cost evolution over the years for Project 4

5.3. Chapter Summary

Having acquired a solid realization of the problem, a probable solution to deal with it was investigated in this chapter. The conceptual framework of Figure 9 describes two particular characteristics of replacement projects that further escalates the presence of budget overruns in their preliminary estimations. For that reason, the process of seeking a solution to deal with the general problem was shifted to searching for a way to target the cost overrun factors resulting from these two characteristics. The result of the process was a second framework that consisted of two building blocks. Each of them intended to target the two different subsets of factors attributed to the replacement budget's specific characteristics. In the first building block, it is described that when available data are available for preliminary estimating the costs with Class 5 estimates, this method is preferred as it is easier, faster and can lead to relatively accurate results. When these data are lacking, a probabilistic assessment would be conducted as it can better capture the uncertainties included in the early phases in which replacement budgets are usually structured. A second component of the framework is also needed to have a more reliable preliminary cost indication as an output from this first building block. This should be intended for dealing with the factors related to the long-term asset planning process in which replacement budgets are structured. This research proposed that historical prices and a stochastic model can be used to deal with the price (de) escalation effect usually present in these types of projects.

Once the framework was developed in the first part of this chapter, then in the following one, the framework was validated by applying it to a single case study and obtaining expert elicitation. The results from its application to the case study and the opinion of experts indicated that the framework could provide better results than the current practices. More specifically, except for the more reliable forecast, the framework provided two significant and additional contributions. The first one is associated with the ability of the framework to offer a range of costs in the case of probabilistic assessment instead of a single value resulting from the current practices. The second contribution of the model is the ability to provide a projection of costs that is currently missing from the estimates. This can facilitate the communication between the asset managers and the clients by making it more transparent.

6. Research conclusions

This whole dissertation was initiated to deal with a particular problem observed both in the industry and the scientific community. It is structured in two phases. The first phase resembles an effort to understand further the cost overrun phenomenon in replacement projects observed in the construction industry. The second phase reflects an effort to limit this issue by providing a more structured way to assess the costs by considering the specific characteristics that influence the accuracy of the cost estimation process in replacement projects. Both research phases have been designed in such a way that eventually their outputs can lead to answering the main research question which has been formulated in the beginning of this research as:

"How can the current practices of estimating the replacement budget for an engineering asset become better with respect to the accuracy of the cost indication that they provide?

This Chapter concludes all the findings of this research and helps verify whether the goals of this research set in Chapter 1 have been accomplished.

6.1. First phase of the research

As mentioned, in the first part of the research, there was an effort to understand the specific's problem context. For that purpose, the first phase of the research was again decomposed in two stages. In the first one, a theoretical analysis of the problem was conducted, while in the second step, the problem was analyzed on a practical level.

In the beginning of the first phase and the theoretical analysis there was an effort to identify the various factors contributing to the phenomenon and are observed in the literature. As little or no scientific information was available related to the budget exceedance issue in replacement projects, all the literature gathered was concerning factors contributing to cost overruns in new infrastructure projects. All the identified factors were grouped in four broader explanations category namely political, psychological, economic and technical.

In the next step, all the factors identified and grouped into the four categories were specified and analyzed for the particular case of replacement projects. It was concluded that even though for new infrastructure projects, political explanations might highly contribute to to the cost overrun issue, in the case of replacements these factors are considered to have less influence. The main rationale behind this assumption was that usually replacement is not part of any decision-making process and therefore all the respective political factors associated with that process present lower applicability to the phenomenon. With respect to economic, psychological and technical factors these are consider equally important both for new infrastructure projects and replacements. However, the first two were left out of this scope's research due to limited time frame and there was a demarcation in this research to identify the technical factors associated with the cost overrun issue in replacement projects.

The theoretical analysis indicated that, there are two particular characteristics of replacement projects that affect the accuracy of their budget estimation. The first is in connection with the preliminary nature of their estimations, meaning that these are usually conducted in early phases when little information is available and can be used as an input for the assessment. This characteristic is associated with many factors that affect the accuracy of cost assessments, such as the ones related to the limited level of project definition and the methods used in these early assessments. The second characteristic is related to the long-term asset planning process in which the replacement budgets are usually structured. Many replacement budgets are structured when the asset is first constructed, while the replacement works are most likely to be initiated at the end of the asset's service life. In the meantime, many changes can happen, such as increasing prices for materials, equipment, personnel, and labor. Therefore, the initially estimated budget in the long-term asset planning process can strongly vary from the one that is needed when the actual replacement works are conducted. The identification of the various technical factors led in developing a first conceptual framework which was presented in Figure 9 of Chapter 3 and aims at explaining to a certain extent the context of this particular issue in the case of reconstruction projects.

Having identified in the theoretical analysis the various technical factors that can lead to budget overruns in replacement projects, all these factors positioned in the conceptual framework of Figure 9 were tested on a practical level. This was done by conducting a multiple case study analysis in which nine past bridge replacement projects were examined. From the analysis it was concluded that, the limited level of project definition that exists when conducting preliminary cost assessments significantly affects the accuracy of the estimations. More specifically, there was a significant deviation between the costs estimated in Class 3 and Class 1 assessments. This was mainly attributed to the difficulty in predicting the exact quantities and prices in the preliminary Class 3 evaluations. Align with that; it was observed that this difficulty of predicting the exact quantities and prices in determining the replacement budgets was further escalated due to the deterministic methods used in the early estimation phases. Even though probabilistic assessments are generally suggested for preliminary estimating costs, this was not observed in practice as only deterministic techniques are used for estimating the costs for small-scale replacement projects.

Also, when referring to Class 5 estimates, which are very rough, it was observed that in the deterministic methods, the inputs used were not reliable in some instances. More particularly, for bridge replacement projects, it was observed that the current unit prices used for the assessments provide relatively accurate results for longer bridges ($\mathrm{L} \gg \mathrm{W}$) while this is not the case for the wider ones ($L \approx w$)

Besides the practical analysis conducted to get an insight into the effect of the factors associated with the first characteristic of replacement budgets, a practical analysis was also undertaken to realize the extent to which the price (de) escalation affects the accuracy of replacement budgets. By examining historical price indices related to bridge construction and calculating the annual escalation rate, it was observed that the initially estimated costs would have increased significantly over the years. More particularly, it was observed that the initially estimated costs would have been raised by 1.81% every year, leading to approximately a 36% if a replacement had been actually initiated 20 years later.

This twofold analysis contributed to setting the specific problem context and answering the several sub-research questions defined in the first Chapter. Also, overall, it helped achieve the first objective of this research, which was to further understand the cost overrun phenomenon observed in replacement projects.

6.2. Second phase of the research

All the analyses conducted in the first phase of the research highlighted the importance of dealing with all the factors that negatively affect the accuracy of replacement budget estimations. The process of seeking a solution to a particular problem resulted in developing an integrated framework presented in Figure 16. The proposed framework consists of two building blocks, each of them intended to deal with the two respective characteristics of replacement budgets. Both building blocks describe particular processes that need to be followed when determining replacement costs.

More particularly, in the first building block, the framework indicates that when reliable data exists for estimating the replacement costs with deterministic Class 5 assessments, this should be preferred as it is fast, easy to use, and in some instances, can lead to accurate forecasts. In contrast, in the absence of data for Class 5 estimates, a probabilistic Class 3 or Class 4 assessment needs to be executed in a work package or activity level. The result from either the one or the other sub-process indicates costs at the specific point of time in the assessment is conducted.

If the execution of replacement costs is initiated after certain years of the initial estimation, the price escalation effect needs to be incorporated into the estimated costs as this would have a significant impact if ignored. This is done in the second building block of the framework in which historical price indices and a stochastic model are used to forecast future costs. More specifically, historical price indices from the Dutch CBS open-data space were mentioned as suitable for the forecast for predicting the costs. Apart from the indices, the proposed stochastic model is the Geometric Brownian motion (GBM). Using both, with the process described in the framework, an indication of future costs can be acquired.

Once the entire framework was structured, in Chapter 5, this was also validated by applying it to a single case study and by interviewing two experts. The validation process indicated that after following the process included in the first building block of the framework, better cost results in terms of accuracy were provided than with the current practices. Further to that, the probabilistic cost assessment indicated by the model provided an additional feature which was missing from the current practices and refers to the possibility of having a cost indication expressed in a form of range. This is done by obtaining from the probabilistic assessment a low and a high value with respect to the cost result

Following the described probabilistic process, another additional feature that is added to the cost estimation process, concerns the possibility of forecasting replacement costs at a specific future point when a probable execution of replacement works would commence. Based on the validation the stochastic model was capable of providing a relatively sufficient future cost indication and a specific range that expresses variation between the average forecasted replacement cost.

Overall, the validation process indicated that the proposed framework could lead to more reliable preliminary cost estimations for replacement projects than the current practices do and provide a certain indication related to the evolution of replacement costs over the years. Consequently, its application could potentially lead in providing better cost indications and reduce the extent of cost overruns in replacement projects.

7. Discussion, limitations, and recommendations

This final chapter of the research is used for critically reflecting on the whole dissertation thesis by making explicit the various implications and limitations that accompany this research. At the end of this chapter, probable future steps for further research are suggested, which can better enrich the scientific knowledge about this particular topic and further reduce the knowledge gap.

7.1. Discussion

In the whole research, there are some aspects in which various assumptions were made and could probably influence, to a certain level, the research outcome. Thus, it is worth mentioning the most crucial ones and making them more explicit.

First of all, as mentioned in the theoretical chapter, little or no literature was available in connection with the budget exceedance issue in replacement projects. For that reason, and in order to explain the phenomenon, the various factors that contribute to the similar issue for new infrastructure projects were assessed in order to validate their applicability to reconstruction projects. Due to the limited timeframe of this research, there was a demarcation only on the technical factors; others, such as political, phycological and economic, were not examined in detail.

Based on the argumentation of this research, the political factors contribute less to the cost overrun issue in replacement projects than the other explanations, as these kinds of projects are usually not part of any decision-making process. However, with regard to the psychological and economic factors, they were left out of scope due to the limited timeframe of this research. Nevertheless, their contribution to the issue might be equally significant to the technical factors identified and analyzed in this research. Therefore, it would be valuable in future research to delve more deeply into these and investigate their contribution.

Also, in the case of technical factors, there was a particular focus on the factors connected with the two special characteristics of replacement projects. Therefore, many other technical factors which could probably have a significant contribution to the issue have not been incorporated into the analysis.

A second implication of the research is that, in the practical analysis and in order to get an indication of the cost overruns in replacement projects, the Class 1 assessments were used for comparisons due to the lack of data regarding the actual replacement costs. This assumption was based on the fact that the actual costs are usually relatively higher than the final estimated costs; thus, the actual cost overrun volume could be the same or even higher than the one estimated in this research. However, this is just an assumption, and it has quite some subjectivity.

Another specific point of attention is related to the stochastic model selected for forecasting future replacement costs. In the present research the Geometric Brownian motion was selected as it is relatively straightforward and only a few inputs are needed. However, there are many other stochastic models that can be used, the selection of the most prominent one varies per case. Other well-known forecasting methods are the Autoregressive Integrated Moving Average (ARIMA), Mean-Reverting Jump-Diffusion (MRJD), ARCH/GARCH, Bayesian belief networks, multi-factor price forecasting methods and many more. However, these more advanced methods need detailed data to provide relatively accurate predictions. In that case, and in all cases when there is a lack of data, the GBM should be preferred.

7.2. Research limitations

Apart from the various assumptions in this research, a few limitations might influence the outcome of this research to a certain extent.

First of all, one of the most critical limitations of this research concerns the number of available case studies used. Nine past bridge replacement projects were selected for conducting the research analysis and developing the model, which can be considered a limited number of cases that do not reassure the validity of the results. With respect to the results, the limited number of case studies for considering the model might have various implications. A crucial one is that it might be the case that for other past bridge replacement projects, the cost indications provided by using the current practices could lead to fair results without the presence of significant cost overruns observed in the particular sample examined.

Also, as only past bridge replacement projects were examined, there is a certain doubt regarding the cross-case applicability of the findings to other types of assets such as roads, tunnels etc. This means that it might be the case that the developed model not to be readily applicable to different asset types, and significant modifications might be needed. A reason for that, for example, might be the difficulty in decomposing the replacement costs in common work packages. This would affect the applicability of the model's first part, referring to the probabilistic cost assessment.

Another significant limitation concerns the availability of cost estimates per case study. In most cases, Class 5 and Class 1 cost assessments were available, while only for a few Classes 3 estimates were also present. It would be very valuable for this research if more cost assessments such as Class 4 and Class 2 were available in order to get a better snapshot of the degree of budget exceedance in all preliminary cost estimation phases.

An additional limitation concerns the adoption of the cost classification system from the AACE. This was done by collecting data regarding the cost expectations of various public entities and examining the respective practices within a single organization. This, of course, might imply that different organizations might conduct cost assessments in different phases and with different methods. Therefore, adopting this classification might not be applicable in their cases. In that direction, future research which examines the different phases, methods and respective levels of accuracy of cost estimations in various construction organizations would be considered extremely valuable.

A fourth limitation of this research concerns the definition of the best-fit distribution for the work packages described in the first building block of the model. The best fit distribution as defined in this research is based on the chi-square test. However, only the work packages included in the nine case studies were used to define the best fit distribution for every work package, and its outcome should be viewed very critically. Chi-square usually requires a high volume of data for accurately determining the ideal distribution, which was lacking in this research. Nevertheless, in this research, it was valuable to describe the process of defining the best fit distribution.

A fifth limitation of this research concerns the usage of historical prices and a stochastic model to forecast the evolution of costs. Even though this technique has been widely applied in the finance sector, the results should be seen with extreme care. This technique provides an indication of the future costs but in neither case this result should be considered 100% reliable.

A final and a more general limitation concerns the developed model for dealing with cost overruns in replacement projects. The validation of the model applied to a single case study indicated that the model provided better results with respect to their accuracy than the existing practices. However, the model was used in a single case study, and further application is needed in order to reassure the model's validity. Also, with respect to the model, the validation by two experts indicated that the model could provide better results; however, concerns were raised regarding its applicability in their everyday practices. An important drawback they highlighted is that a probabilistic technique could significantly increase the time for the estimation. Also, they stressed that such a model requires a significant amount of reference data for conducting the cost assessments, which is currently missing from their organization.

7.3. Recommendations

In this final Sub-chapter, it is valuable to present some recommendations for further research related to the specific content of this research. There are various directions in which further research can be conducted and add additional knowledge in understanding the budget overruns in construction projects and help deal with them.

First of all, as has also been mentioned in the previous sub-chapter of limitations, this research was conducted in collaboration with Sweco, a leading engineering organization with a presence in various countries across Europe. The whole practical analysis of the issue was done based on data extracted from its employees and previous projects. Therefore, some results such as included but not limited to the different phases in which cost estimations are conducted, the methods used for conducting the estimates, and the level of cost overruns that might influence the outputs of the research. Therefore, it is worth investigating the validity of some respective outcomes within other organizations within the construction industry in the Netherlands and abroad. In that way, the validity of the results will be reassured, and inputs will be added to the source of knowledge.

In addition, as mentioned, the number of case studies examined in this research can be considered insufficient as only nine past bridge replacements were examined. Further research can review more case studies to obtain a more comprehensive view of the level at which replacement budgets are exceeded. Also, a valuable contribution to further research could be examining replacement projects concerning different municipal asset types such as roads, tunnels etc. In addition, in another probable research, other factors that contribute to the issue and have not been investigated in depth here could be examined.

Except for the direction that can be followed, which is connected with the further examination of the issue, another direction could be related to the respected model itself. More specifically, in another research, additional validation of the developed model can be conducted by applying it to more case studies and different asset types. Also, for another study, it would be valuable if the best fit distributions for various work packages included in the budget assessments are further investigated by examining more case studies.

Also, it is worth researching how stochastic models other than the GBM, such as those mentioned in the discussion section, could function in forecasting replacement costs by using the proposed model. Finally, in the proposed model, it is mentioned that there is a particular assumption when determining the critical year after which the price escalation significantly affects the estimated budgets. It is worth investigating more in-depth the different perspectives about this aspect and helps determine the specific point of time after price escalation becomes critical.

All in all, multiple paths can be followed to investigate further the extent of the issue in replacement projects, the factors that contribute to that and possible ways to reduce its impact. This research constitutes a small step in that direction. Hopefully, more research will focus on targeting the cost overrun issue not only in new infrastructure projects but also for the replacement ones, which will be increased in the upcoming years.

Appendix A – Description of case studies

Project number	Description	
Project 1	The project concerns a concrete municipal bridge which is located in the Friesland Province. The bridge has a span of 6.7m and a width of 4.5m. The bridge operates as a road bridge and is part of a municipal road.	
Project 2	The project concerns a concrete municipal bridge which is located in the Friesland Province. The bridge has a span of 12.3m and a width of 4.5. The bridge is mainly intended for pedestrians and bicycles.	
Project 3	The project concerns a concrete municipal bridge which is located in the Friesland Province. The bridge has a span of 13m and a width of 5.5 m The bridge is mainly intended for pedestrians and bicycles.	
Project 4	The project concerns a concrete road bridge which is located in the Friesland Province. The bridge has a span of 6.7m and a width of 5.2 m. The bridge is mainly intended for vehicles crossing	
Project 5	The project concerns a concrete municipal	

	bridge which is located in North Holland. The bridge has a span of 17.2m and a width of 7.2 m The bridge is mainly intended for pedestrians and bicycles.	
Project 6	The project concerns a concrete municipal bridge which is located in North Holland. The bridge has a span of 17.2m and a width of 7.2 m The bridge is mainly intended for pedestrians and bicycles.	
Project 7	The project concerns a concrete municipal bridge which is located in North Holland. The bridge has a span of 17.2m and a width of 7.6 m The bridge is mainly intended for pedestrians and bicycles.	
Project 8	The project concerns a concrete movable bridge which is located in the province of Friesland. The bridge has a span of 10.5m and a width of 8 m. The bridge operates as a road bridge and is part of a municipal road.	
Project 9	The project concerns a steel movable bridge which is located in the province of Friesland. The bridge has a span of 7.1m and a width of 3 m. The bridge operates as a road bridge and is part of a municipal road.	 

Appendix B – Archival documents from public entities

https://gemeente.groningen.nl/sites/default/files/Kaders-en-eisen-kostenramingen.pdf

https://www.prorail.nl/siteassets/homepage/samenwerken/leveranciers/documenten/brochure-leidraad-kostenramingen.pdf

https://www.montferland.info/sites/default/files/2020-04/SSK%20raming%20incl.%20bijlagen%20v5.0%20def.%208%20april%202019.pdf

Table 18: Classification of estimates by public entities in the Netherlands.

<table>
<tr><th>Public entity</th><th colspan="6">Classification of estimates</th></tr>
<tr><td>AACE</td><td>Class 5</td><td>Class 4</td><td colspan="2">Class 3</td><td>Class 2</td><td>Class 1</td></tr>
<tr><td>Public entity 1</td><td>Research estimate (ON)</td><td>Sketch design (SO)</td><td colspan="2">Preliminary draft (VO)</td><td>Final design (DO)</td><td>-</td></tr>
<tr><td>Public entity 2</td><td>Exploration study (ON)</td><td>Sketch design (SO)</td><td colspan="2">Preliminary design (SO)</td><td>Final design (DO)</td><td>Contract estimate</td></tr>
<tr><td>Public entity 3</td><td>Sketch design</td><td>Preliminary research</td><td colspan="2">Preliminary draft</td><td>Final design</td><td>Contract estimate</td></tr>
<tr><td>Public entity 4</td><td colspan="2">Exploration (SO)</td><td colspan="2">Plan study (VO)</td><td>Plan elaboration (DO)</td><td>-</td></tr>
<tr><td>Public entity 5</td><td>-</td><td>Sketch design</td><td colspan="2">Preliminary Design</td><td>Final Design</td><td>Contract estimate</td></tr>
<tr><td>Public entity 6</td><td>Comparison</td><td>Sketch design</td><td>Prototype</td><td>Preliminary design</td><td>Final design</td><td>Contract estimate</td></tr>
<tr><td>Public entity 7</td><td>Study phase</td><td>Status report</td><td colspan="3">Pre-contractual</td><td>Contract estimate</td></tr>
</table>

Table 19: Expected level of accuracy per estimate for different public entities in the Netherlands.

<table>
<tr><th>Public entity</th><th colspan="6">Expected levels of accuracy per estimate</th></tr>
<tr><td>ACCE</td><td>L: -20% to -50
H: +30% to +100%</td><td>L: -15% to -30%
H: +20% to +50%</td><td colspan="2">L: -10% to -20%
H: +10% to +30%</td><td>L: -5% to -15%
H: +5% to +20%</td><td>L: -3% to -10%
H: +3% to +15%</td></tr>
<tr><td>Public entity 1</td><td>L: -45%, H: +45%</td><td>L: -25% to -35%
H: +25% to +35%</td><td colspan="2">L: -25%, H: +25%</td><td>L: -10%, H: +10%</td><td>-</td></tr>
<tr><td>Public entity 2</td><td>L: -40%, H: +40%</td><td>L: -30%, H: +30%</td><td colspan="2">L: -25%, H: +25%</td><td>20%</td><td>L: -10% H: +10%</td></tr>
<tr><td>Public entity 3</td><td>L: -25%, H: +25%</td><td>L: -20%, H: +20%</td><td colspan="2">L: -15%, H: +15%</td><td>L: -10%, H: +10%</td><td>Not applicable</td></tr>
<tr><td>Public entity 4</td><td colspan="2">L: -25% to -40%
H: +25% to +40%</td><td colspan="2">L: -20% to -35%
H: +20% to +35%</td><td>L: -10% to -25%
H: +20% to +35%</td><td>-</td></tr>
<tr><td>Public entity 5</td><td colspan="2">L: -40%, H: +30%</td><td colspan="2">L: -30%, H: +20%</td><td>L: -15%, H: +10%</td><td>L: -5%, H: +5%</td></tr>
<tr><td>Public entity 6</td><td>L: -30%, H: +30%</td><td>L: -15% to -25%
H: +15% to +25%</td><td>L: -20%
H: +20%</td><td>L: -15%
H: +15%</td><td>L: -10%, H: +10%</td><td>n.v.t</td></tr>
<tr><td>Public entity 7</td><td>L: -30%, H: +30%</td><td>L: -20%, H: +20%</td><td colspan="3">L: -15%, H: +15%</td><td>L: -10% H: +10%</td></tr>
</table>

Appendix C – Transcript of interview with Sweco cost estimator

Table 20: Interview details

Interview details	
Date of Interview:	18-02-2022
Interviewee:	Anne Bonthuis, Cost expert Sweco Nederland BV.
Contact information:	anne.bonthuis@sweco.nl
Interviewer:	Konstantinos Krousoratis
Contact information:	K.krousoratis@tudelft.nl
Location of interview:	Online (Microsoft Teams)
List of Acronyms:	AB= Anne Bonthuis, IN= Interviewer

<u>Start of interview:</u>

IN: What are the different phases in which you conduct cost estimates in Sweco?

AB: Well, it depends a little bit on the client, but we usually have SO -, VO-, DO – Definitiet ontwerp and Bestek ontwerp, so in fact, there are four phases. However, when working with clients like RWS, the cost estimation phases are fewer because they usually ask the contractors to do more design work.

IN: In each phase, what is the project definition, and what inputs do you use for the estimations?

AB: Well, it strongly varies from project to project; however, usually in the SO phase, you typically have the length, the width, the type of object, and sometimes you have some drawings, but they don't have so much detail. Also, in that phase, it depends on the book price that we have. When we have good data about an object, let's say that we replaced some bridges in the past and use some of these to define the cost for the project examined if we don't have good data, we break it down into activities. So, in general, we use m2 prices per object in the SO phase.

IN: Well, wo in the SO phase, you primarily use rough drawings or essential characteristics of the asset and then unit prices per m2. In VO and DO?

AB: In VO, we have better drawings, and we break down the cost into activities about which we have information. A source for this activity costs can be GWW, CROW, etc. In DO, we do mostly the same as VO, but we have the final design and can better estimate the cost of activities.

IN: Alright, what methods do you use to estimate the costs for each phase?

AB: In all phases, we mostly do deterministic estimates. We use probabilistic forecast only for more complex projects and when the client asks for it. For example, RWS and Pro rail ask probabilistic estimates in all project phases.

IN: They ask even for probabilistic even in the final pre-design phases? For example, in the DO phase?

AB: Yes, yes, they ask even for these phases, and they have different standard deviation requirements for each stage.

IN: Ok! One last question. What is the expected accuracy for each cost estimation phase?

AB: Well... It’s hard to say! I know that it usually depends on the client and their expectations, so there is no general rule.

Appendix D – Contribution of work packages based on case studies.

Appendix D:1.1 – Contribution of work packages in two different cost estimation phases and their respective deviation.

Table 21: Contribution of work packages to the total cost for Projects 1, 4, 8 & 9 in Class 3 & 1 cost assessments

	Project 1			Project 4			Project 8			Project 9		
	Class 3	Class 1	Dev	Class 3	Class 1	**Dev**	Class 3	Class 1	**Dev**	Class 3	Class 1	Dev
Foundation	9.7%	13.9%	**-43.4%**	5.0%	10.0%	**-102%**	1.1%	1.5%	**-33.8%**	1.1%	1.3%	**-19%**
Substructure	13.4%	23.0%	**-71.7%**	6.0%	12.8%	**-113%**	0.9%	1.6%	**-33.8%**	1%	1.4%	**-19%**
Superstructure	15.2%	17.8%	**-17.3%**	27.2%	37.5%	**-38%**	69%	50%	**28.6%**	40.7%	34%	**16%**
Preparations	9.5%	9.5%	**0.5%**	16.2%	1.2%	**93%**	8%	24%	**-200%**	2.2%	1.7%	**26%**
Earthworks	2.9%	1.4%	**52.0%**	4.0%	2.3%	**43%**	0%	0%	**0%**	0%	0%	**0%**
Piping& Drainage	2.4%	2.7%	**-10.2%**	1.7%	0.8%	**51%**	0%	0%	**0%**	0.8%	1%	**-29%**
Clearance works	9.3%	5.5%	**41.1%**	10.4%	7.5%	**28%**	1%	1.2%	**-26.8%**	1.7%	6.3%	**-271%**
Terrain design & shore	5.8%	4.2%	**28.4%**	0.7%	0.2%	**73%**	1.2%	1.1%	**15.2%**	0.1%	0.2%	**-84%**
General work	13.9%	6.2%	**55.6%**	8.3%	9.2%	**-11%**	10%	2%	**74.5%**	12.2%	13.2%	**-7%**
Tail posts	17.9%	16.0%	**10.9%**	20.6%	18.4%	**11%**	13%	8%	**43.6%**	13.4%	2.3%	**83%**
Bridge Movement Mechanism	-	-	-	-	-	-	3%	13%	**-327.1%**	27.7%	40%	**-45%**

Appendix D:1.2 – Final estimated contribution of work packages in all projects

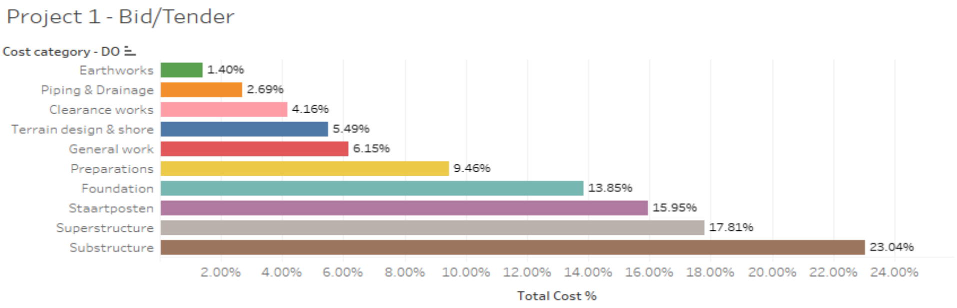


Figure 18: Project 1 - Class 1 Estimate

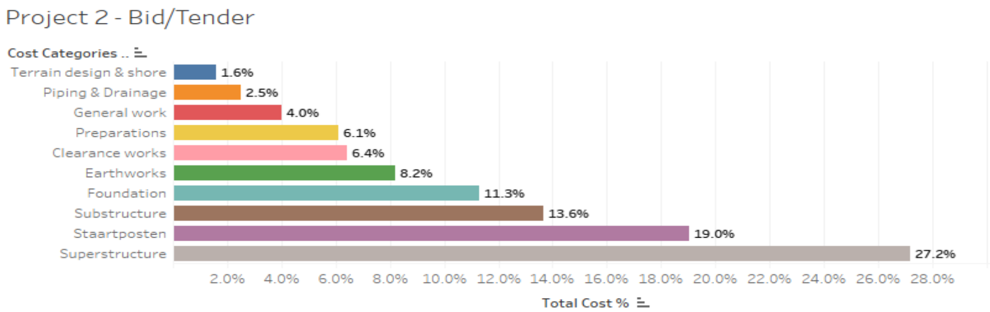


Figure 19: Project 2 - Class 1 Estimate

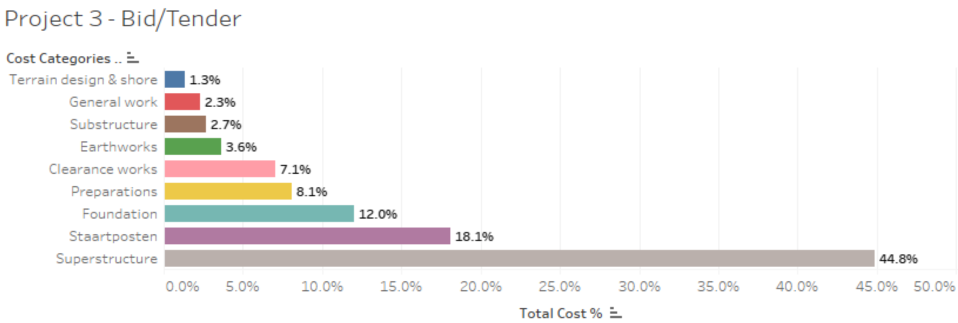


Figure 20: Project 3 - Class 1 Estimate

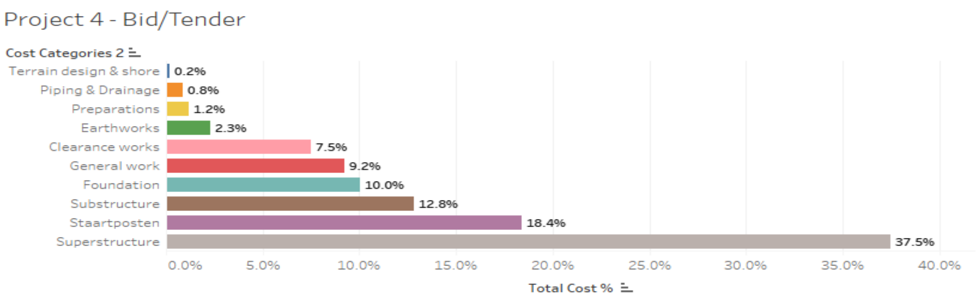


Figure 21: Project 4 - Class 1 Estimate

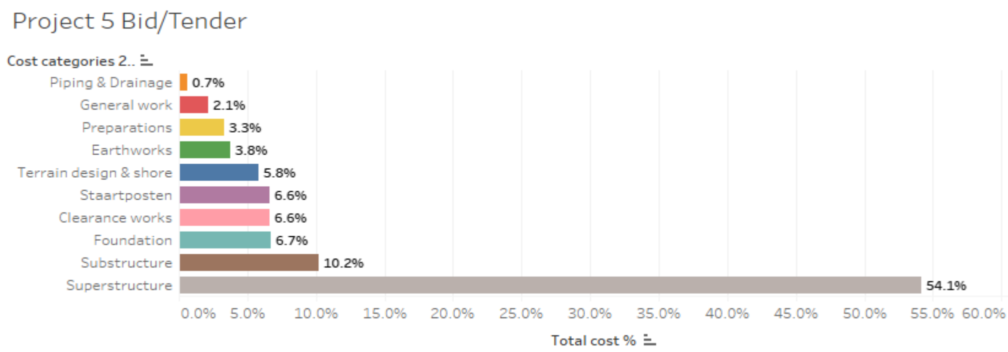


Figure 22: Project 5 - Class 1 Estimate

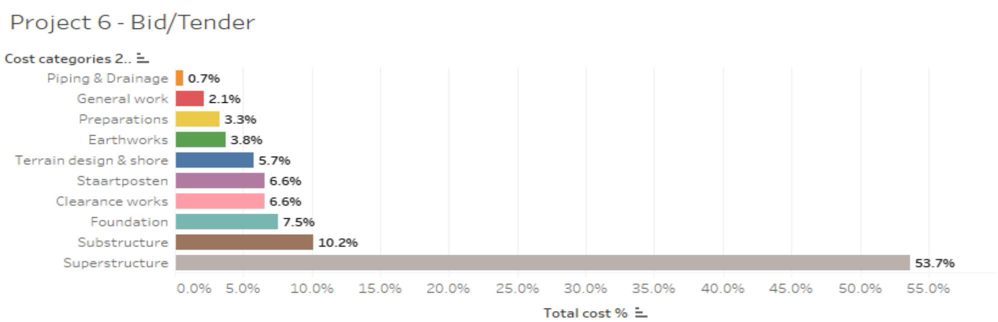


Figure 23: Project 6 - Class 1 Estimate

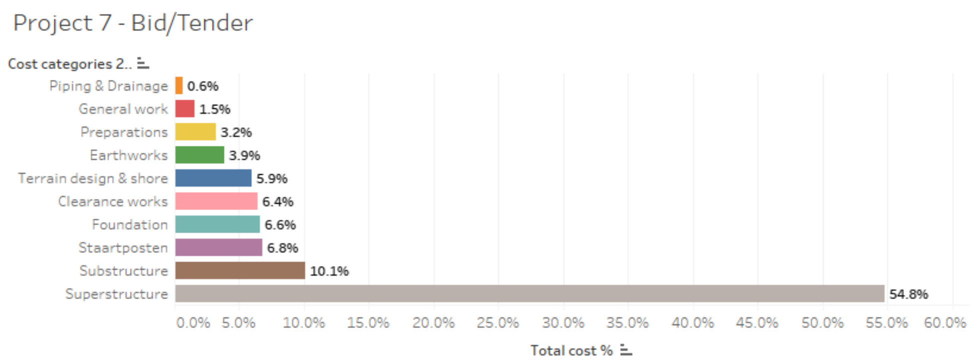


Figure 24: Project 7 - Class 1 Estimate

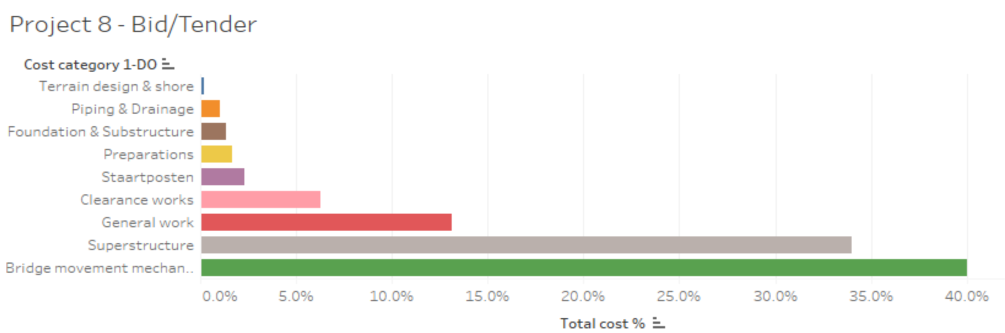


Figure 25: Project 8 - Class 1 Estimate

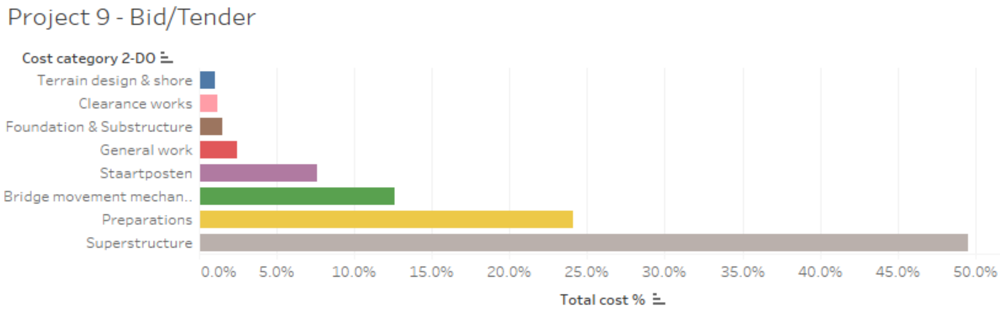


Figure 26: Project 9 - Class 1 Estimate

Appendix D:1.3 – Contribution of Superstructure to the total cost in the examined case studies

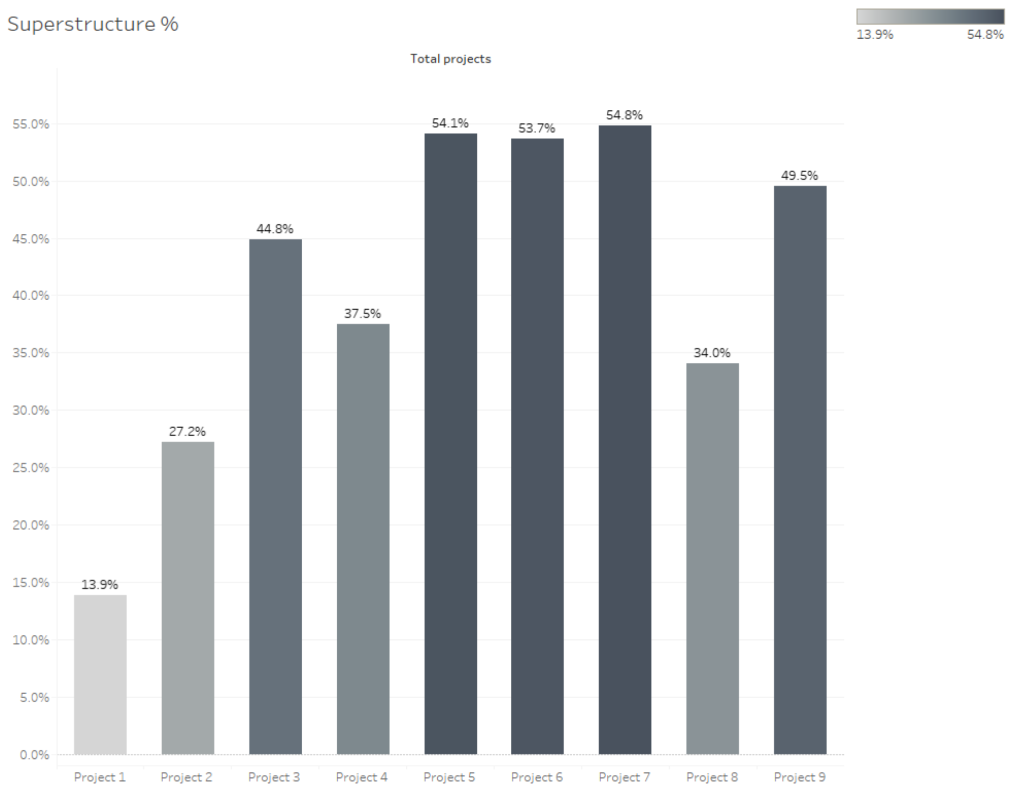


Figure 27: Contribution of Superstructure in each case study

Table 22: Contribution of each work package to the total cost for all projects

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9
Preparations	9.46%	6.11%	8.08%	1.20%	3.29%	3.26%	3.19%	1.66%	10.10%
Clearance works	5.50%	6.41%	7.07%	7.49%	6.63%	6.58%	6.43%	6.27%	6.80%
Earthworks	1.40%	8.19%	3.60%	2.27%	3.79%	3.76%	3.90%	3.00%	2.00%
Foundation	12.50%	11.31%	12.04%	10.05%	6.71%	7.53%	6.63%	3.30%	4.50%
Substructure	23.04%	13.64%	2.69%	12.84%	10.24%	10.15%	10.11%	4.50%	4.80%
Superstructure	17.81%	27.19%	44.84%	37.46%	54.13%	53.66%	54.80%	34.03%	49.52%
Piping & Drainage	2.69%	2.51%	0.00%	0.85%	0.66%	0.66%	0.64%	1.05%	0.00%
Terrain design & Shore	5.49%	1.60%	1.31%	0.18%	5.78%	5.72%	5.95%	0.18%	1.06%
General works	6.15%	4.02%	2.29%	9.24%	2.13%	2.13%	1.53%	13.15%	4.40%
Bridge mechanism	-	-	-	-	-	-	-	40.00%	14.00%
Tail posts	15.95%	19.02%	18.07%	18.42%	6.63%	6.57%	6.81%	4.33%	7.57%

Appendix E: Price escalation analysis

Appendix E:1.1 – CBS indices

Table 23: Historical price indices for bridge construction works in the Netherlands (Source: CBS)

<table>
<tr><td colspan="8">Input Price Index 4213 Bridge construction Source: CBS
https://opendata.cbs.nl/#/CBS/nl/dataset/81139ned/table?dl=62E7B</td></tr>
<tr><td colspan="8">Ground, road and hydraulic engineering (GWW); input price index 2000 = 100, from 1979</td></tr>
<tr><th>Period</th><th>Index</th><th>Period</th><th>Index</th><th>Period</th><th>Index</th><th>Period</th><th>Index</th></tr>
<tr><td>2000 Apr</td><td>99.3</td><td>2006 Jul</td><td>114.2</td><td>2013 Jan</td><td>126.0</td><td>2019 Jul</td><td>136.3</td></tr>
<tr><td>2000 Jul</td><td>100.7</td><td>2006 Oct</td><td>115.5</td><td>2013 Apr</td><td>125.6</td><td>2019 Oct</td><td>135.6</td></tr>
<tr><td>2000 Oct</td><td>101.5</td><td>2007 Jan</td><td>117.6</td><td>2013 Jul</td><td>124.9</td><td>2020 Jan</td><td>137.5</td></tr>
<tr><td>2001 Jan</td><td>104.7</td><td>2007 Jul</td><td>118.5</td><td>2013 Oct</td><td>125.4</td><td>2020 Apr</td><td>136.7</td></tr>
<tr><td>2001 Apr</td><td>105.1</td><td>2007 Oct</td><td>118.4</td><td>2014 Jan</td><td>126.4</td><td>2020 Jul</td><td>137.7</td></tr>
<tr><td>2001 July</td><td>105.5</td><td>2008 Jan</td><td>122.0</td><td>2014 Apr</td><td>125.6</td><td>2020 Oct</td><td>137.9</td></tr>
<tr><td>2001 Oct</td><td>105.5</td><td>2008 Apr</td><td>125.8</td><td>2014 July</td><td>125.3</td><td>2021 Jan</td><td>142.8</td></tr>
<tr><td>2002 Jan</td><td>107.1</td><td>2008 Jul</td><td>132.9</td><td>2014 Oct</td><td>125.6</td><td>2021 Apr</td><td>144.7</td></tr>
<tr><td>2002 Apr</td><td>107.5</td><td>2008 Oct</td><td>131.6</td><td>2015 Jan</td><td>124.7</td><td>2021 Jul</td><td>151.9</td></tr>
<tr><td>2002 July</td><td>108.4</td><td>2009 Jan</td><td>130.9</td><td>2015 Apr</td><td>125.0</td><td>2021 Oct</td><td>154.8</td></tr>
<tr><td>2002 Oct</td><td>108.0</td><td>2009 Apr</td><td>127.4</td><td>2015 Jul</td><td>125.5</td><td colspan="2" rowspan="3">Estimating from the indices:</td></tr>
<tr><td>2003 Jan</td><td>107.9</td><td>2009 Jul</td><td>123.8</td><td>2015 Oct</td><td>124.7</td></tr>
<tr><td>2003 Apr</td><td>107.4</td><td>2009 Oct</td><td>120.5</td><td>2016 Jan</td><td>124.1</td></tr>
<tr><td>2003 Jul</td><td>107.2</td><td>2010 Jan</td><td>119.0</td><td>2016 July</td><td>126.9</td><td rowspan="3">ln (P_j)</td><td rowspan="3">ln (P_{j-1})</td></tr>
<tr><td>2003 Oct</td><td>106.7</td><td>2010 Apr</td><td>120.5</td><td>2016 Oct</td><td>126.6</td></tr>
<tr><td>2004 Jan</td><td>106.5</td><td>2010 Jul</td><td>120.6</td><td>2017 Jan</td><td>128.2</td></tr>
<tr><td>2004 Apr</td><td>108.2</td><td>2010 Oct</td><td>120.3</td><td>2017 Apr</td><td>128.9</td><td rowspan="3">Drift</td><td rowspan="3">Volatility</td></tr>
<tr><td>2004 Jul</td><td>109.7</td><td>2011 Jan</td><td>123.5</td><td>2017 Jul</td><td>129.3</td></tr>
<tr><td>2004 Oct</td><td>107.8</td><td>2011 Apr</td><td>122.7</td><td>2017 Oct</td><td>131.5</td></tr>
<tr><td>2005 Jan</td><td>107.1</td><td>2011 Jul</td><td>123.3</td><td>2018 Jan</td><td>132.6</td><td rowspan="3">Average of:
ln (P_j-P_{j-1})</td><td rowspan="3">St.dev of:
ln (P_j-P_{j-1})</td></tr>
<tr><td>2005 Apr</td><td>107.5</td><td>2011 Oct</td><td>123.3</td><td>2018 Apr</td><td>132.7</td></tr>
<tr><td>2005 Jul</td><td>107.6</td><td>2012 Jan</td><td>124.5</td><td>2018 Jul</td><td>134.0</td></tr>
<tr><td>2005 Oct</td><td>108.6</td><td>2012 Apr</td><td>124.8</td><td>2018 Oct</td><td>134.7</td><td rowspan="3">=
0.00529</td><td rowspan="3">=
0.01394</td></tr>
<tr><td>2006 Jan</td><td>111.4</td><td>2012 Jul</td><td>125.4</td><td>2019 Jan</td><td>135.3</td></tr>
<tr><td>2006 Apr</td><td>112.2</td><td>2012 Oct</td><td>125.8</td><td>2019 Apr</td><td>135.4</td></tr>
</table>

Appendix E:1.2 – Evolution of costs in the examined case studies

Table 24: Evolution of Replacement costs over the years due to price escalation

Column1	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9
2008 Apr	195,000€								
2008 Jul	206,006€								
2008 Oct	203,990€								
2009 Jan	202,905€								
2009 Apr	197,480€								
2009 Jul	191,900€								
2009 Oct	186,785€								
2010 Jan	184,459€								
2010 Apr	186,785€								
2010 Jul	186,940€								
2010 Oct	186,475€								
2011 Jan	191,435€								
2011 Apr	190,195€								
2011 Jul	191,125€								
2011 Oct	191,125€								
2012 Jan	192,985€								
2012 Apr	193,450€								
2012 July	194,380€								
2012 Oct	195,000€								
2013 Jan	195,310€								
2013 Apr	194,690€	202,703€	142,006€						
2013 July	193,605€	201,573€	141,215€						
2013 Oct	194,380€	202,380€	141,780€						
2014 Jan	195,930€	203,994€	142,910€						
2014 Apr	194,690€	202,703€	142,006€						
2014 Jul	194,225€	202,219€	141,667€						
2014 Oct	194,690€	202,703€	142,006€						
2015 Jan	193,295€	201,251€	140,988€						
2015 Apr	193,760€	201,735€	141,328€						
2015 Jul	194,535€	202,542€	141,893€					515,605€	297,043€
2015 Oct	193,295€	201,251€	140,988€					512,318€	295,149€
2016 Apr	193,915€	201,896€	141,441€					513,962€	296,096€
2016 Jul	196,705€	204,801€	143,476€	182,067 €				521,357€	300,357€
2016 Oct	196,240€	204,317€	143,137€	241,827€				520,124€	299,647€
2017 Jan	198,720€	206,899€	144,946€	244,883€				526,698€	303,434€
2017 Apr	199,805€	208,029€	145,737€	246,220€				529,574€	305,090€
2017 Jul	200,425€	208,674€	146,189€	246,984€				531,217€	306,037€
2017 Oct	203,835€	212,225€	148,677€	251,187€				540,255€	311,244€
2018 Jan	205,541€	214,000€	149,920€	253,288€				544,775€	313,848€
2018 Apr	205,696€	214,162€	150,033€	253,479€				545,186€	314,085€
2018 Jul	207,711€	216,260€	151,503€	255,962€				550,526€	317,161€
2018 Oct	208,796€	217,389€	152,295€	257,299€	321,801€	324,651€	332,061€	553,402€	318,818€
2019 Jan	209,726€	218,358€	152,973€	258,445€	323,234€	326,097€	333,540€	555,867€	320,238€
2019 Apr	209,881€	218,519€	153,086€	258,636€	323,473€	326,338€	333,787€	556,278€	320,475€
2019 Jul	211,276€	219,971€	154,104€	260,356€	325,623€	328,507€	336,005€	559,976€	322,605€
2019 Oct	210,191€	218,842€	153,312€	259,018€	323,951€	326,820€	334,280€	557,100€	320,948€
2020 Jan	213,136€	221,908€	155,460€	262,648€	328,490€	331,399€	338,964€	564,906€	325,446€
2020 Apr	211,896€	220,617€	154,556€	261,120€	326,579€	329,471€	336,991€	561,619€	323,552€
2020 Jul	213,446€	222,231€	155,687€	263,030€	328,968€	331,882€	339,457€	565,728€	325,919€
2020 Oct	213,756€	222,554€	155,913€	263,412€	329,446€	332,364€	339,950€	566,549€	326,392€
2021 Jan	221,351€	230,462€	161,453€	272,772€	341,152€	344,173€	352,029€	586,680€	337,990€
2021 Apr	224,297€	233,528€	163,601€	276,401€	345,691€	348,753€	356,713€	594,486€	342,487€
2021 Jul	235,457€	245,148€	171,741€	290,154€	362,892€	366,106€	374,462€	624,067€	359,529€
2021 Oct	239,952€	249,828€	175,020€	295,694€	369,820€	373,096€	381,611€	635,981€	366,392€

Appendix E:1.3 – Graphical illustration of the evolution of costs in the examined case studies

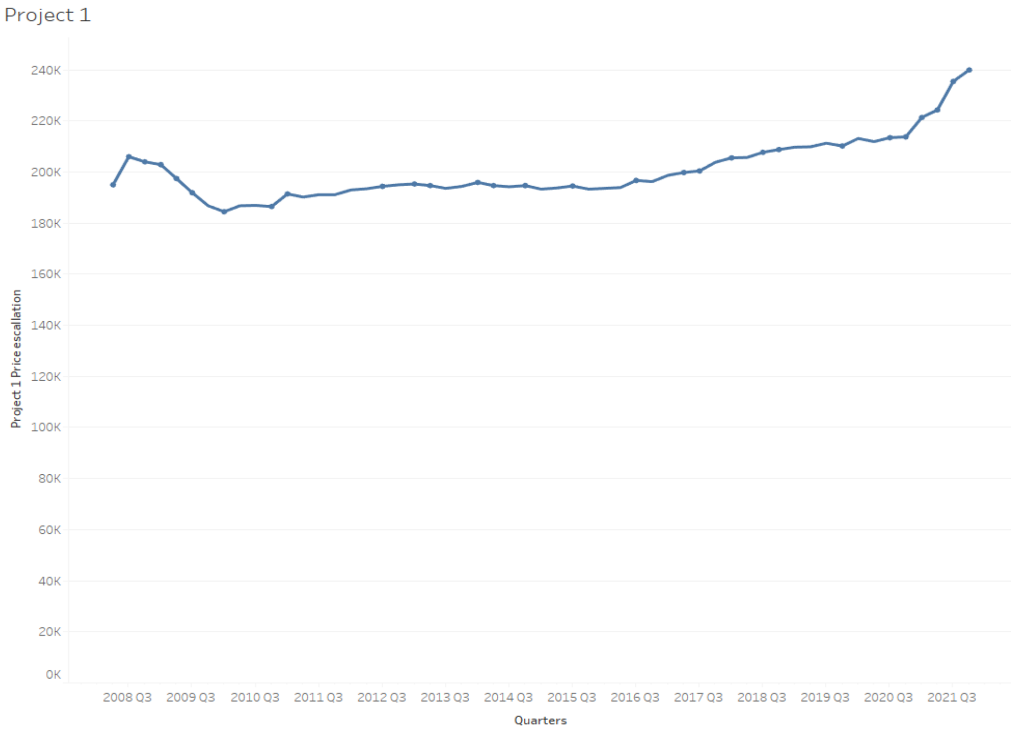


Figure 28: Price escalation over the years for Project 1

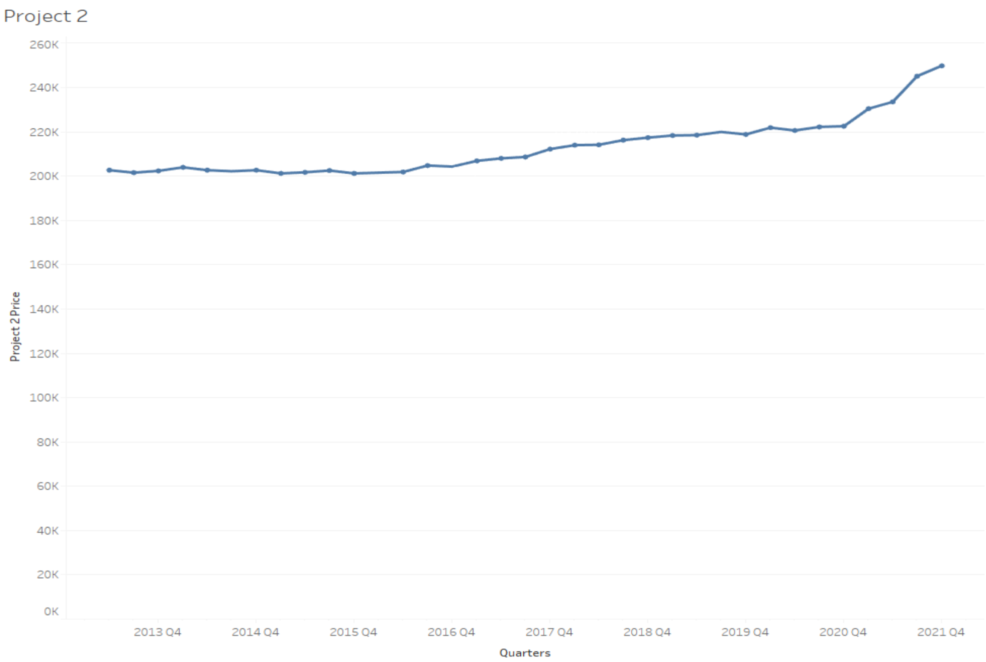


Figure 29: Price escalation over the years for Project 2

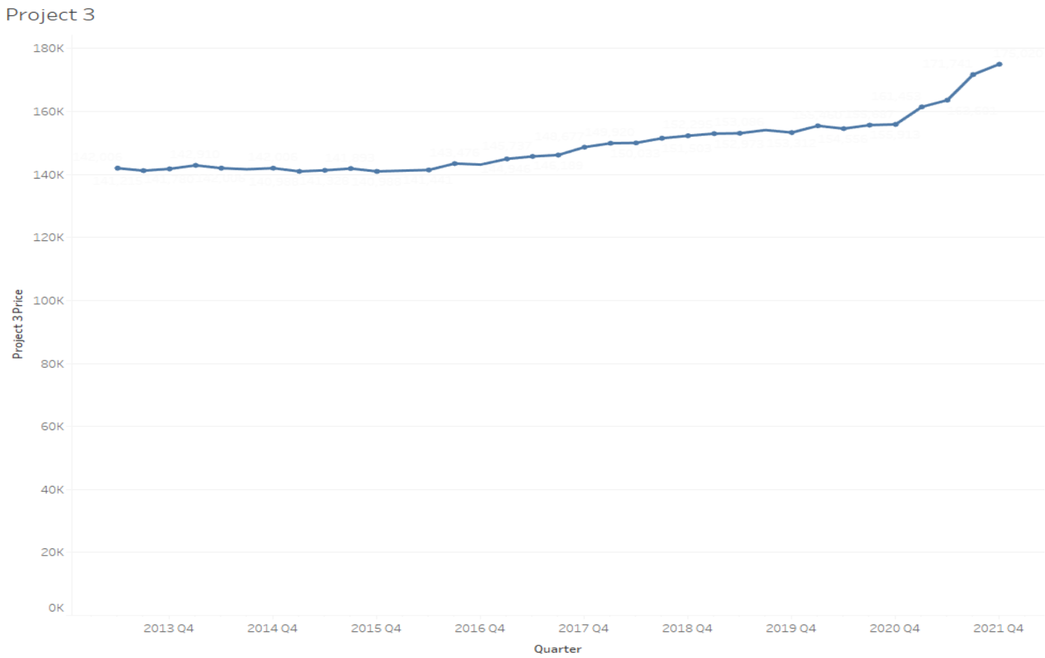


Figure 30: Price escalation over the years for Project 3

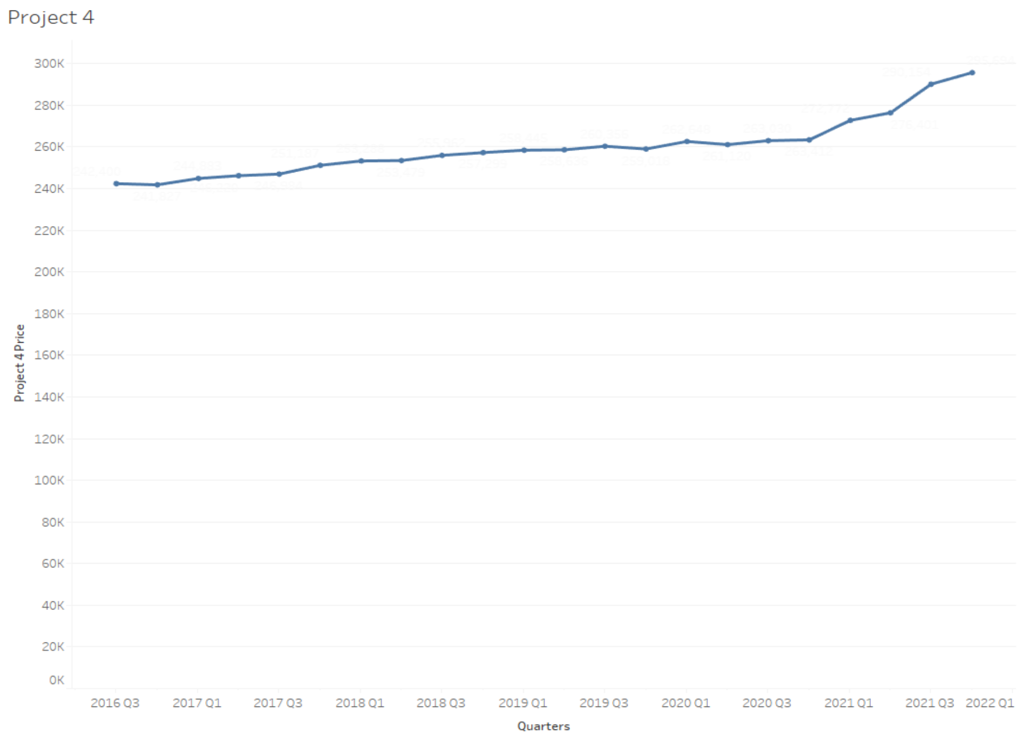


Figure 31: Price escalation over the years for Project 4

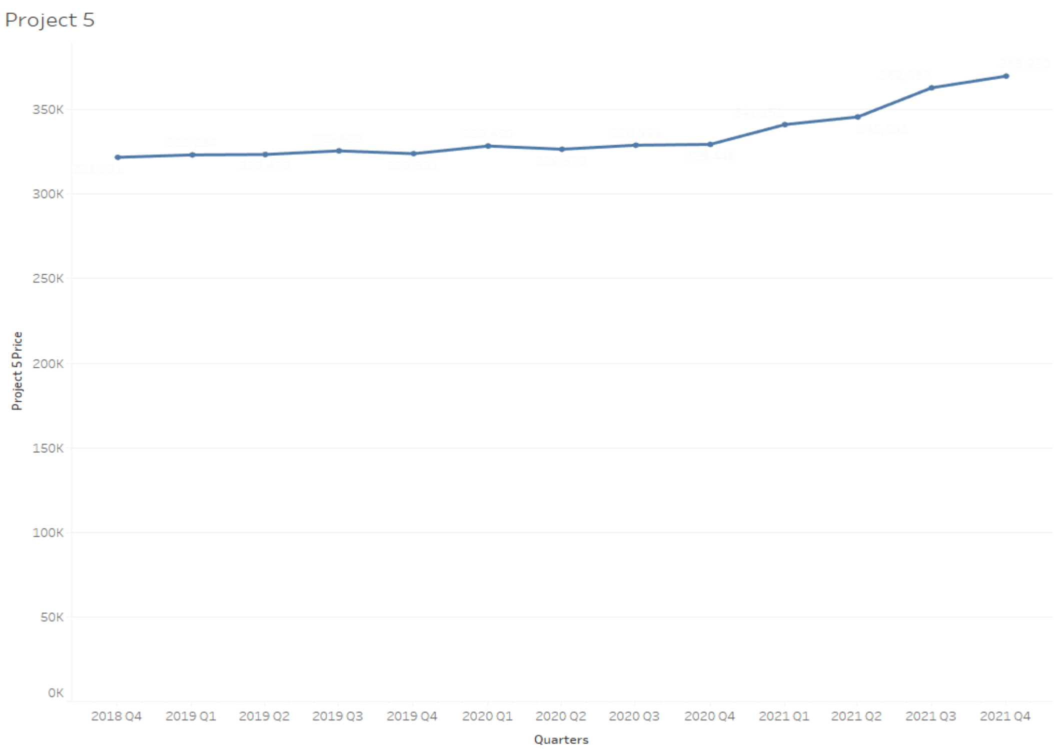


Figure 32: Price escalation over the years for Project 5

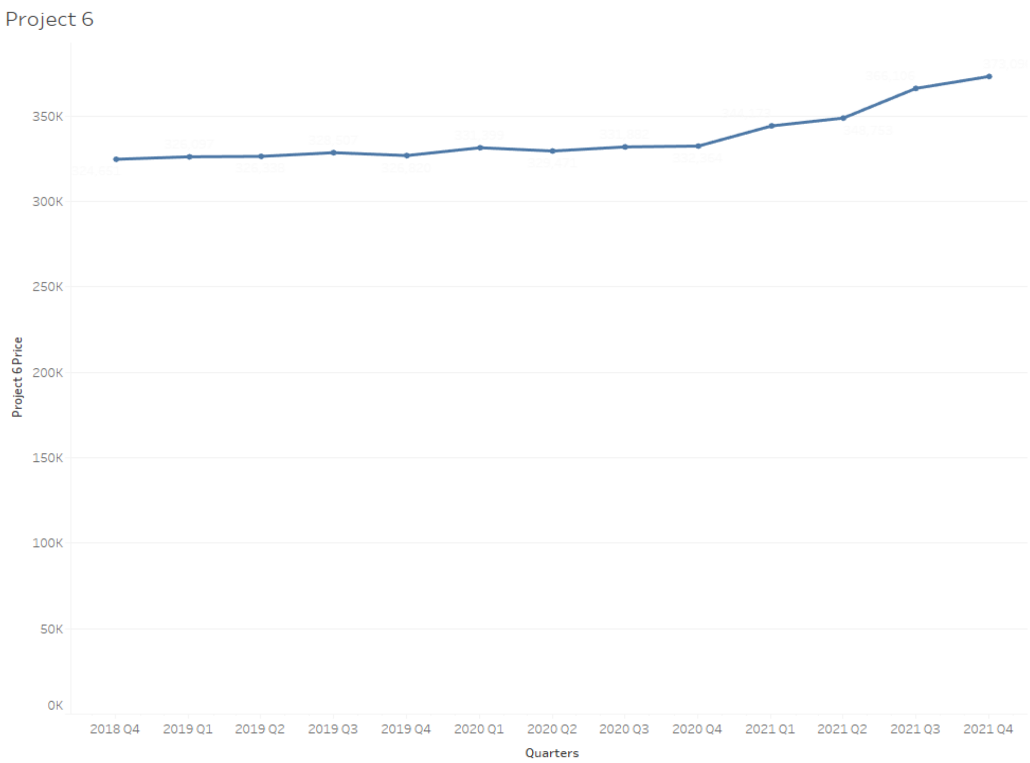


Figure 33: Price escalation over the years for Project 6

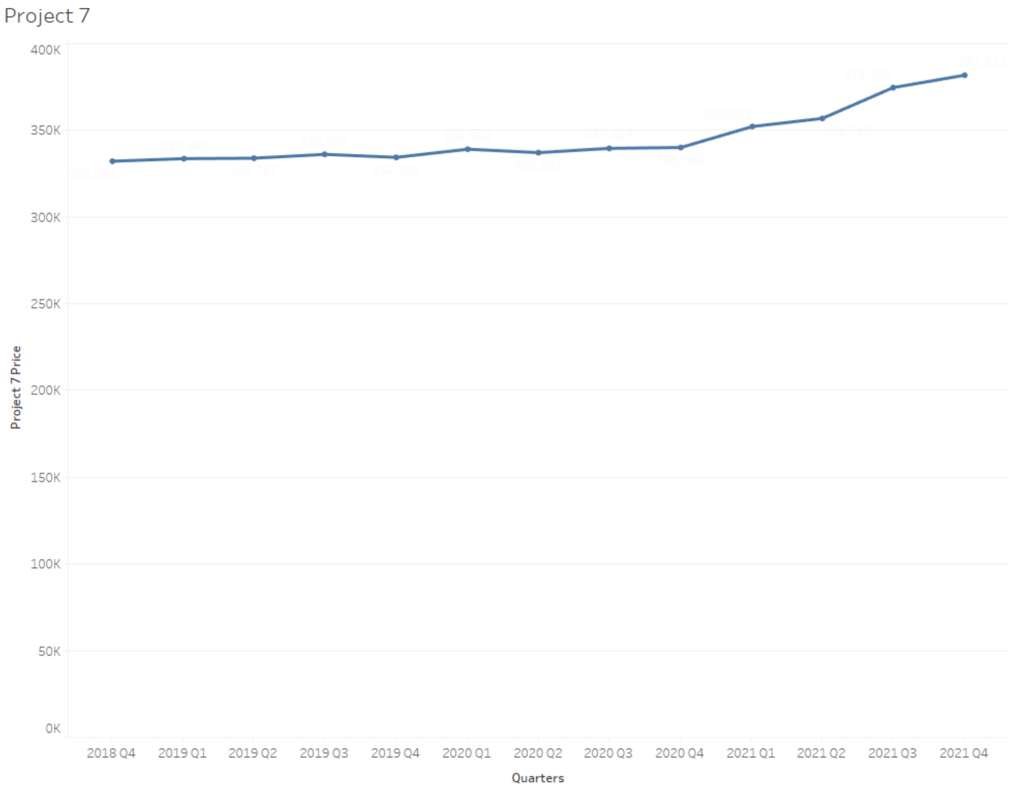


Figure 34: Price escalation over the years for Project 7

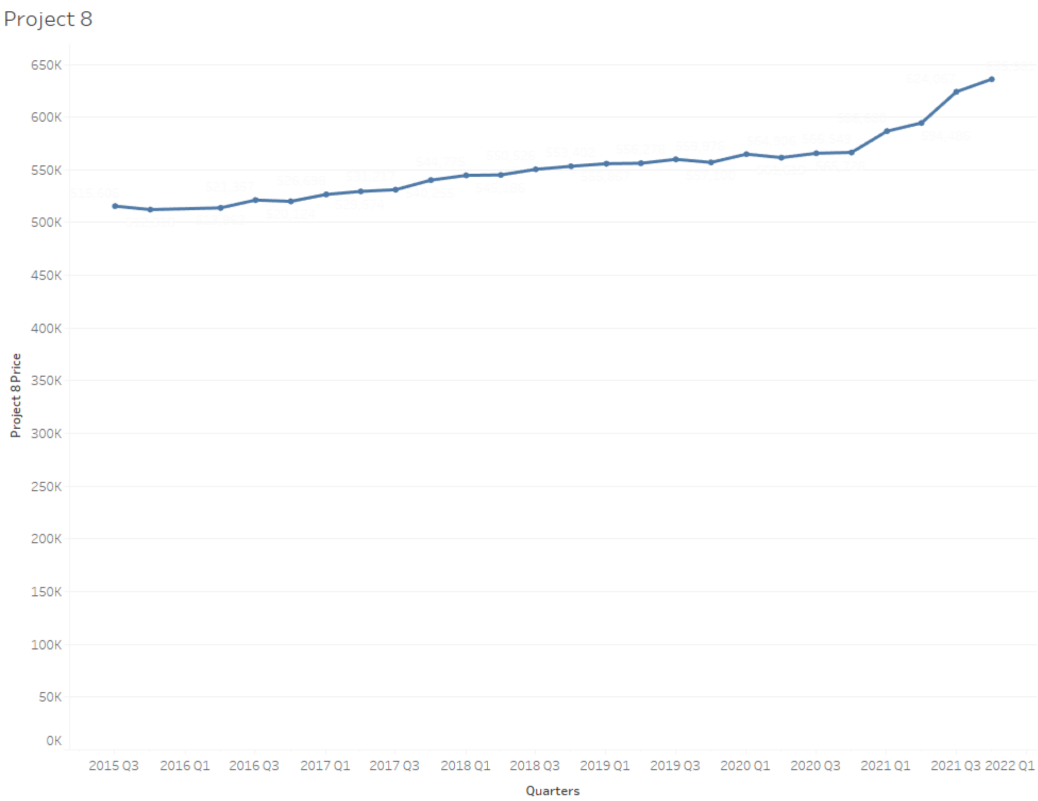


Figure 35: Price escalation over the years for Project 8

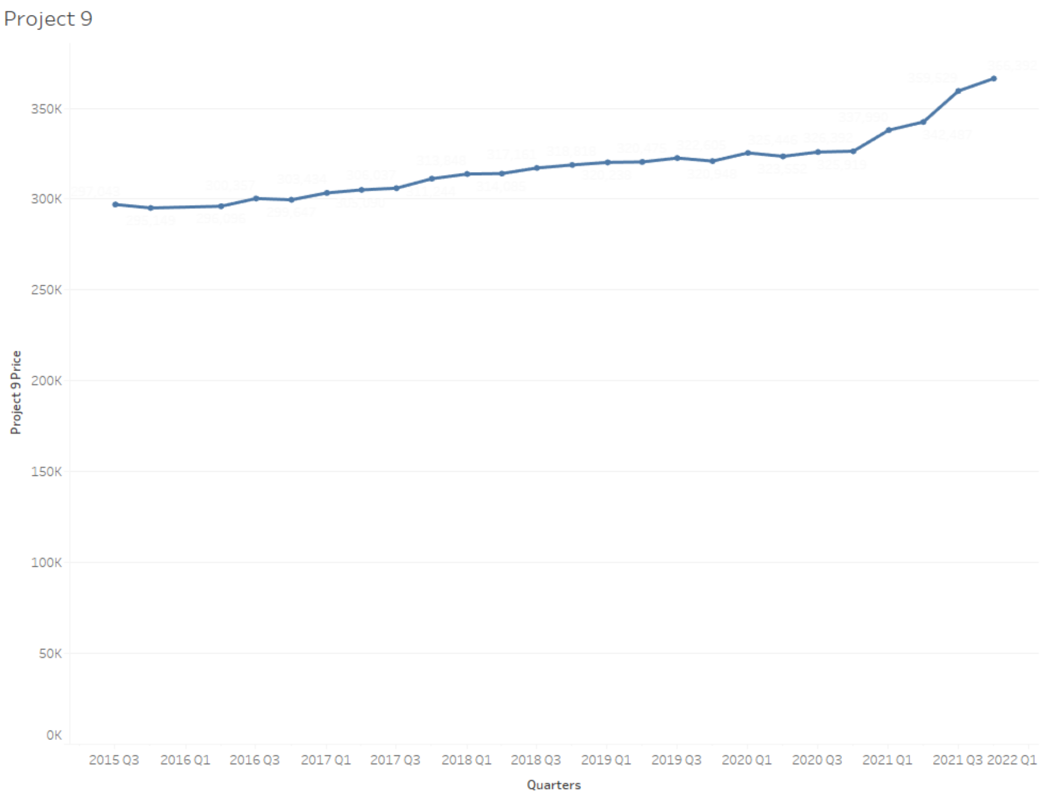
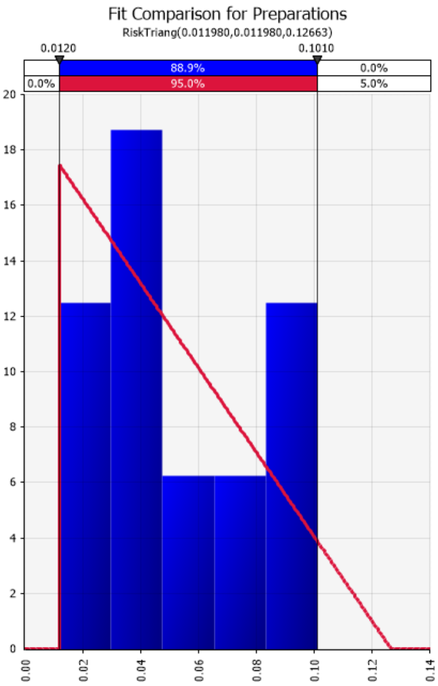


Figure 36: Price escalation over the years for Project 9

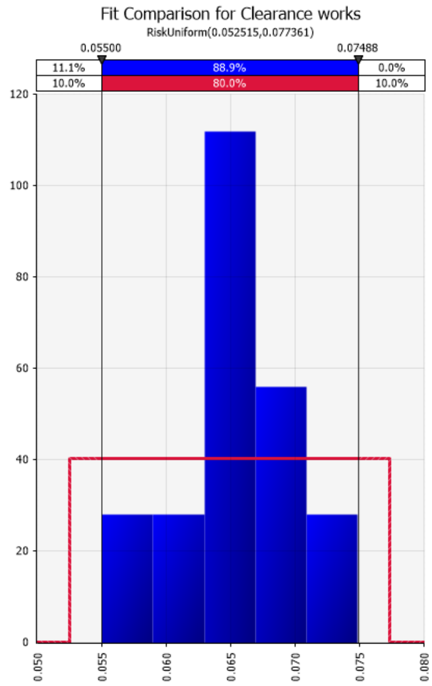
Appendix F – Framework development & Validation

Appendix F: 1 – Best fit distributions



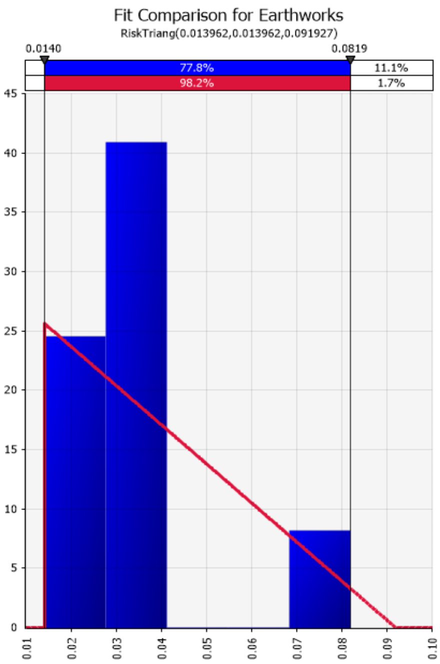
Statistics	Input	Triang
Minimum	0.011980	0.01198
Maximum	0.101000	0.12663
Mean	0.051492	0.05020
Mode	≈0.032010	0.01198
Median	0.032884	0.04556
Std Dev	0.033789	0.02702
Skewness	0.4276	0.5657
Kurtosis	1.4159	2.4000
Left X	0.0120	0.0120
Left P	11.1%	0.0%
Right X	0.1010	0.1010
Right P	100.0%	95.0%
Dif. X	0.089000	0.08900
Dif. P	88.9%	95.0%
1%	0.011980	0.01255
2.5%	0.011980	0.01342
5%	0.011980	0.01488
10%	0.011980	0.01786
20%	0.016563	0.02408
25%	0.031868	0.02734
30%	0.031868	0.03071
35%	0.032595	0.03420
40%	0.032595	0.03782
45%	0.032884	0.04160
50%	0.032884	0.04556
55%	0.032884	0.04972
60%	0.061084	0.05412
65%	0.061084	0.05880
70%	0.080841	0.06384
75%	0.080841	0.06931
80%	0.094615	0.07536
90%	0.101000	0.09038
95%	0.101000	0.10100

Figure 37: Best fit distribution for Preparations



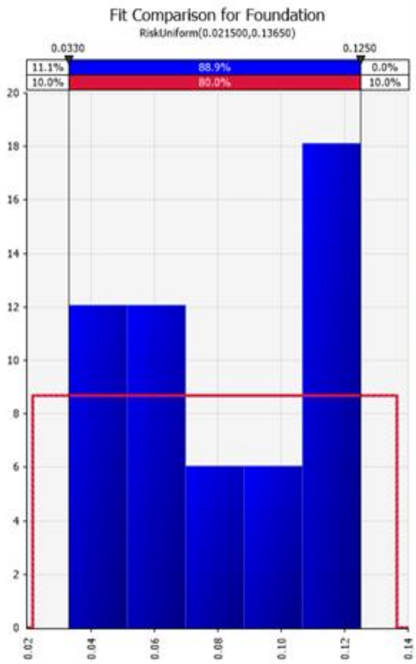
Statistics	Input	Uniform
Minimum	0.055000	0.052515
Maximum	0.074876	0.077361
Mean	0.065748	0.064938
Mode	≈0.064441	N/A
Median	0.065755	0.064938
Std Dev	0.005504	0.007172
Skewness	-0.3731	0.0000
Kurtosis	4.5561	1.8000
Left X	0.05500	0.05500
Left P	11.1%	10.0%
Right X	0.07488	0.07488
Right P	100.0%	90.0%
Dif. X	0.019880	0.019880
Dif. P	88.9%	80.0%
1%	0.055000	0.052764
2.5%	0.055000	0.053137
5%	0.055000	0.053758
10%	0.055000	0.055000
20%	0.062720	0.057485
25%	0.064105	0.058727
30%	0.064105	0.059969
35%	0.064288	0.061211
40%	0.064288	0.062454
45%	0.065755	0.063696
50%	0.065755	0.064938
55%	0.065755	0.066180
60%	0.066338	0.067423
65%	0.066338	0.068665
70%	0.068000	0.069907
75%	0.068000	0.071149
80%	0.070653	0.072392
90%	0.074876	0.074876
95%	0.074876	0.076118

Figure 38: Best fit distribution for Clearance Works



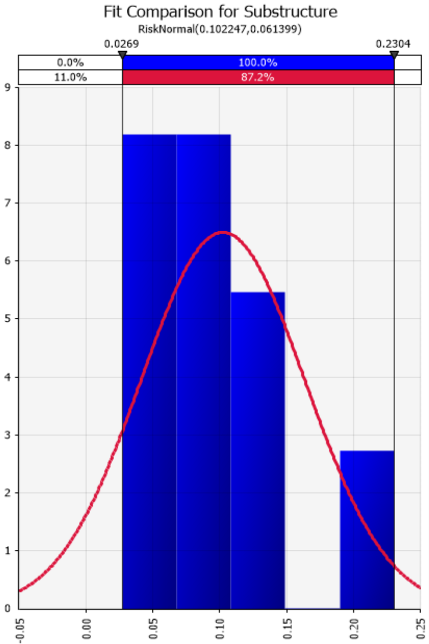
Statistics	Input	Triang
Minimum	0.013962	0.013962
Maximum	0.081914	0.091927
Mean	0.035452	0.039950
Mode	≈0.036046	0.013962
Median	0.035987	0.036797
Std Dev	0.019605	0.018377
Skewness	1.8029	0.5657
Kurtosis	7.4187	2.4000
Left X	0.0140	0.0140
Left P	11.1%	0.1%
Right X	0.0819	0.0819
Right P	88.9%	98.3%
Dif. X	0.067900	0.067900
Dif. P	77.8%	98.2%
1%	0.013962	0.014352
2.5%	0.013962	0.014942
5%	0.013962	0.015936
10%	0.013962	0.017962
20%	0.020000	0.022193
25%	0.022712	0.024407
30%	0.022712	0.026696
35%	0.030000	0.029069
40%	0.030000	0.031535
45%	0.035987	0.034106
50%	0.035987	0.036797
55%	0.035987	0.039626
60%	0.037589	0.042617
65%	0.037589	0.045802
70%	0.037922	0.049224
75%	0.037922	0.052944
80%	0.038978	0.057060
90%	0.081914	0.067272
95%	0.081914	0.074494

Figure 39: Best fit distribution for Earthworks



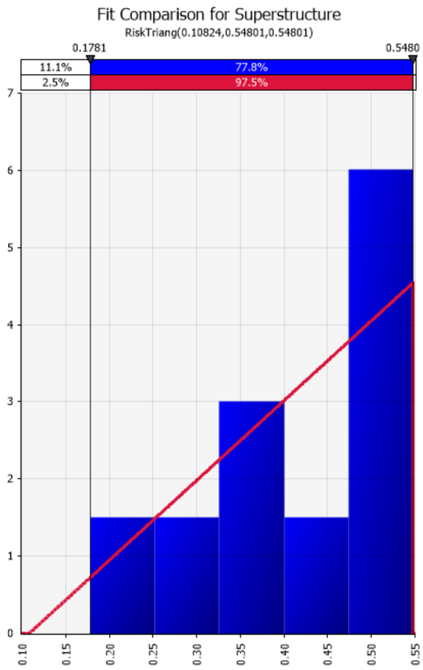
Statistics	Input	Uniform
Minimum	0.033000	0.02150
Maximum	0.125000	0.13650
Mean	0.082853	0.07900
Mode	≈0.067500	N/A
Median	0.075293	0.07900
Std Dev	0.033366	0.03320
Skewness	-0.1130	0.0000
Kurtosis	1.5500	1.8000
Left X	0.0330	0.0330
Left P	11.1%	10.0%
Right X	0.1250	0.1250
Right P	100.0%	90.0%
Dif. X	0.092000	0.09200
Dif. P	88.9%	80.0%
1%	0.033000	0.02265
2.5%	0.033000	0.02438
5%	0.033000	0.02725
10%	0.033000	0.03300
20%	0.045000	0.04450
25%	0.066331	0.05025
30%	0.066331	0.05600
35%	0.067104	0.06175
40%	0.067104	0.06750
45%	0.075293	0.07325
50%	0.075293	0.07900
55%	0.075293	0.08475
60%	0.100484	0.09050
65%	0.100484	0.09625
70%	0.113056	0.10200
75%	0.113056	0.10775
80%	0.120409	0.11350
90%	0.125000	0.12500
95%	0.125000	0.13075

Figure 40: Best fit distribution for Foundation



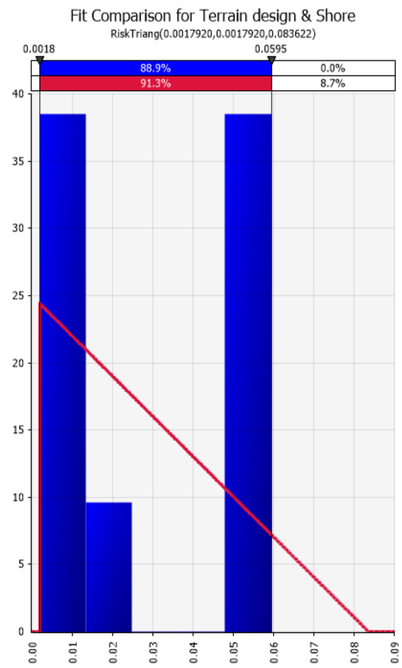
Statistics	Input	Normal
Minimum	0.02692	−∞
Maximum	0.23036	+∞
Mean	0.10225	0.10225
Mode	≈0.10321	0.10225
Median	0.10154	0.10225
Std Dev	0.06140	0.06140
Skewness	0.9621	0.0000
Kurtosis	4.5120	3.0000
Left X	0.0269	0.0269
Left P	0.0%	11.0%
Right X	0.2304	0.2304
Right P	100.0%	98.2%
Dif. X	0.20350	0.20350
Dif. P	100.0%	87.2%
1%	0.02692	-0.04059
2.5%	0.02692	-0.01809
5%	0.02692	0.00125
10%	0.02692	0.02356
20%	0.04500	0.05057
25%	0.04800	0.06083
30%	0.04800	0.07005
35%	0.10114	0.07859
40%	0.10114	0.08669
45%	0.10154	0.09453
50%	0.10154	0.10225
55%	0.10154	0.10996
60%	0.10244	0.11780
65%	0.10244	0.12591
70%	0.12839	0.13445
75%	0.12839	0.14366
80%	0.13643	0.15392
90%	0.23036	0.18093
95%	0.23036	0.20324

Figure 41: Best fit distribution for Substructure



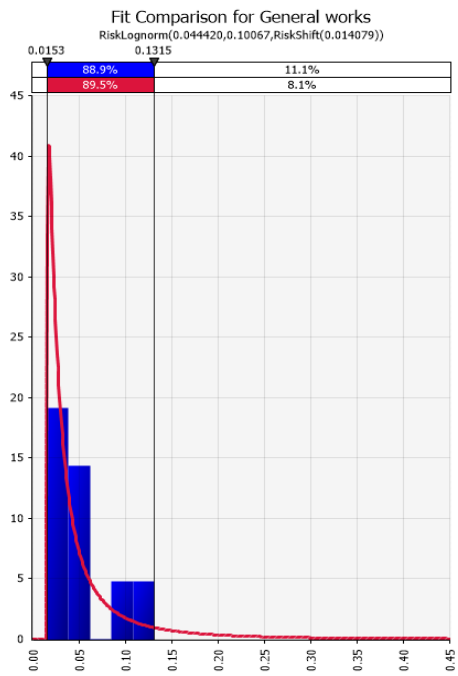
Statistics	Input	Triang
Minimum	0.17809	0.10824
Maximum	0.54801	0.54801
Mean	0.41495	0.40142
Mode	≈0.53877	0.54801
Median	0.44842	0.41921
Std Dev	0.13220	0.10366
Skewness	-0.6931	-0.5657
Kurtosis	2.3137	2.4000
Left X	0.1781	0.1781
Left P	11.1%	2.5%
Right X	0.5480	0.5480
Right P	88.9%	100.0%
Dif. X	0.36990	0.36990
Dif. P	77.8%	97.5%
1%	0.17809	0.15222
2.5%	0.17809	0.17778
5%	0.17809	0.20658
10%	0.17809	0.24731
20%	0.27192	0.30491
25%	0.34025	0.32813
30%	0.34025	0.34911
35%	0.37463	0.36841
40%	0.37463	0.38638
45%	0.44842	0.40325
50%	0.44842	0.41921
55%	0.44842	0.43438
60%	0.49523	0.44889
65%	0.49523	0.46280
70%	0.53660	0.47618
75%	0.53660	0.48909
80%	0.54135	0.50159
90%	0.54801	0.52545
95%	0.54801	0.53688

Figure 42: Best fit distribution for Superstructure



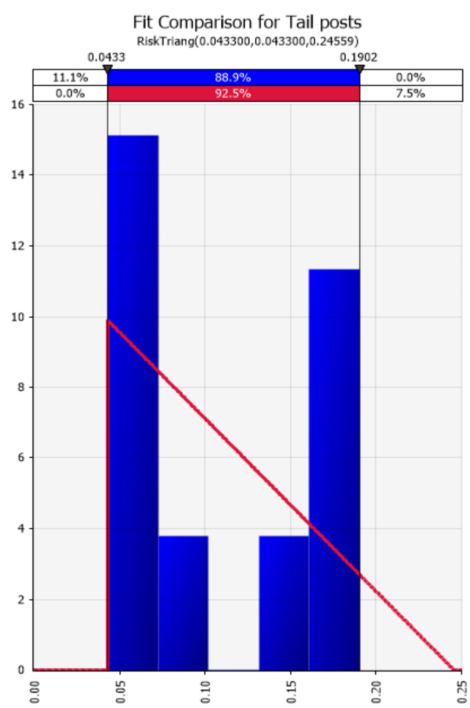
Statistics	Input	Triang
Minimum	0.001792	0.001792
Maximum	0.059492	0.083622
Mean	0.030305	0.029069
Mode	≈0.058050	0.001792
Median	0.016009	0.025759
Std Dev	0.026101	0.019288
Skewness	0.1632	0.5657
Kurtosis	0.6143	2.4000
Left X	0.0018	0.0018
Left P	11.1%	0.0%
Right X	0.0595	0.0595
Right P	100.0%	91.3%
Dif. X	0.057700	0.057700
Dif. P	88.9%	91.3%
1%	0.001792	0.002202
2.5%	0.001792	0.002821
5%	0.001792	0.003864
10%	0.001792	0.005991
20%	0.001813	0.010431
25%	0.010581	0.012755
30%	0.010581	0.015158
35%	0.013133	0.017649
40%	0.013133	0.020237
45%	0.016009	0.022935
50%	0.016009	0.025759
55%	0.016009	0.028729
60%	0.054923	0.031868
65%	0.054923	0.035211
70%	0.057246	0.038802
75%	0.057246	0.042707
80%	0.057753	0.047027
90%	0.059492	0.057745
95%	0.059492	0.065324

Figure 43: Best fit distribution for Terrain design & Shore



Statistics	Input	Lognorm
Minimum	0.01534	0.01408
Maximum	0.13153	+∞
Mean	0.05003	0.05850
Mode	≈0.01824	0.01700
Median	0.04021	0.03201
Std Dev	0.03922	0.10067
Skewness	1.3530	18.4379
Kurtosis	4.1708	1,989.4000
Left X	0.0153	0.0153
Left P	0.0%	2.3%
Right X	0.1315	0.1315
Right P	88.9%	91.9%
Dif. X	0.11620	0.11620
Dif. P	88.9%	89.5%
1%	0.01534	0.01486
2.5%	0.01534	0.01536
5%	0.01534	0.01604
10%	0.01534	0.01727
20%	0.02110	0.01985
25%	0.02129	0.02131
30%	0.02129	0.02293
35%	0.02289	0.02475
40%	0.02289	0.02683
45%	0.04021	0.02922
50%	0.04021	0.03201
55%	0.04021	0.03532
60%	0.04400	0.03930
65%	0.04400	0.04421
70%	0.06154	0.05042
75%	0.06154	0.05856
80%	0.09242	0.06979
90%	0.13153	0.11484
95%	0.13153	0.17844

Figure 44: Best fit distribution for General works

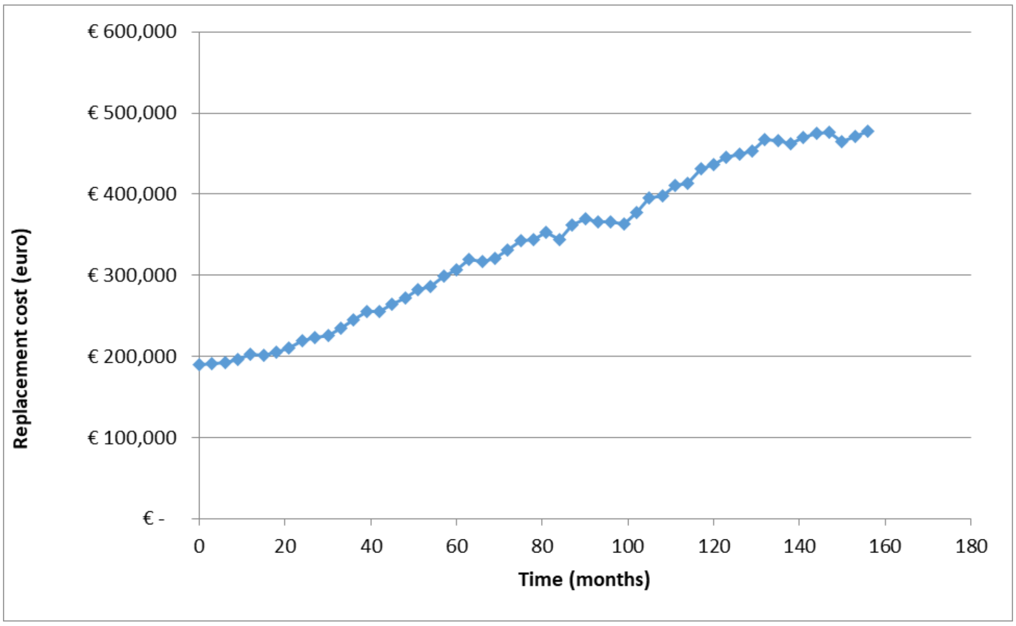
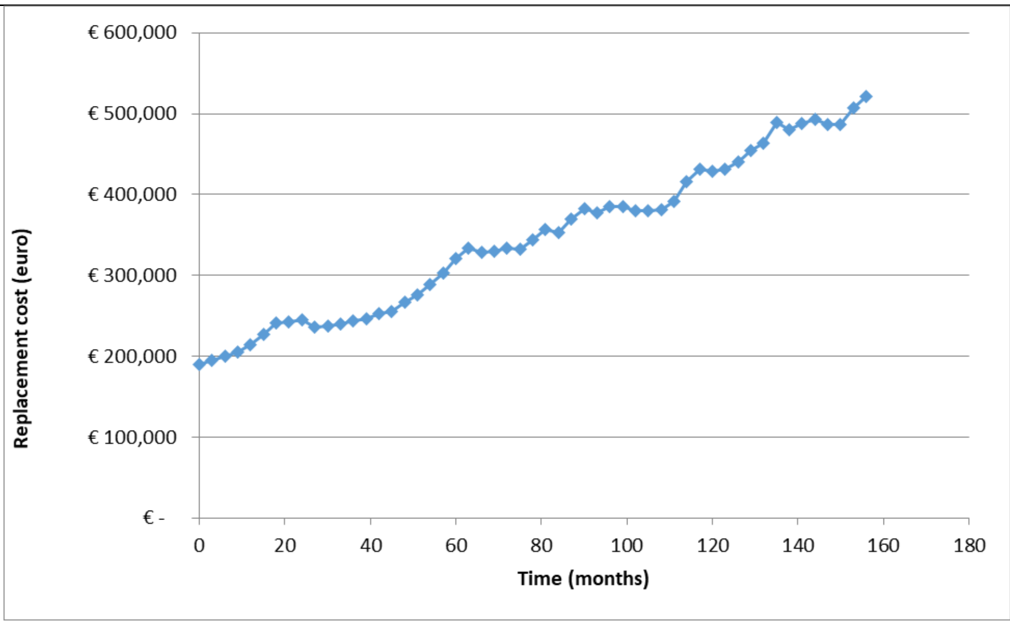


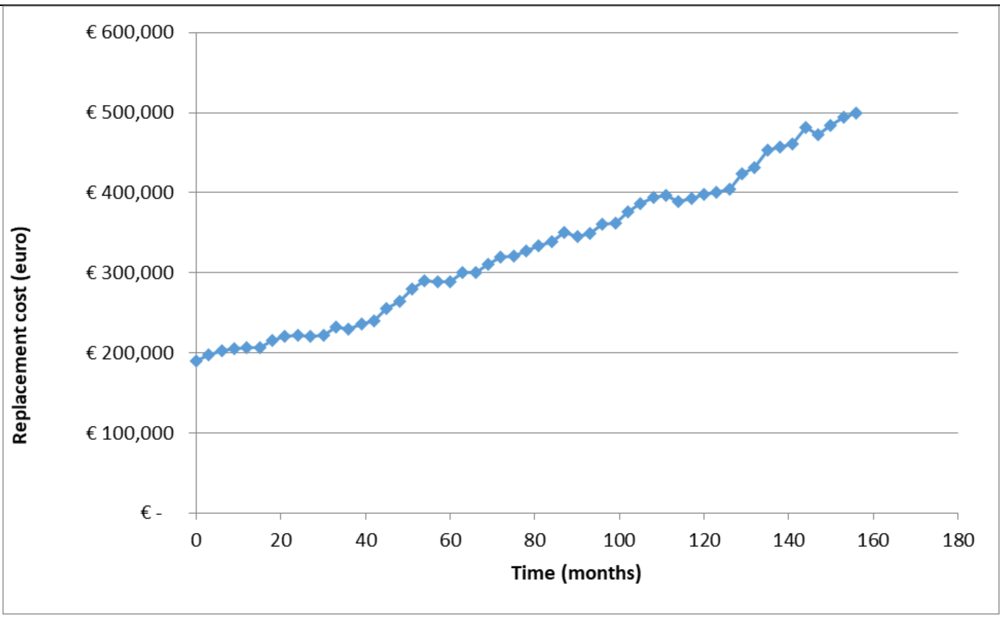
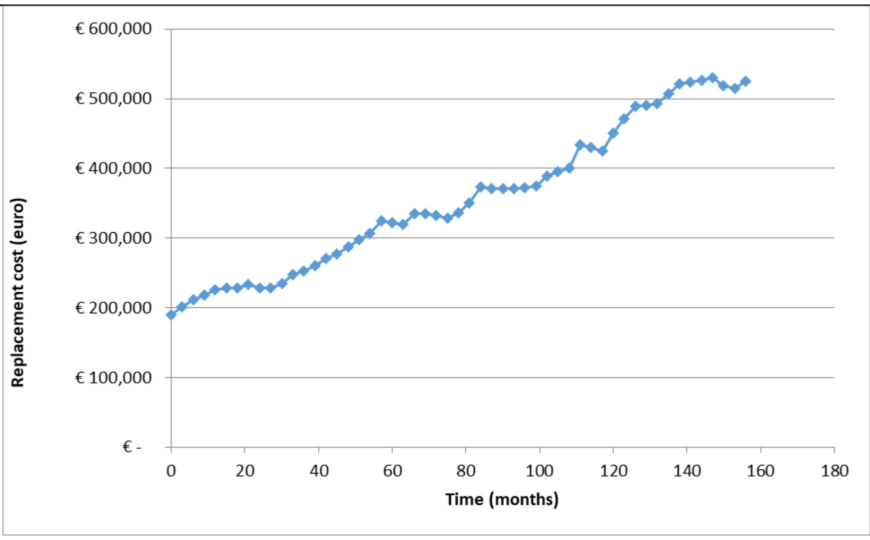
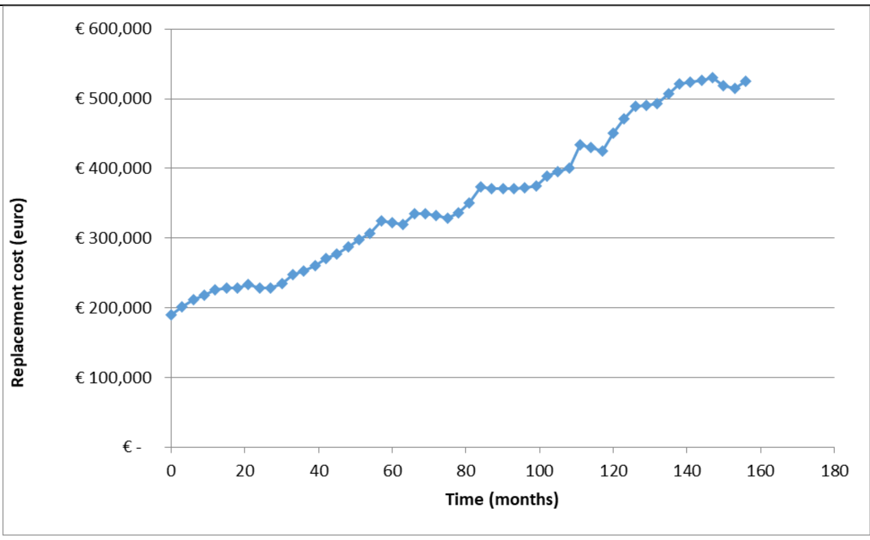
Statistics	Input	Triang
Minimum	0.04330	0.04330
Maximum	0.19017	0.24559
Mean	0.11487	0.11073
Mode	≈0.06900	0.04330
Median	0.07572	0.10255
Std Dev	0.06168	0.04768
Skewness	0.2559	0.5657
Kurtosis	0.7031	2.4000
Left X	0.0433	0.0433
Left P	11.1%	0.0%
Right X	0.1902	0.1902
Right P	100.0%	92.5%
Dif. X	0.14690	0.14690
Dif. P	88.9%	92.5%
1%	0.04330	0.04431
2.5%	0.04330	0.04584
5%	0.04330	0.04842
10%	0.04330	0.05368
20%	0.06570	0.06466
25%	0.06628	0.07040
30%	0.06628	0.07634
35%	0.06813	0.08250
40%	0.06813	0.08890
45%	0.07572	0.09557
50%	0.07572	0.10255
55%	0.07572	0.10989
60%	0.15952	0.11765
65%	0.15952	0.12591
70%	0.18074	0.13479
75%	0.18074	0.14445
80%	0.18423	0.15512
90%	0.19017	0.18162
95%	0.19017	0.20036

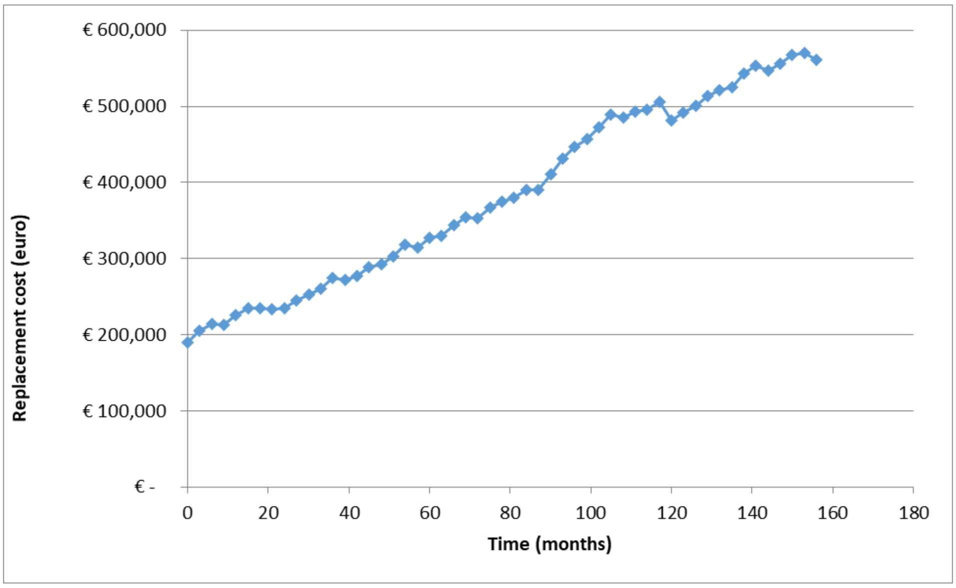
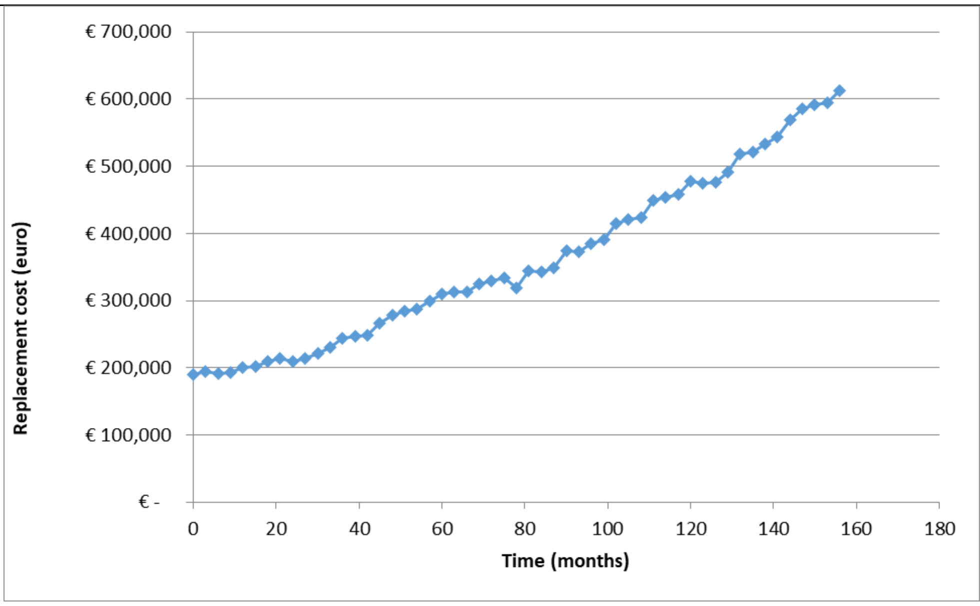
Figure 44: Best fit distribution for Tail posts

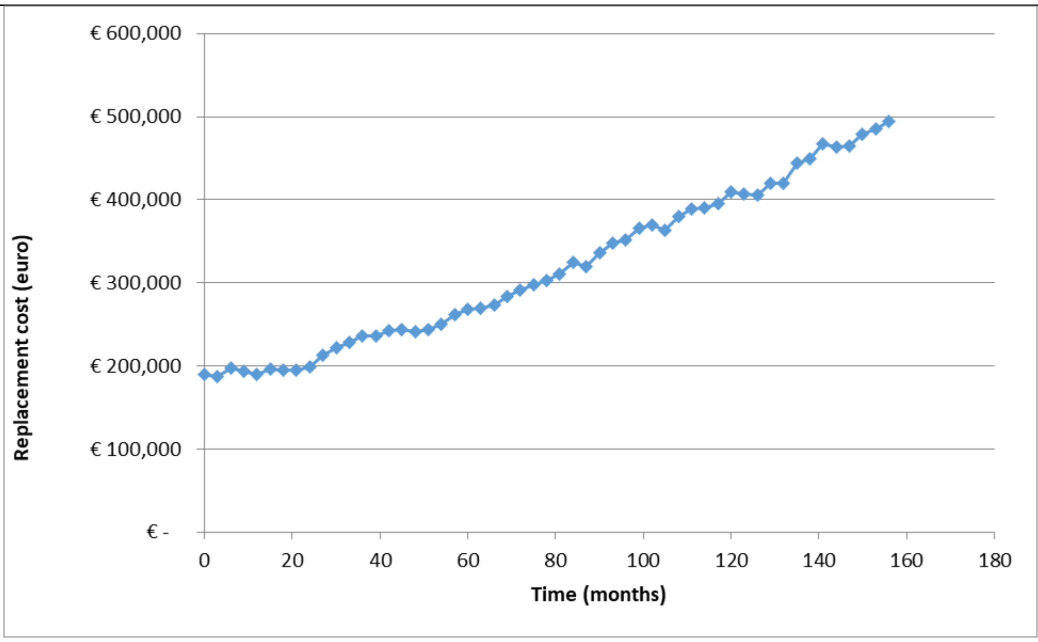
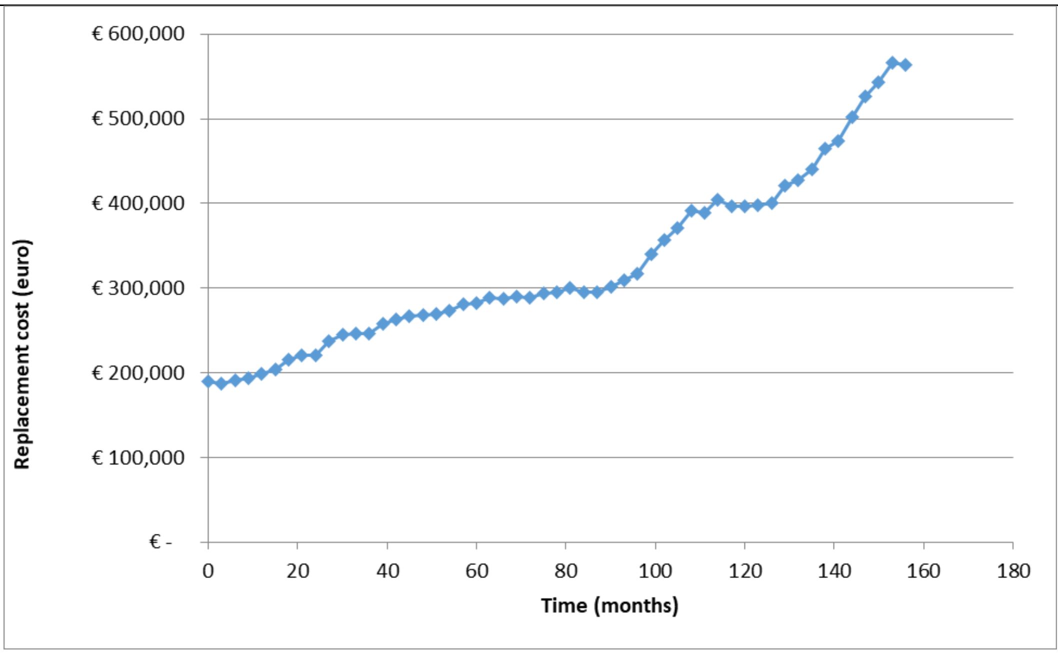
Appendix F: 2 – Stochastic model different iterations

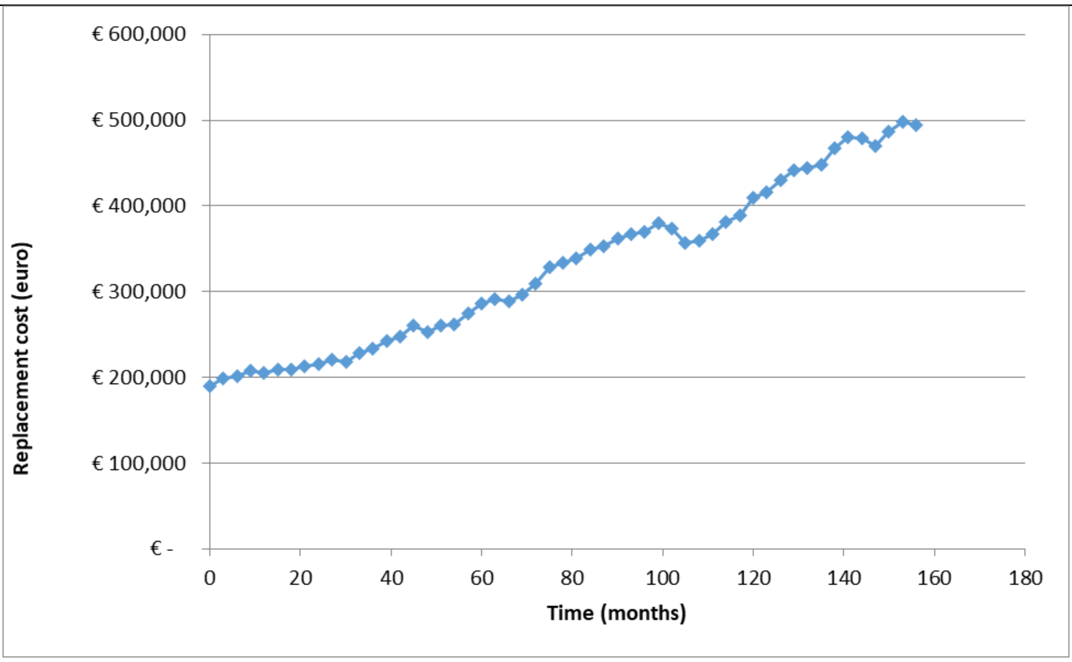
Table 25: Different stochastic model analysis

1ST	
2ND	
3D	

	€ 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)
4TH	€ 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)
5TH	€ 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)

6TH	€ 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)
7TH	€ 700,000 € 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)

8	€ 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)
9	€ 600,000 € 500,000 € 400,000 € 300,000 € 200,000 € 100,000 € - Replacement cost (euro) 0 20 40 60 80 100 120 140 160 180 Time (months)
10	

	€ 600,000
€ 500,000
€ 400,000
€ 300,000
€ 200,000
€ 100,000
€ -
Replacement cost (euro)
0
20
40
60
80
100
120
140
160
180
Time (months)

Appendix F: 3 – Model validation through interviews – Transcript of Interview

Table 26: Validation Interview details

Interview details	
Date of Interview:	30-04-2022
Interviewee 1:	Anne Bonthuis, Cost expert Sweco Nederland BV.
Contact information:	anne.bonthuis@sweco.nl
Interviewee 2:	Ben Visser, Project leader, Asset Manager Sweco Nederland BV.
Contact information:	ben.visser@sweco.nl
Interviewer:	Konstantinos Krousoratis
Contact information:	K.krousoratis@tudelft.nl
Location of interview:	Online (Microsoft Teams)
List of Acronyms:	AB= Anne Bonthuis, BV=Ben Visser IN= Interviewer

Interview with Cost estimator

Start of interview:

IN: Based on the results, the model seems capable of providing a cost indication better than the current practices. According to your perception, what are the advantages of the model?

AB: The model provided better results when applied in the specific case study. Also, it helps cost estimators conduct faster probabilistic estimates as there is no need for defining upper and lower limits for every activity but the entire work package.

IN: According to your perception, what are the disadvantages of the model?

AB: Probabilistic techniques like the one in your model indeed provide more reliable results, as the CROW specification indicates. However, they require more time and effort to conduct the estimate. For large CAPEX projects, it is useful, but for small municipal replacement works, it is not so practical due to the high volume of assets for which we have to conduct estimates.

IN: Do you think that you will implement the model in your current practices?

AB: It is an interesting model, especially the part intended for dealing with price escalation. However, the model requires the systematic collection of data to find the best fit distribution and the respective parameters for all work packages and all types of assets. Therefore, it will take time to improve it and implement it in the current practices.

End of interview

Interview with Asset manager

Start of interview:

IN: Based on the results, the model seems capable of providing a cost indication better than the current practices. According to your perception, what are the advantages of the model?

BV: The model indeed provided better results, and also it allows us to provide a range to the municipalities rather than a single point estimate. Also, a powerful feature is that it can give a future indication of the costs currently missing from our practices.

IN: According to your perception, what are the disadvantages of the model?

BV: It has been tested only for bridge replacement projects, and its applicability to other assets needs to be investigated.

IN: Do you think that you will implement the model in your current practices?

BV: **Y**es, we could implement the model in our practices as clients would prefer to see range estimates rather than point estimates. However, we need to test its applicability to more cases.

End of interview

References

Abourizk, S., & Mohamed, Y. (2002, December). Optimal construction project planning. In *Proceedings of the Winter Simulation Conference* (Vol. 2, pp. 1704-1708). IEEE.

Amirataee, B., Montaseri, M., & Rezaei, H. (2014). Assessment of goodness of fit methods in determining the best regional probability distribution of rainfall data.

Anderson, S. D., Molenaar, K. R., & Schexnayder, C. J. (2007). *Guidance for cost estimation and management for highway projects during planning, programming, and preconstruction* (Vol. 574). Transportation Research Board.

Annamalaisami, C. D., & Kuppuswamy, A. (2019). Reckoning construction cost overruns in building projects through methodological consequences. *International Journal of Construction Management*, 1-11.

ASCE. (2021). *A COMPREHENSIVE ASSESSMENT OF AMERICA'S INFRASTRUCTURE*. Retrieved from:

https://infrastructurereportcard.org/wp-content/uploads/2020/12/National_IRC_2021-report.pdf

Baccarini, D., & Love, P. E. (2014). Statistical characteristics of cost contingency in water infrastructure projects. *Journal of Construction Engineering and Management*, *140* (3), 04013063.

Boomen, M. M. V. D., Bakker, H. M., Schraven, D. J., & Hertogh, M. M. (2021). Probabilistic life cycle cash flow forecasting with price uncertainty following a geometric Brownian motion. *Structure and Infrastructure Engineering*, *18*(1), 15-29.

Bruzelius, N., Flyvbjerg, B., & Rothengatter, W. (2002). Big decisions, big risks. Improving accountability in mega projects. *Transport Policy*, *9*(2), 143-154.

Cantarelli, C. C., Flybjerg, B., Molin, E. J., & Van Wee, B. (2013). Cost overruns in large-scale transportation infrastructure projects: Explanations and their theoretical embeddedness. *arXiv preprint arXiv:1307.2176*.

Chong, U., & Hopkins, O. (2016). An international experience on the evolution of road costs during the project life cycle. *Transport Policy*, *48*, 60-66.

Chou, J. S. (2009). Web-based CBR system applied to early cost budgeting for pavement maintenance project. *Expert Systems with Applications*, *36*(2), 2947-2960.

Chou, J. S. (2011). Cost simulation in an item-based project involving construction engineering and management. International Journal of Project Management, 29(6), 706-717.

Christensen, P., Dysert, L. R., Bates, J., Burton, D., Creese, R. C., & Hollmann, J. (2005). Cost Estimate Classification system-as applied in engineering, procurement, and construction for the process industries. *AACE, Inc*, *2011*.

Cooke, R. (1991). Experts in Uncertainty: Opinion and Subjective Probability in Science. *Oxford, England: Oxford University Press.*

Crotty, M. (2020). *The foundations of social research: Meaning and perspective in the research process*. Routledge.

CROW. (2018b). Kennismodule kostenmanagement (standardized method for budgeting). Retrieved from: https://www.crow.nl/onlinekennis-tools/kennismodule-kostenmanagement.

Dandan, T. H., Sweis, G., Sukkari, L. S., & Sweis, R. J. (2019). Factors affecting the accuracy of cost estimates during various design stages. *Journal of Engineering, Design, and Technology*.

Dubois, A., & Gadde, L. E. (2002). Systematic combining: an abductive approach to case research. *Journal of business research*, *55*(7), 553-560.

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of management review*, *14*(4), 532-550.

Enshassi, A., Mohamed, S., & Abdel-Hadi, M. (2013). Factors affecting the accuracy of pre-tender cost estimates in the Gaza Strip. *Journal of Construction in Developing Countries*, *18*(1).

Flyvbjerg, B. (2018). Planning fallacy or hiding hand: Which is the better explanation? *arXiv preprint arXiv:1802.09999*.

Flyvbjerg, B., Holm, M. S., & Buhl, S. (2002). Underestimating costs in public works projects: Error or lie? *Journal of the American planning association*, *68*(3), 279-295.

Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2003). How common and how large are cost overruns in transport infrastructure projects? *Transport reviews*, *23*(1), 71-88.

Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2005). How (in) accurate are demand forecasts in public works projects? The case of transportation. *Journal of the American planning association*, *71*(2), 131-146.

Fouracre, P. R., Allport, R. J., & Thomson, J. M. (1990). *The performance and impact of rail mass transit in developing countries* (No. 78).

Fragkakis, N., Lambropoulos, S., & Pantouvakis, J. P. (2010). A cost estimate method for bridge superstructures using regression analysis and bootstrap. *Organization, technology & management in construction: an international journal*, *2*(2), 182-190.

Frangopol, D. M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges 1. *Structure and infrastructure Engineering*, *7*(6), 389-413.

Garvey, P. R., Book, S. A., & Covert, R. P. (2016). *Probability methods for cost uncertainty analysis: A systems engineering perspective*. CRC Press.

Geberemariam, T. K. (2018). Deterministic and Probabilistic Engineering Cost Estimating Approaches for Complex Urban Drainage Infrastructure Capital Improvement (CIP) Programs.

Geberemariam, T. K. (2018). Deterministic and Probabilistic Engineering Cost Estimating Approaches for Complex Urban Drainage Infrastructure Capital Improvement (CIP) Programs.

Gladwin, M., 2006. From bombs to buildings. The Building. October, London

Hammad, M. W., Abbasi, A., & Ryan, M. J. (2016). Allocation and management of cost contingency in projects. *Journal of management in engineering*, *32*(6), 04016014.

Hatamleh, M. T., Hiyassat, M., Sweis, G. J., & Sweis, R. J. (2018). Factors affecting the accuracy of cost estimate: the case of Jordan. *Engineering, Construction, and Architectural Management*.

Hendrickson, C., Hendrickson, C. T., & Au, T. (1989). *Project management for construction: Fundamental concepts for owners, engineers, architects, and builders*. Chris Hendrickson.

Herrera, R. F., Sánchez, O., Castañeda, K., & Porras, H. (2020). Cost overrun causative factors in road infrastructure projects: A frequency and importance analysis. *Applied Sciences*, *10*(16), 5506.

Hoseini, E., Bosch-Rekveldt, M., & Hertogh, M. (2020). Cost contingency and cost evolvement of construction projects in the preconstruction phase. *Journal of Construction Engineering and Management*, *146*(6), 05020006.

Hou, W., Liu, X., & Chen, D. (2011). Payment problems, cash flow and profitability of construction project: a system dynamics model. *International Journal of Economics and Management Engineering*, *5*(10), 1266-1272. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/625380/TAG_unit_a1.2_cost_estimation_jul17.pdf.

Ilbeigi, M., Castro-Lacouture, D., & Joukar, A. (2017). Generalized autoregressive conditional heteroscedasticity model to quantify and forecast uncertainty in the price of asphalt cement. *Journal of management in engineering*, *33*(5), 04017026.

Infrastructure Australia (2021, August) Assessment Framework. Retrieved from: https://www.infrastructureaustralia.gov.au/sites/default/files/202107/Assessment%20Framework%202021%20Overview.pdf

Ioannou, A., Angus, A., & Brennan, F. (2018, October). Effect of electricity market price uncertainty modeling on the profitability assessment of offshore wind energy through an integrated lifecycle techno-economic model. In *Journal of Physics: Conference Series* (Vol. 1102, No. 1, p. 012027). IOP Publishing.

ITEP. (2019, June). *Most States Have Raised Gas Taxes in Recent Years*. Retrieved from: https://itep.org/most-states-have-raised-gas-taxes-in-recent-years-0419/

Jensen, U. (2002). Probabilistic Risk Analysis: Foundations and Methods. (Book Reviews). *Journal of the American Statistical Association*, *97*(459), 925-926.

Jørgensen, M., Welde, M., & Halkjelsvik, T. (2021). Evaluation of Probabilistic Project Cost Estimates. *IEEE Transactions on Engineering Management*.

Klatter, H. E., & Van Noortwijk, J. M. (2003, April). Life-cycle cost approach to bridge management in the Netherlands. In *Proceedings of the 9th International Bridge Management Conference, April 28-30, 2003, Orlando, Florida, USA* (pp. 179-188).

Klatter, L., Vrouwenvelder, T., & Van Noortwijk, J. M. (2009). Societal and reliability aspects of bridge management in the Netherlands. *Structure & Infrastructure Engineering*, *5*(1), 11-24.

Larsson Ivanov, O., Honfi, D., Santandrea, F., & Stripple, H. (2019). Consideration of uncertainties in LCA for infrastructure using probabilistic methods. Structure and Infrastructure Engineering, 15(6), 711-724.

Lee, K. P., Lee, H. S., Park, M., Kim, D. Y., & Jung, M. (2017). Management-reserve estimation for international construction projects based on risk-informed k-NN. *Journal of Management in Engineering*, *33*(4), 04017002.

Lhee, S. C., Issa, R. R., & Flood, I. (2012). Prediction of financial contingency for asphalt resurfacing projects using artificial neural networks. *Journal of Construction Engineering and Management*, *138*(1), 22-30.

Lind, H., & Muyingo, H. (2012). Building maintenance strategies: planning under uncertainty. *Property Management*.

Loosemore, M., Raftery, J., Reilly, C., & Higgon, D. (2012). *Risk management in projects*. Routledge.

Love, P. E., Wang, X., Sing, C. P., & Tiong, R. L. (2013). Determining the probability of project cost overruns. *Journal of Construction Engineering and Management*, *139*(3), 321-330.

Lundman, P. (2011). *Cost management for underground infrastructure projects: A case study on cost increase and its causes* (Doctoral dissertation).

Mak, S., & Picken, D. (2000). Using risk analysis to determine construction project contingencies. *Journal of Construction Engineering and Management*, *126*(2), 130-136.

Melnikovas, A. (2018). Towards an explicit research methodology: Adapting research onion model for futures studies. *Journal of Futures Studies*, *23*(2), 29-44.

Modarres, M. (2006). *Risk analysis in engineering: techniques, tools, and trends*. CRC press.

NASA. (2015). NASA cost estimating handbook Version 4.0 – Appendix G cost risk and uncertainty methodologies. Retrieved from:

nasa.gov/sites/default/files/files/CEH_AppG.pdf.

Ng, S. T., Cheung, S. O., Skitmore, M., & Wong, T. C. (2004). An integrated regression analysis and time series model for construction tender price index forecasting. *Construction Management and Economics*, *22*(5), 483-493.

NIC. (2021, November). / *The Second National Infrastructure Assessment: Baseline Report*. UK National Infrastructure Commission. Retrieved from: https://nic.org.uk/app/uploads/Revised-Second-National-Infrastructure-Assessment-Baseline-Report.pdf

Orcesi, A., 2016. CEDR transnational road research programme: re-gen risk assessment of ageing infrastructure. Brussels, Belgium: CEDR Transnational Road Research Programme.

Panthi, K., Ahmed, S. M., & Ogunlana, S. O. (2009). Contingency estimation for construction projects through risk analysis. *International journal of construction education and research*, *5*(2), 79-94.

Park, C. S. (2016). *Contemporary Engineering Economics*. Pearson.

Project Management Institute. (2017). *PMBOKGuideAgilePG* p. 156-161

Rehan, R., Younis, R., Unger, A. J., Shapton, B., Budimir, F., & Knight, M. A. (2016). Development of unit cost indices and database for water and wastewater pipelines capital works. *Journal of cost analysis and parametrics*, *9*(2), 127-160.

Reilly, J. J., Moergeli, A., & Sander, P. (2015). Risk-Based, Probabilistic Cost Estimating Methods. In *International Tunneling Association, World Tunnel Congress, Dubrovnik May*.

Ridder, H-G., Hoon, C. and McCandless Baluch, A. (2014) 'Entering a dialogue: Positioning case study findings towards theory,' *British Journal of Management*, Vol. 25, No. 2, pp. 373–87

Shin, H., Jung, Y., Jeong, C., & Heo, J. H. (2012). Assessment of modified Anderson–Darling test statistics for the generalized extreme value and generalized logistic distributions. *Stochastic Environmental Research and Risk Assessment*, *26*(1), 105-114.

Stewart, M. G. (2001). Reliability-based assessment of ageing bridges using risk ranking and life cycle cost decision analyses. *Reliability engineering & system safety*, *74*(3), 263-273.

Swei, O., Gregory, J., & Kirchain, R. (2017). A probabilistic approach for long-run price projections: A case study of concrete and asphalt. *Journal of construction engineering and management*, *143*(1), 05016018.

Thal Jr, A. E., Cook, J. J., & White III, E. D. (2010). Estimation of cost contingency for air force construction projects. *Journal of Construction Engineering and Management*, *136*(11), 1181-1188.

Towey D. 2013. Cost management of construction projects. UK: Wiley Blackwell. Retrieved from: http://147.252.1.45/record=b2505544.

Trost, S. M., & Oberlender, G. D. (2003). Predicting the accuracy of early cost estimates using factor analysis and multivariate regression. *Journal of Construction Engineering and Management*, *129*(2), 198-204.

U.S Department of Transportation. (2020, October). *Status of the Nation's Highway, Bridges, and Transit: Conditions and Performance Report to Congress (C&P Report)* (23 Edition).

U.S Department of Transportation. (2020, October). *Status of the Nation's Highway, Bridges, and Transit: Conditions and Performance Report to Congress (C&P Report)* (23 Edition). Retrieved from: https://www.fhwa.dot.gov/policy/23cpr/pdfs.cfm

UK Department for Transport. (2017). TAG UNIT A1.2 Scheme costs – transport analysis guidelines. Retrieved from:

Van den Boomen, M., Spaan, M. T., Shang, Y., & Wolfert, A. R. M. (2020). Infrastructure maintenance and replacement optimization under multiple uncertainties and managerial flexibility. *Construction management and economics*, *38*(1), 91-107.

Van Wee, B. (2007). Large infrastructure projects: a review of the quality of demand forecasts and cost estimations. *Environment and Planning B: Planning and Design*, *34*(4), 611-625.

Verschuren, P., Doorewaard, H., & Mellion, M. (2010). *Designing a research project* (Vol. 2). The Hague: Eleven International Publishing.

Wachs, M. (1989). When planners lie with numbers. *American Planning Association. Journal of the American Planning Association*, *55*(4), 476.

Wachs, M. (1990). Ethics and advocacy in forecasting for public policy. *Business & professional ethics journal*, 141-157.

Wang, N., Chang, Y. C., & El-Sheikh, A. A. (2012). Monte Carlo simulation approach to life cycle cost management. *Structure and Infrastructure Engineering*, *8* (8), 739-746.

Wibowo, A., & Wuryanti, W. (2007). Capacity factor-based cost models for buildings of various functions. *Civil Engineering Dimension*, *9*(2), 70-76.

Xenidis, Y., & Stavrakas, E. (2013). Risk-based budgeting of infrastructure projects. *Procedia-Social and Behavioral Sciences*, *74*, 478-487.

Yin, R. K. (2009). *Case study research: Design and methods* (Vol. 5). sage.

Younis, R., Rehan, R., Unger, A. J., Yu, S., & Knight, M. A. (2016). Forecasting the unit price of water and wastewater pipelines capital works and estimating contractors' markup. *Journal of cost analysis and parametrics*, *9*(1), 46-68.

Zhong, B., Li, H., Luo, H., Zhou, J., Fang, W., & Xing, X. (2020). Ontology-based semantic modeling of knowledge in construction: classification and identification of hazards implied in images. *Journal of construction engineering and management*, *146*(4), 04020013.