Extension of the Mitigation Controller for construction costing on the run

Minimizing cost overruns for construction projects

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2021

TU Delft

Master Thesis

Construction Management & Engineering

EXTENSION OF THE MITIGATION CONTROLLER FOR CONSTRUCTION COSTING ON THE RUN

MINIMIZING COST OVERRUNS FOR CONSTRUCTION PROJECTS

A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of

Master of Science in Construction Management and Engineering
Faculty of Civil Engineering & Geosciences

by

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October 2021

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ABSTRACT

The construction industry is notorious for its cost overruns in projects. It is important for any project manager to have as much grip on the financial situation of the project as possible. As most projects have an adequate risk management strategy, this study mainly focuses on dealing with the uncertainty within cost items.

For a project manager to formulate an effective mitigation strategy to reduce the cost of a project, a focus on the added value that mitigating measures have. Due to the experience that project managers have had in the past (both positive and negative), their views will very likely be coloured by an subconscious bias. To come to an effective mitigation strategy it is important that the impact of that bias is reduced as much as possible.

The main aim of this study is to find a way in which an optimal mitigation strategy can be found, which can maximise the probability of staying within budget given certain constraints. This has been done by developing a tool, which focuses on maximising mitigation strategy utility . The utility for all mitigating measures has been computed using their respective cost reduction and the associated project delay.

The tool that has been developed, the mitigation selector, is built up from three parts. In order to set the context in which the mitigation strategy has to be defined, a cost estimation is made. Using three-point estimations within a Cost Breakdown Structure and Monte Carlo Simulations, an estimate is defined. After this estimation, all potential mitigating measures are evaluated based on the ratio between their real cost reduction and delay. This ratio is the utility of each measure. The utility of a mitigation strategy is maximised in order to find an optimised mitigation strategy for each (over budget) iteration in the Monte Carlo Simulations. Once this individual optimisation has been completed, a generalisation is made in order to provide the project manager with a useful advise. Based on the most frequently used mitigating measures within all individual strategies, a strategy is defined which maximises the probability of staying within the project budget.

The mitigation selector was validated by using a real life case, the Roggebot bridge. The probability of staying within the initial cost estimation of €19.52 million had dropped from 70% to 21.2% after risks fired early in the construction phase. The mitigation selector was used to get this likelihood up to an acceptable level. After the mitigation controller ran, the most frequently used mitigating measures were presented.

In order to validate the tool, an evaluation mitigation strategy was defined which increased the probability of success to 74.6%. This strategy was compared to a group of project managers who had defined their own mitigation strategy based on the given case. The project managers were very consistent in that the results were very similar, which lead to their results being aggregated. This resulted in achieving a probability of 70.3%. This means that the mitigation controller outperformed the project managers.

To conclude, the mitigation controller is very capable of advising a project manager as to which mitigating measures are most effective in that specific situation. It is however important that the mitigation controller is not used merely once but is used continuously during the construction phase, as to keep up with the dynamic nature of the industry. However, the mitigation controller is capable of outperforming industry practitioners as it is not limited by subconscious bias.

PREFACE

With this thesis I finalise my Master of Science degree in Construction Management & Engineering, ending a long time studying at Delft University of Technology. The road to come to this point has been long and has had its fair share of difficulties. Without the help of certain people I would not have come to this point, for which I would like to thank everyone that has helped me during this journey. Starting with the members of my thesis committee: Prof.dr.ir. A.R.M. Wolfert, Dr.ir. R. Binnekampand Dr.ir. O. Kammouh. Thank you all for the insights that you have given me, even if they were not what I wanted to hear at those times.

A special thanks goes out to Mark Vlaanderen Oldenzeel, without whom I would not be where I am today with regards to this thesis. You have helped me tremendously with insights to the construction industry and with gathering data required for this thesis. I would also like to thank Jan Vonk and Bard Louis, who have helped me in the conceptual stages by asking questions surrounding how I envisioned certain elements of my thesis.

Besides the people that have helped me on the theoretical side of this thesis, I would also like to thank Olga Peters. As the Elite Sports coordinator at Delft University of Technology, you have listened to me ramble on about the combination of my rugby, thesis and work. Always available when I needed to talk and then coming up with an action plan has helped me get through this long journey.

Finally my biggest gratitude goes out to Eline Brandt, without whom I would have lost my mind on multiple occasions. You have also ensured that I kept on working on my thesis when the process did get rough, encouraging me that I could do it and that the end was in sight.

I hope you enjoy reading my thesis,

Rik van Dijk,
's Gravenhage, October 2021

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Part I

INTRODUCTION

1 INTRODUCTION

1.1 CONTEXT

The construction industry is one of the biggest contributors to a country's Gross Domestic Product. For example in the Netherlands, construction accounts for 5.4% of the Dutch GDP (Centraal Bureau voor de Statistiek, nd). Given this large contribution (third largest after manufacturing and sales), one would expect that the industry would be one that is efficient and utilises modern techniques. However this is not the case, according to a report by McKinsey & Company (2019) the construction industry has not had any major increase in productivity in the US since 1947. In contrast, both manufacturing and agriculture have experienced major developments in productivity (by a factor 8 and 16 respectively). These increases can mostly be explained by automation of the industries.

This makes one wonder why the construction industry stayed behind on other industries. It is apparent that manufacturing is the ideal industry to innovate in, as far as automation is concerned. A similar case could be made for agriculture, however is it fair to assume that construction is an industry that cannot be automated on a large scale? McKinsey & Company state that this assumption is not valid as there are three ways in which the industry can innovate in order to boost productivity. The first of which is the automation of the construction processes, e.g. robots doing physical tasks on a building site such as brick laying. The second manner is the use of automation in order to pre-fabricate elements of a construction using technology such as 3-D printing. The third and final way focuses on the digitisation of the design and management processes.

The third manner in which the construction industry can innovate using automation is vital for this thesis. McKinsey & Company is not the only big consultancy firm that addresses this potential change, KPMG (nd) agrees that the efficiency in the construction industry should be increased. KPMG does however focus on more than simply the efficiency in the construction process. It is stated that to ensure that the industry does not receive as much negative press as they do now, something should be done about how risks are dealt with during a project. To deal with these risks, one should identify them as soon as possible to ensure that they can be mitigated as effectively as possible. This effectiveness of the mitigation measures is, at this moment in time, still not at the level where it should be (according to KPMG).

To further help automate the construction industry, Deloitte (2020) states that using a more digital approach to cost estimations could yield large benefits. Deloitte speaks about this for the design phase. These methods can however also be used during the construction phase, to keep track of how the actual costs hold against the initial budget. If, during the design phase, a digital approach is used but a project manager reverts back to 'old' methods during the construction phase, they might lose track of the uncertainty that is ever present in the project. It is therefore important that during all phases of a construction project, the digital element is used for cost estimations.

1.2 PROBLEM DEFINITION

In section 1.1 it is shown that major steps can be taken in how the construction industry deals with the automation of its processes, both managerial and on the building site. One of the major areas that is being heavily researched already is cost estimation. As this is the case, this thesis will not focus on these estimations. The focus of this thesis will however lie with how to mitigate the risk of going over budget during the construction phase. This was also brought forward by KPMG as one of the important areas that strides should be taken in.

The construction industry, in its current state, is an industry that is wary of taking major leaps in modernisation. Certain steps are being made, for example the growing use of Building Information Modelling systems, but there seems to be a certain unease with changing how things are done. This keeps certain processes from being done in an efficient manner, which will maintain a sub-optimal way of working as long as no changes are made in the industry's processes. A good example of one of those sub-optimal processes is choosing which measures a project manager should implement in order to mitigate the cost overrun risks and uncertainty that a construction project carries.

The fact that this process is not automated, does not directly mean that the current practise is dysfunctional. A project manager will probably be capable to finding an acceptable strategy to mitigate the cost that is linked to the risks and uncertainties of a project. The mitigation strategy that is chosen might be able to reduce the project cost by such an amount that a cost overrun can be averted. However, it can be assumed that within a complex project environment the process of choosing this strategy is a difficult and tedious task.

Keeping in mind that it is indeed a tedious task and that it is not guaranteed that a project manager will choose the strategy with the best fit. A project manager wants to maintain the highest level of control over their project, without having to spend all their time on figuring out the best fitting mitigation strategy. To ensure that this is possible, the selection process should be taken away from the current manual fashion and be brought to an efficient method that has a transparent procedure (to maintain control over this specific process).

1.2.1 Development Gap

Current Situation: In the current situation a project manager manually picks a given set mitigating measures in order to reduce project cost. This process will most likely only reduce the cost overrun, even when there is a specific set of mitigating measures that would reduce the project cost to stay within budget.

Development Gap: The process that a project manager goes through to in order to mitigate a potential cost overrun of the project should be automated in order to obtain an optimised mitigation strategy. If this process is optimised and automated, the probability of a project staying within budget at the completion date will rise significantly.

1.3 DEVELOPMENT STATEMENT

Based on the development gap that has been described in the last sections, a development statement has been formulated. This thesis has the aim to reach this development statement within this study. Whether this has been the case will be discussed in chapter 7. This study's development statement is defined as:

"To develop a software tool that automates the process of finding the optimal cost mitigation strategy to enhance the probability of construction projects staying within budget"

To reach this development goal, several elements should be considered. The main considerations are stated below:

1. *What type of cost estimation is fitting for this tool?*
2. *In what ways can a project manager control project cost?*
3. *How can the selection process of a mitigation strategy be optimised?*
4. *How do the results of the proposed method compare to current practise?*

1.4 THESIS STRUCTURE

This report aims to work towards the development statement as posed in section 1.3. To do this the structure shown in Figure 1.1 will be used. This structure will be elaborated upon slightly below, where the contents of each chapter will be further explained in section 2.2.

Chapter 2 will hold the research methodology used for this research project. This chapter will talk about the detailed steps that will be conducted over the course of this report. Elements such as modelling techniques, data selection and the build-up of the research will be discussed.

In chapters 3 and 4 the first part of the actual research will be conducted as this will hold the analysis of the problem. This segment will focus on the literature study, to ensure that the elements of this report are based on a scientific foundation.

chapter 5 will provide information on how the proposed method works. Certain elements are explained further in depth, to provide further clarity about the proposed method.

In chapter 6 the proposed method will be evaluated and compared to current practise. This chapter is aimed at showing the added value that the proposed method brings.

Chapter 7 will be focused at evaluation the development goal, based on the chapters that lead up to the conclusion. Followed by section 7.3 in which the recommendations will be done for further research.

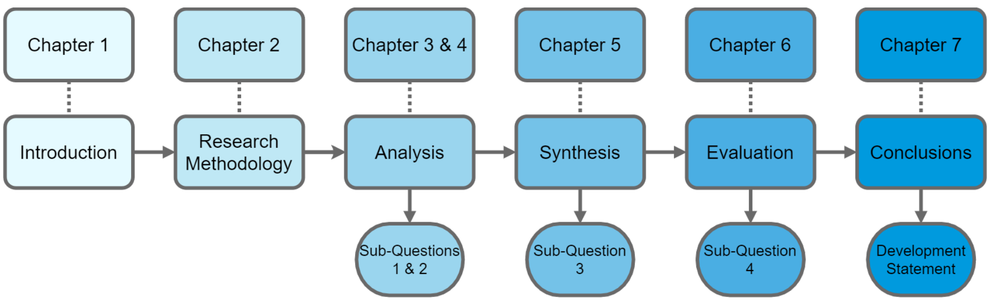

Figure 1.1: Thesis Outline

2 RESEARCH METHODOLOGY

This chapter will take the reader through the technicalities of this research project. Initially an explanation will be given as to why certain elements of this project are the way they are. After these elements have been elaborated on further, the lay-out and phasing of this research project will be shown and explained.

2.1 SCOPE

This research project will focus on how cost overruns can be minimised within the construction industry. This means that any projects outside of this industry will not be taken into account. The reason for this specific industry is the fact that it has a unique characteristic in its projects. As construction projects are mostly one-off projects that have an pre-established price, cost overruns can be disastrous for a construction project. As opposed to for example software or manufacturing projects where a cost overrun can be compensated for in the product's price.

A construction project is a system in which there are many interdependencies. This creates a situation in which it can be hard to analyse one element in this system. To ensure that this research project does not end up in a tangled and overly complex situation, certain assumptions must be made.

The first of which is focused on the balance between financial resources and time. As the goal for this thesis is to find a way in which a financial overrun can be minimised, it is assumed that any delay in the project does not cost the project any money. This assumption will be addressed in section 7.3, so that further research can take this into account.

The second assumption is based on the project phase that this research will focus on. This phase is the construction phase, more specifically the construction phase of a project that appears to go over budget. The reason for this assumption is the fact that if a project is running smoothly, there would be no reason to mitigate costs and this would therefore deem the research unnecessary.

The third assumption revolves around the mitigation measures that will be used during this research. For any mitigating measures used, a negative effect or 'price' will be defined. This means that a mitigating measures cannot be used without consequence. Within this research project, the negative effect of any mitigating measures will be a delay of the project. This choice has been made to ensure that one will never reduce the scope or quality of a project, in order to reduce the project cost. Following the triple-constraint trade-off, a project can never reduce either cost, time or scope without affecting at least one other negatively (Project Management Institute (PMI), 2017).

2.2 RESEARCH STRATEGY

As opposed to many theses, this report will not be structured based on the scientific method which is based on a scientific curiosity. This thesis will be mostly based on a more design focused method, which gets its basis from a practical need. This research project will also be built up in line with the grounds on which it is based. This leads to the research being split in three separate phases, which are based on the "three-phase design process" as presented by Khan (2006). This process calls for the following phases: analysis, synthesis and evaluation. The latter of which must be done in both a local (i.e. at every independent level) and the global level (i.e. the overall system level).

The process that is described by Khan is specified on discrete product design, however the outlined phases are useful within any engineering design process. This is the reason why the specifics of all the phases is not used exactly as prescribed. The general notion of these phases however will be translated to this specific design process. What these three phases hold, will be elaborated upon in the sections below (subsection 2.2.1, subsection 2.2.2 and subsection 2.2.3).

2.2.1 Analysis

The first phase within the process is the analysis. This phase focuses itself on the exploration of the system or domain in which the design will take its place. This exploration will be done through a literature review. The initial problem definition as described in section 1.2, will be elaborated upon. This will bring a clarification of the research gap with it as well. This research gap will then in itself show the need for a new artefact in this context.

Even though this study builds on the study by Kammouh et al. (2021), certain design choices will still be evaluated, as there is the clear difference between the original Mitigation Controller which was based on project planning and this study which focuses on project cost. Therefore this phase of the study will elaborate on certain design decisions, such as using a probabilistic model. Further details on the theoretical framework in which this thesis has been written will also be shown and explained.

After the theoretical framework is apparent, the first steps into the basic lay-out of the model will be taken as well. This means that during this stage of the research project, a conceptual model will be made, in order to ensure that the basic dynamics of the model are all clearly defined and well thought through. These dynamics will flow through from the theoretical framework that has been presented. The elements that have been mentioned in this subsection can be found in chapter 3 and 4.

2.2.2 Synthesis

Within the second phase of this research project the model will actually be designed in depth and will be made operational. Given the information that is provided in previous chapters a working model will be created during the synthesis. In order to obtain this model, an iterative method will be used. As each iterative step will have to provide a fully functional addition to the model, it is possible to verify the model during the process. This will simplify the process of finding bugs or unexpected outcomes, before the model grows too complex to find these errors.

The synthesis phase for this research will be split into two major elements. The first of which will focus on creating a well functioning cost estimation tool, based on the requirements that have been defined in chapter 3. Based on this estimation tool, further steps will be taken towards the development of the tool that will help answer the central research question. The details of this tool will be described in chapter 5. This chapter, however, will focus mostly on the development and technical aspects of the tool as the output and results from this step will be discussed in the next phase.

2.2.3 Evaluation

As mentioned, the evaluation will look at the output of the tool that has been developed in the synthesis phase. During this period of the research the usability and effectiveness of the proposed method will be looked into. This is all part of the verification and validation process. The focus in this phase will lie on the validation of the tool.

The model will be evaluated through an empirical experiment which is explained in subsection 6.3.1. This experiment will look at the difference between the proposed method and how practitioners in the field actually work. This comparison will be looked at through visual and statistical methods in section 6.3.

Required Case

In order to validate the tool, a real-world case must be obtained. This real-world project will be used as a test whether the tool can be useful on the construction site, as opposed to only being useful within research. In order to ensure that the tool can be validated, it is important that the case that is used has certain characteristics. The requirements for the case will become clear in the analysis phase of this research. The case that will be used, will be briefly introduced in section 6.1.

Part II

ANALYSIS

3 COST ESTIMATIONS

"In competitive, hard-money bids the cost estimate is the single most important element involved in the series of events that leads to profitable completion of a contract. Without an accurate cost estimate nothing, short of an act of god, can be done to prevent a loss, regardless of management competence, financial strength of the contractor, or know-how." Hicks (1992)

The quote above by Hicks shows the importance of a good cost estimation. Even if a manager is certain in their prowess in project management, a project is doomed to fail if the cost estimation is not done right. This is why this chapter focuses on cost estimations, prior to focusing on the influence of project managers on project costs. This chapter looks into different types of cost estimations that are used in the industry. Based on the information in this chapter a choice will be made as to the type of cost estimation fits this research project best.

3.1 TYPES OF COST ESTIMATIONS

Prior to diving into methodologies for cost estimations, the term cost estimation must be defined clearly first. To do that the definition of the International Cost Estimating & Analysis Association is used, which reads as follows: "Cost estimating is the process of collecting and analyzing historical data, and applying quantitative models, techniques, tools and databases in order to predict an estimate of the future cost of an item, product, program or task. Cost Estimating is the application of the art and the technology of approximating the probable worth (or cost), extent, or character of something based on information available at the time" (Mislick and Nussbaum, 2015).

This definition gives an insight in the elements that are needed to conduct a good cost estimation. The two elements that are most important for this thesis are *"...applying quantitative models, techniques, tools and databases..."* and *"...based on information available at the time"*.

The latter is one that this thesis finds part of its need in. As the definition says, an estimation is based on the knowledge that an estimator has while conduction the estimation. As most initial cost estimations are done prior to the final design being finished, not every piece of information is known to the level of detail needed. This might be the cause for certain underestimations of cost items. One can say that as the design has not been finalised yet in the design phase (or even tender phase) that a cost estimation in that project phase will always lead to issues further down the line. These issues could be mitigated by the tool that will be developed during this research project.

The former (*"...applying quantitative models, techniques, tools and databases..."*) is focused on the way that the information is dealt with. This method that is used to work with the data makes the difference in the quality of the estimate. According to PMI (2017), there are six different ways in which a general cost estimation can be conducted. These methods are listed as: expert judgement, analogous estimating, parametric estimating, bottom-up estimating, three-point estimating and data-analysis. These methods are used in general project management, which means that they should all be evaluated on being applicable on the construction industry. To do this, all six methods will be explored and evaluated.

Expert judgement is one of the least intensive estimation methods. This method relies on the fact that there are experts that have extensive knowledge of the industry and its projects. To come to an estimate, the expert looks at the characteristics of the project and bases their estimate on that. As mentioned in section 2.1, most construction projects are (partly) unique. This leads to the fact that a single estimate by an expert will probably not be reliable for complex construction projects.

Analogous estimations tie in with the concept of comparing the current project to previous projects. This method compares the current project to a historical project with similar characteristics. This is an estimation method that could be fitting for smaller projects in the construction industry. An example for this could be a country road, if recently a project was finished in the same region with similar characteristics, this type of estimation could prove useful to obtain a general idea of the cost of such a project. Unfortunately, this method would not work for the complex nature of most construction projects.

As mentioned construction projects are very often not easily compared to other projects that have been completed already. Parametric estimations add a level of scale to the equation. This estimation method derives its data from historical data, but in stead of using that data directly, it is based on a unit cost. This could for example be useful for a dual carriageway that has to be built. As dual carriageways are relatively uniform in their requirements (given there are no civil engineering structures needed) and with that cost per kilometre, one could use this to estimate the project cost for a newly developed road. Once a level of complexity is added to a project, it becomes harder to maintain this estimation method.

A method that keeps in mind the complexity and characteristics of a project is the bottom-up approach. This approach requires quite a lot of data in order to estimate the project cost. This method is based on the Work Breakdown Structure of a project. For all work packages a price is determined and by accumulating all these costs into one single price, a cost estimate can be provided. The cost of each item is a deterministic value, which ignores the uncertainty in the cost items.

The uncertainty that is missing in the bottom-up approach, is the basis on which the three-point estimation method is established. As the name implies, this method bases its estimate on three points. These points are the individual estimates for an optimistic, most likely and pessimistic situation. Based on the distribution that is used (triangular or Beta distributions) an expected value can be defined to define the estimation. Even though this method keeps in mind the uncertainty of the project as a whole, it does not incorporate the uniqueness of a project properly.

The sixth and final method is also the most complex one. This method is based on data-analysis. In recent years this method has been used in the construction industry, by using multiple types of Artificial Intelligence (Kim et al., 2013). This method requires the highest level of data from the six mentioned estimation methods. Through the analysis of large sets of data, patterns are found which lead to an estimate, given the projects characteristics (Matel et al., 2019). This method is used often by contractors in an early stage of a project as it gives a quick estimate without needing a high level of detail for the design. This early stage is also the moment in which these types of estimations are the most useful, as this will provide a reliable estimation based on limited information.

3.1.1 Fitting Estimation Method

The previous section has described the six most prominent types of cost estimating techniques, this section will discuss the best fitting method for this research project. This selection will be made through the characteristics of a large construction project. As mentioned at the beginning of the chapter, the cost estimation of a project might not be the main focus of this research project. However, if the initial costs estimation (that will be used as input for the proposed method) is flawed then this would also negatively influence the model that stands at the centre of this research project.

Implicitly, the characteristics of a large construction project have already been used in section 3.1 as this has been the basis on which certain methods have been critiqued. Generally speaking, large construction projects can be characterised as being uncertain and complex within potentially an even more complex and uncertain context (van Marrewijk et al., 2008).

The complexity of large construction projects demands a different approach to the uncertainty that is involved. This is why a hybrid method will be used for this research project. To work towards the complexity of a project, it is important that a high level of detail is included in the cost estimation. To do this the bottom-up approach will be utilised, in order to find the most realistic estimate based on the complexity. To facilitate the uncertainty of both the project and its context, the three-point estimate method will be added to the cost estimator that will be used for this thesis. This estimation method is also congruent with the method that is used by Kammouh et al. (2021) in their paper, which has the same aim as this thesis but is aimed at project planning in stead of project cost.

3.2 PROBABILISTIC ESTIMATION

The estimation method that has been chosen is the best fit for this research project, given the options that were presented by PMI (2017). The methods that were proposed by PMI are all of a deterministic nature. Even the three-point estimate is based on the expected value that is calculated through the pessimistic, most likely and optimistic estimations. As uncertainty is the key characteristic that will be focused on, it must be properly represented in the initial cost estimation. In order to do this the method that has been chosen, will be transformed into a probabilistic estimation method.

The combination of a bottom-up approach and the three-point estimate in a stochastic setting is not a novel approach. Introduced by Elkjaer (2000), this approach works for both the complexity and the uncertainty of larger construction projects. The manner in which Elkjaer transformed the hybrid deterministic estimation method to one of a stochastic probabilistic type is by running a high number of Monte Carlo Simulations (MCS). By drawing stochastic values (based on the three-point estimates) for all work-packages in the Work Breakdown Structure (WBS), before combining them to an expected project cost, the uncertainty is added for each and every cost item within all simulation. By doing this a high number of times, it can be assumed that this method approaches the 'true' expected value, based on the distributions used. The idea behind MCS will be elaborated upon in subsection 3.2.1.

By defining overarching risk items for the project (by defining both the probability and the effect based on a three point estimate), Elkjaer doesn't focus simply on the uncertainty within the cost items but also adds an overall uncertainty over the project. The types of risks that are included here are focused mainly on external influences, such as a subcontractor going bankrupt or contractual issues with the client.

One of the missing elements of the approach presented by Elkjaer is the fact that the estimation is based on a three-point estimate for each work-item in the WBS. As stated by Zhu et al. (2016), most large construction projects have a timeline that spans over multiple years. This large timeline leads to a situation where the unit price for materials will most probably not stay constant over the course of the project. By defining the separate underlying elements that constitute to the height of a cost item, the cost estimation can be expected to be closer to the true expected cost of a project.

3.2.1 Monte Carlo Simulations

In this section the idea behind MCS will be elaborated upon in order to define elements that can be taken into account in chapter 5. For this chapter a light will be shone on what MCS actually are and why it is useful within a probabilistic cost estimation as well as the elements that are needed in order to use Monte Carlo Simulations

Monte Carlo Simulations are basically experiments that get simulated a large number of times in order to obtain the statistics of the output variables. The statistics of the output are needed in order to understand what type of behaviour is present within the system that is being analysed. If, for this research project, the method proposed in subsection 3.1.1 would be used, a singular deterministic expected value would be produced. Even though the expected value would be based on the three-point estimates (therefore including the uncertainty of the cost elements), this single value would not show the range in which the expected project cost would lie. The output that is associated with MCS within the construction industry is an S-curve. The S-curve, as showed in Figure 3.1, is another name for the Cumulative Density Function (CDF). This curve shows the probability for any given value on that curve.

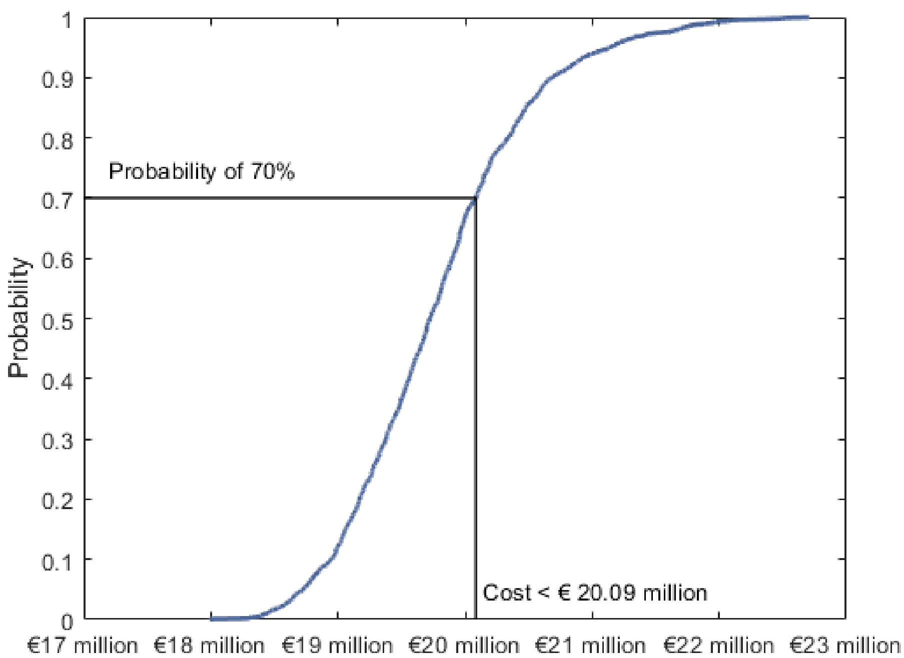

Figure 3.1: S-Curve for project cost

This curve allows for a project manager to define a budget as well as decide whether they need to act in order to reduce the project cost. As has been mentioned previously in chapter 3, cost estimations are based on *"...information available at the time"* (Mislick and Nussbaum, 2015). The fact that more information is available as the project moves in time, leads to cost estimations changing throughout the duration of a project. The S-curve that is based on these estimations will therefore also change. Once a project manager sees that their budget will reach a certain (arbitrary) low probability, they will need to act in order to keep the costs within bounds.

Now that the use of the Monte Carlo Simulations has been made clear, a closer look will be taken at what is needed in order to run MCS. As Monte Carlo Simulations are used in a multitude of research areas, there are a high number of tools that can help with conducting MCS. Regardless of the tool that one uses, any MCS boils down to three universal steps (IBM, nd), as stated below.

1. Define a mathematical model, which will be executed each iteration of the Monte Carlo Simulations.
2. Define the underlying statistical distributions for the independent variables used in the mathematical model.
3. Run the simulation a high number of times, generating random values for all independent variables in the mathematical model.

Of these three steps in the process to conduct MCS, the first will be handled in chapter 5 as this is a clear element of the synthesis phase. Defining the distribution that will be used has already been touched upon in subsection 3.1.1, this step however will be further elaborated upon in the next section. The third and final element is one that is more a practical step, rather than one that needs to be defined strictly such as the first two steps.

3.2.2 Probability distributions of random variables

As mentioned in subsection 3.2.1, the distribution from which the random values for each independent variable is drawn, is of high importance to the quality and validity of the MCS. To add to this Elkjaer (2000) states that there can be multiple types of distributions that are underlying to all cost items. This section focuses on the different types of distributions that can be used.

The distribution that will be used in this research has to be as match to the three-point estimation method as defined by PMI (2017). This means that any distribution will have to be adjustable to the three estimates that will be done for each and every cost item. Elkjaer speaks about two distributions specifically in his article, the triangular distribution and an Erlang-5 distribution. The latter of which is a specific case of a Gamma distribution. Vanhoucke (2013) mentions another distribution that is commonly used within project estimations, which is an specialised Beta distribution. Based on the Programme Evaluation and Review Technique (PERT), this distribution is tailored to a three-point estimate method.

In order to evaluate the fit for these distributions, one must use a clear set of conditions. For this, the conditions set by Back et al. (2000) will be used. Back et al. defined the following four conditions that a probability distribution within cost estimations should be held to. All three distributions that are looked at will be evaluated based upon these conditions, all three however are continuous distributions. This condition will therefore not be mentioned during the evaluation.

1. The distribution should have an upper and lower limit, in order to ensure that the input estimation will not be exceeded
2. The distribution should be continuous
3. The distribution should be unimodal, meaning that there can only be one maximum in the distribution
4. The distribution should be able to have greater freedom to be higher that lower in regards to the estimation. With this skewness of the distribution should be expected.

Triangular Distribution

The first distribution that will be looked at is the triangular distribution. As can be seen in Figure 3.2 the PDF of this distribution is a relatively straight forward one. The shape of this distribution is defined by three parameters. It has two parameters [a,c] that define the fixed interval in which the distribution exists. On top of that there is another parameter [b], which is the mode of the distribution (Jonkman et al., 2017). For Figure 3.2 the mode is the *most likely* value, where the fixed interval is defined by the *minimum* and *maximum*. For a distribution as 'simple' as the triangular distribution, the mean and the variance are also acquired relatively simple through Equation 3.1 and 3.2 respectively (Vose, 2008).

$$E(X) = \mu = \frac{(a+b+c)}{3} \tag{3.1}$$

$$\sigma^2 = \frac{(a^2+b^2+c^2-ab-ac-bc)}{18} \tag{3.2}$$

To evaluate whether this distribution could be fitting, the conditions by Back et al. will be looked at. It is clear that there is an upper and lower limit, as the parameters define a fixed interval. The same can be said for a single mode, as the *b* parameter is the mode of the distribution. As can be seen in Figure 3.2, the triangular distribution can provide a situation where there is a certain level of skewness, based on the mode and the extremities that define the fixed interval. This distribution complies to the conditions by Back et al. and can therefore be considered for this research.

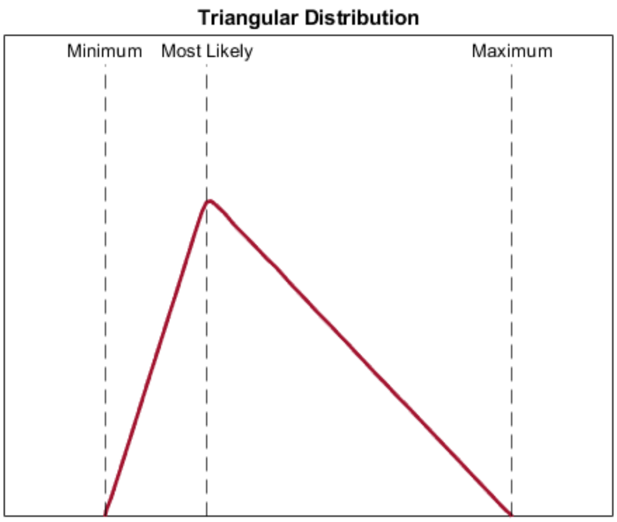

Figure 3.2: PDF for a Triangular Distribution

Erlang-5 Distribution

The second distribution that will be looked at is the Erlang-5 distribution that was mentioned by Elkjaer (2000). As mentioned previously the Erlang-5 distribution is a specific case for a Gamma distribution. Both distributions are defined by two parameters, being the shape parameter [k] and the scale parameter [θ]. A Gamma distribution in which k is a positive integer is equal to an Erlang-k distribution with the same θ. Based on the three-point estimation method that is used, the θ parameter can be calculated using Equation 3.3 and 3.4 (Salling, nd). Equation 3.5 shows the way in which the variance of the distribution can be found (Vose, 2008).

$$E(X) = \mu = \frac{min + 2.9 * ML + max}{4.9} \tag{3.3}$$

$$\theta = \frac{\mu}{k} \tag{3.4}$$

$$\sigma^2 = k * \theta^2 \tag{3.5}$$

Now that the distribution's parameters can be defined based on the estimation method that will be used, a closed look can be taken at the conditions by Back et al. as done before. As can be seen in Figure 3.3 the PDF of the Erlang-5 distribution is unimodal, with the mode close to the value that is the Most Likely value. The possibility for skewness of the distribution can also be seen clearly in Figure 3.3. However, as far as the first condition goes, having an upper and a lower limit, this distribution does not comply to the conditions that were set. As can be seen in Figure 3.3, values occur beyond the minimum and maximum values as defined in the three point estimate. This element of the distribution ensures that Erlang-5 is not compatible with this research project.

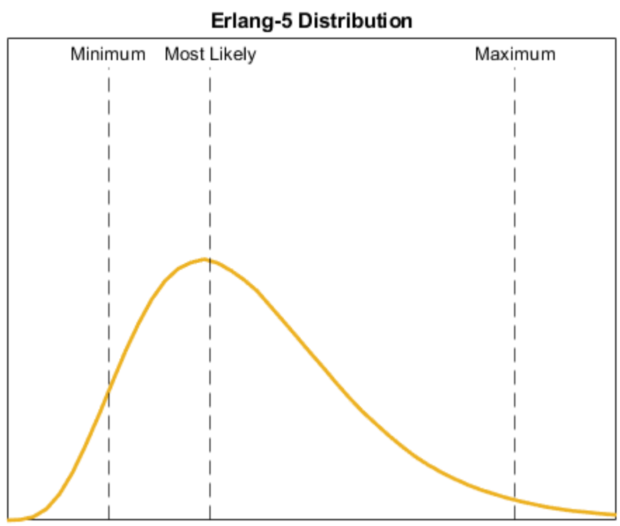

Figure 3.3: PDF for an Erlang-5 Distribution

Beta-PERT Distribution

The third and final distribution that will be looked at is the Beta-PERT distribution, which is a specific Beta distribution. As opposed to the standard Beta shape parameters [α&β], this distribution is defined by the same parameters as the triangular distribution; namely the minimum [a], most likely [b] and maximum [c] estimations. The shape of the PDF of this distribution is more bell shaped than the triangular distribution. This leads to values around the tails (especially the upper tail) being less likely to be drawn from a Beta-PERT distribution than from a triangular distribution. This also leads to different ways in which the expected value and the variance of this distribution can be calculated; as can be seen in Equation 3.6 and 3.7 (Vose, 2008).

$$E(X) = \mu = \frac{a + 4b + c}{6} \tag{3.6}$$

$$\sigma^2 = \left(\frac{c - a}{6}\right)^2 \tag{3.7}$$

With the parameters for the distribution given, as well as the expected value and variance, this distribution will also be tested to the previously mentioned conditions. This will be done by visually inspecting Figure 3.4 for its compliance to the conditions. If Figure 3.4 is inspected, one can see that the PDF of the PERT distribution is bound by parameters a & b as well as having only one mode in parameter c. Through this the first three conditions are met. The final condition is that the distribution should be able to have a skewness, which again can be seen in Figure 3.4. Through this visual inspection it can be concluded that the Beta-PERT distribution could be a fit for this research project.

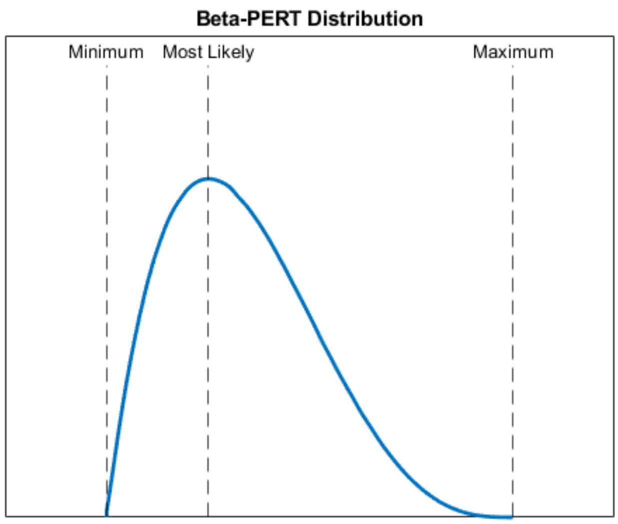

Figure 3.4: PDF for a Beta-PERT Distribution

Distribution Choice

Now that the three distributions have been checked to the conditions set by Back et al. (2000), only two are left. These are the Triangular and Beta-PERT distributions. This also falls in line with expectations, as these two distributions are fairly similar. The Beta-PERT distribution is a more natural version of the triangular distribution. This is the case as (due to the bell-like shape) the extreme values on the pessimistic side of the estimation are much less likely to occur than in the triangular distribution (as can be seen in Figure 3.5).
The fact that the probability on the upper bound is rounded on the Beta-PERT distribution makes for values that are centred around the most likely value more than is the case with the triangular distribution. This will, given an expert estimation, ensure that a project will not be overestimated as quickly as with a Beta-PERT distribution (Department of Transport and Main Roads, 2017). An overestimation of a project would lead to a higher need to mitigate cost overruns, which would lead to a situation where the project would have a longer duration due to mitigations being applied. Based on the fact that the Beta-PERT distribution is less likely to overestimate project cost when there is an expert estimation present, this will be the distribution that will be used for this research. It can be assumed that in any large construction project, the estimations that are used are either based on comparable historical data or on an expert estimation. This makes it reasonable to believe that the actual cost of any cost item will lie close to the estimation.

Adding to this is the fact that the standard deviation for the Beta-PERT distribution is lower than a triangular distribution with the same parameters. Using Equation 3.2 and Equation 3.7, one can see that the standard deviation will be lower. Given an estimate with: Minimum = 5, Most Likely = 10 and Maximum = 25; the standard deviations for the triangular and Beta-PERT distributions are 4.25 and 3.33 respectively. The lower the standard deviation of the individual cost items, the more specific the final project cost estimation is. This again leads to the choice of the Beta-PERT distribution for this research project.

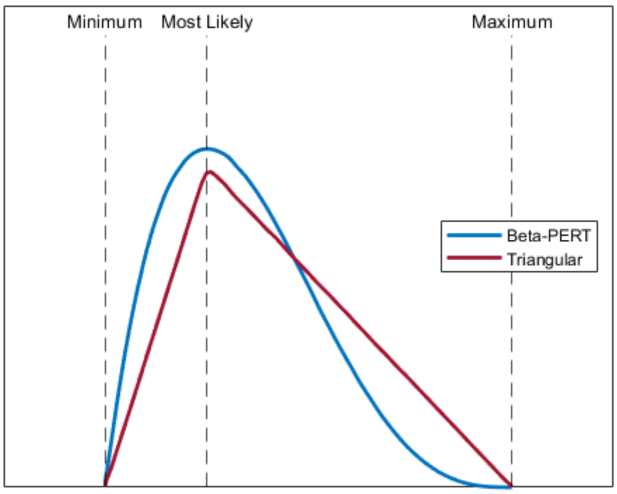

Figure 3.5: PDF for Beta-PERT and Triangular Distribution

3.3 CHAPTER SUMMARY

Within the construction industry cost estimations will always be the basis that a budget will be built on. A project manager will be held accountable to ensure that this budget stays within reach. In order for this budget to be achievable, the initial cost estimation should have a high level of realism.

The basis of this study lies with a realistic cost estimation. For that reason, types of cost estimators have been looked at in this chapter. Given the requirements that the construction industry presents, a choice has been made to use a combination between a bottom-up approach and three-point estimates.

A deterministic approach does not work with the uncertain nature that the construction industry has. This is why the earlier mentioned type of estimator that will be used, will be incorporated into a probabilistic model. In order to do this, Monte Carlo Simulations will be used in which random variables will be drawn from Beta-PERT distributions that are defined by the three point estimates

After all values are drawn for both cost items as well as risks for each iteration, they are all combined into a project cost. For all iterations within the MCS this cost will be determined, which will lead to a S-curve from which the cost estimate can be taken. The estimate that is used for this thesis will be the value that refers to a probability of 70%.

4 INFLUENCES ON PROJECT COST

Thus far the focus has been placed mostly on a field that is already being heavily researched, being cost estimations. This chapter however will shift that focus more towards the main aim of this research project, being influencing project cost. In order to add anything on how project costs can be influenced, one must look at what influences are present on a project already. This is how this chapter will begin with section 4.1, discussing how risk affects projects. In section 4.2 additions will be made to what has been discussed in chapter 3 by looking at the level of uncertainty present in projects, as well as what its effect is on the eventual project cost. To end this chapter, section 4.3 will consider one of the most important areas for this thesis, being what a project manager can do to influence the cost of a project.

As mentioned, this chapter is focused on gaining control over the cost of a project. Besides the obvious fact that there are limited funds in a project organisation, there is a deeper psychological need to gain financial control. Maslow (1943) introduced the hierarchy of needs, as can be seen in Figure 4.1, in which the levels of human needs are depicted. After basic physical needs that are needed to survive, safety is the next level of human needs. Maslow states that if one's needs in the previous level are not met, they cannot focus on a higher level fully. In other words, if someone is stuck working on one of the more basic needs, they cannot excel in their activity. Safety is defined by Oxford English Dictionary (nd) as being: *"the state of being safe and protected from danger or harm"*. Within this definition and the context of a construction project, harm can be seen as either physical or economic damage. This is why a project manager needs to have a certain level of control over the financial status of a project, before they can focus on bigger picture elements of the project.

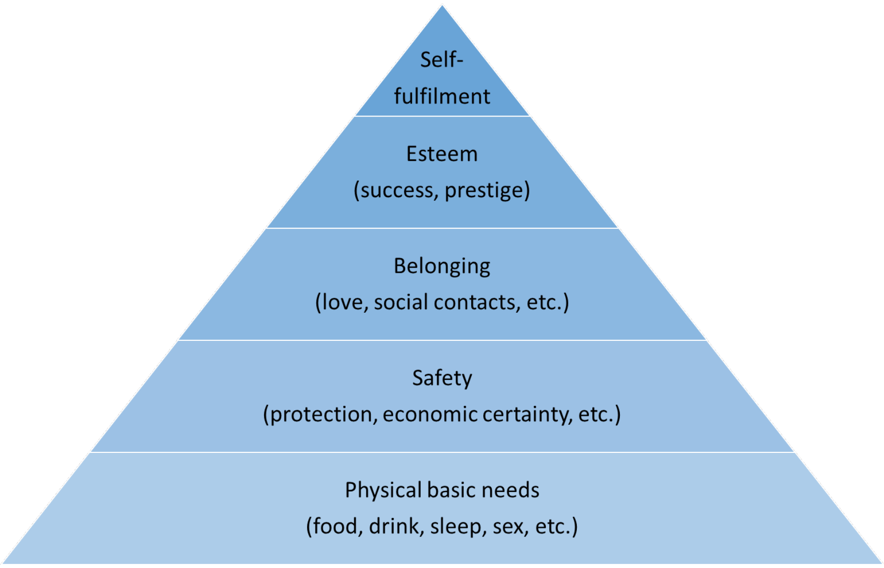

Figure 4.1: Hierarchy of needs (Maslow, 1943)

4.1 RISK

Within the world of risk and project management, risk is not merely a negative effect. For this thesis, the following definition is used: *"Risk is the positive/negative consequence of a potential event (with a given likelihood) on the financial outcome of a project"*(International Organization for Standardization (ISO), 2009a).

This definition ensures that there are both positive and negative risks. In order to ensure clarity within this thesis and to steer away from any individual assumptions, risks will be specified into two categories. The first of which holds the negative risks which will be called threats from here on out. The second category holds the positive risks, which will be called opportunities. Whenever a reference is made to risks, both of these categories are talked about.

Even though risks have a large impact on a project's cost, the formal risk management process falls outside of the scope of this study. This will be further explained in subsection 4.1.1. While 4.1.2 will take a closer look at how risk perception and risk attitude affects the decision-making process of a project manager.

4.1.1 Risk Management

As the concept of risk has been defined for the context of this thesis, the most logical step to take would be to look at how risk management is used within construction projects. Many sources propose certain frameworks to work with risk within construction projects (PMI, 2017; Meyer and Reniers, 2016; ISO, 2009b; Mills, 2001; Al-Bahar and Crandall, 1990). These sources can all be generalised into one basic framework as can be seen in Figure 4.2.

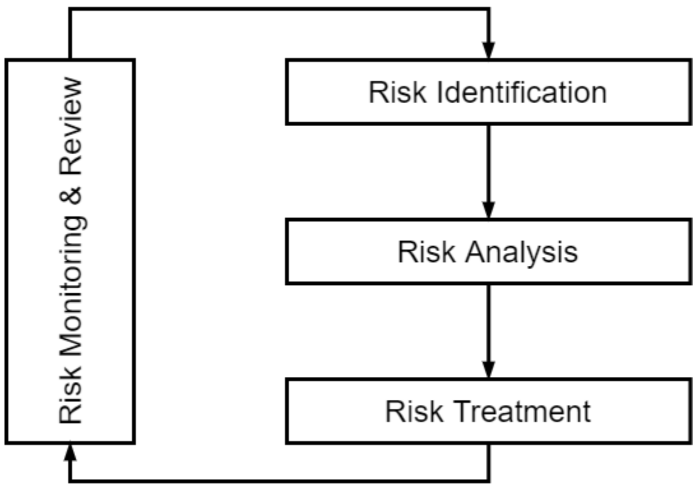

Figure 4.2: Risk Management Framework

The process in Figure 4.2 show the steps that should be taken when dealing with risks, in which the *Identification, Analysis & Treatment* are part of the 'active' process of risk management. *Risk Monitoring & Review* is an ongoing process that must be done continuously.

These 'active' processes of the risk management framework, are largely done within the preparation phases prior to the construction phase. Even though these steps within the framework have a very large impact on whether a project will stay within budget, it is mainly done within the preparation phase. Monitoring and reviewing risks should be done continuously during a project, but will eventually lead back to the 'active' steps within this framework. It is therefore decided that the risk management process falls outside of the scope of this study.

Even though the processes as mentioned are outside the scope for this study, they will still have an effect on the total project cost. For that reason it is assumed that the risk register that is used within the cost estimation has already gone through the risk management process. This means that a project manager has already looked at the following potential actions: eliminating, reducing, assuming or transferring the risk (PMI, 2017; Meyer and Reniers, 2016; ISO, 2009b; Mills, 2001; Al-Bahar and Crandall, 1990). As these actions have already been taken, the effect or likelihood of a risk have already been mitigated as much as possible.

The fact that the project risks have been dealt with as good as possible, does not mean that they are no longer in play. After treating a risk, there will most likely be residual risk that is left after treating it. This could mean that the effect has been reduced, but not eliminated from the project. Another way in which risk could still affect the project, is through secondary risk, which is a whole new risk that has occurred due to the treatment (Meyer and Reniers, 2016).

4.1.2 Risk Perception & Attitude

The way in which a project manager looks at risks has everything to do with their risk perception and risk attitude. Even though it was just stated that the process of risk management is not vital for this study, the way that a project manager looks at risk is very important for a project. This perception of risks as well as the attitude towards those risks, can influence the actions of a project manager massively.

Risk perception and risk attitude are two very different phenomena. Risk perception can be seen as how one perceives either the likelihood or the consequences of a risk. On the other hand, risk attitude has effect what level of risk someone is willing to take in order to achieve project success.

To put this in an analogy, picture someone wants to jump over a brook to make sure they are in time for a meeting. The perceived likelihood of them landing clear of the water and the perceived expected damages if it fails (e.g. damage to belongings or physical harm) are the risk perception. This also includes the perceived time gain from the jump. Whether the person still would jump over the brook, given their risk perception, is their risk attitude. Certain people will never make the jump, even if the perceived likelihood and consequences are low, where other people will always take the jump regardless what the likelihood and cost for failure are.

Risk Perception

The risk perception of anyone is highly dependant on certain psychological processes. According to Tversky and Kahneman (1974), three types of mistakes can be made as to how one perceives risk. Tversky and Kahneman define three 'heuristics' in which several types of cognitive biases are grouped. A cognitive bias is a mental short-cut that can be taken to come to an estimate more quickly, the issue with these biases however is that there can be major flaws in the estimations that are made. Below the three heuristics will be explained, together with selected biases that are then specified for the construction industry.

The first heuristic is *representativeness*. This heuristic tends to look at certain characteristics and expectations that people have of situations or groups. People tend to base their estimates on representative stereotyping in stead of looking at basic statistics and probability. One of the cognitive biases in this group is misconception of chances, which states that people get a faulty idea of probability when they are faced with the idea of randomness. An example for this would be a building site where six excavators are active, they all work on a different area of the site and are therefore independent. They all have a 50% chance of failing. According to this bias, it would seem more 'logical' for someone that three excavators are failing at the same time than all six of them. Statistically however, the events are independent and therefore the probability of any combination is as likely as any other (given the 50% failure rate)

Availability is the second heuristic. This heuristic is based on the fact that people tend to base their estimates on active memories or recent information. A bias within this group is the bias due to retrievability of instances, which describes that things that are top-of-mind will have a larger impact on estimations than things that are not all that present in their minds. Within the field of risk perception, this is seen as the most influential heuristic of the three (Sjoberg, 2000). The way in which this heuristic can show up within the construction industry is relatively easy. If the last project that a contractor undertook went over budget on one element then it is likely that this element will be overestimated (either likelihood or consequence) in the following project. This does not only happen when this happens within their own organisation, if a recent news article reported something about sheet piles failing then this might also have an subconscious effect on their estimation concerning the risk of using sheet piles.

The third and final heuristic is *adjustment & anchoring*. This group is based on not adjusting an estimation far enough away from an initial value. In this case a value can either be an actual estimate from a partial computation, or even a random value. Estimators tend to stick relatively close to that initial value, even when statistically this might not be logical. One of the biases in this group is insufficient adjustment, in which an estimate is made based on a given starting point or based on an incomplete computation. In either cases the estimator will stick close to the given point or the solution of their incomplete computation. Within the construction industry this could for example happen when a project manager asks an estimator what the consequence or likelihood of a certain risk is and already gives their own expectation. According to this cognitive bias the estimator will most probably stick relatively close to this value, even if they would normally estimate a highly differing value.

As mentioned within these three heuristics, multiple cognitive biases are present. The aim of the explanation above is to clarify the fact that based on subconscious cognitive biases, risks can be evaluated in a way that is not statistically or logically sound. This has its effect on how risks are evaluated, as threats can be under-estimated and opportunities over-estimated. Most examples have focused on over-estimations, however these mistakes can also be made to under-estimate risks and their likelihoods. This shows that even if, based on the available risk information, risk management is done well there is still an element of those threats that needs to be dealt with.

To add to the incorrect estimations of the risks, communication surrounding those risks can also create issues within a project. The fact that many have their own definition of risk (e.g. only threats) means that the way in which someone communicates about these risks is not always going to be congruent with theory or a formal definition. In a study by Bryde and Volm (2009), this has proven to generate issues within the project team. The manner in which the risk communication was done lead to sub-optimal risk management from a project manager and project owners, as they were talking about their risk perception in stead of talking about the actual risk.

Risk Attitude

As opposed to risk perception, which is subconscious, risk attitude is a conscious choice. One's risk attitude is a response to the present risk perception. The way in which someone acts is based on their risk perception and attitude. The interconnection between these elements of risk management can be found in the KPABC-cycle (Meyer and Reniers, 2016) as shown in Figure 4.3. This cycle shows that one's behaviour is an effect of their knowledge, perception and attitude. The behaviour that someone shows however, also has its consequences from which they will learn once again. As mentioned previously communication is troublesome if one's risk perception or attitude is different to someone else's.

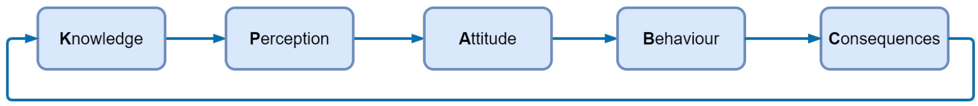

Figure 4.3: KPABC Cycle (Meyer and Reniers, 2016)

Now that it is established that risk attitude finds its basis in risk perception as well as previous experiences, the types of risk attitude can be described. There are three common types of risk attitude: risk-averse, risk-tolerant and risk-seeking. On top of these, two more extreme cases can also be used (risk-addicted and risk-paranoid), these will not be used however as they are very rare (Meyer and Reniers, 2016). In the example of the availability heuristic regarding risk perception, the estimator had developed a risk-averse attitude, based on their perception. This means that they would prefer to have a lower uncertainty within the project, as they have recent experience with the negative consequences of 'accepting' higher risk (as per the KPABC-cycle, Figure 4.3).

The three types of risk attitude have their own implications on the way in which a project manager would approach a project. To fully understand the difference between the three types, a closer look has to be taken at these terms actually mean. These terms are based on the expected value and the potential earnings from a situation. A risk-tolerant or risk-neutral person would go for the situation with the highest expected value, in this sense this attitude is the most rational. A risk-averse person would be willing to take a lower value item if it is guaranteed over a higher expected value, which is based on uncertainty. Risk-seeking behaviour is the exact opposite, as this is where someone would be willing to take a risk in order to get a higher pay-out than the guaranteed pay-out which would be higher than the expected value (Kahneman and Tversky, 1979).

The fact that the behaviour for a project manager can change, due to their risk attitude, means that even with the same project manager it is not always clear how they will deal with risks. Imagine a project team that has worked together on many projects, but their last project was completed for much less that originally budgeted. That could mean that the project manager their risk perception changed to seeing smaller chances of threats firing. This could lead to the project manager becoming risk-seeking, as opposed to risk-adverse (which may have led to the low project cost). If this attitude goes unnoticed, this could lead to overruns in the following projects as the risks will be managed in a way that disregards threats with small likelihoods, even if they have large consequences.

4.2 QUANTIFYING UNCERTAINTY

Within the literature uncertainty and risk are often interchangeable, as uncertainty is such a large portion of risk. According to the earlier stated definition of risk however, uncertainty is merely an element of risk (being the likelihood of a potential event). Uncertainty itself has a broader impact on project cost than merely through the risks that a project endures. The impact and effects that uncertainty can have on projects will be the central point for this section.

It has already been mentioned previously in section 3.2, that uncertainty within the cost items of a project should be taken into account in order to make a realistic cost estimation. This is the reason why probabilistic cost estimations are a better fit than deterministic estimates that only use the expected value or mean of a distribution.

In subsection 3.1.1 a hybrid method was chosen that incorporated both a three-point estimation and the bottom-up method. Where the three-point estimation method has been dealt with as far as the choice of distribution goes, the same cannot be said about the bottom-up estimate. This element of the cost estimation method will be elaborated upon here.

In order to work with the bottom-up approach, a project needs to be dissected into a WBS. The WBS breaks down the project into smaller work packages, that can be easily overseen. Every activity of the project should be included into the WBS, to ensure that all elements are taken into account. When building a house, one could dissect this into work packages that are as small as pouring concrete for the foundation or laying the roof tiles. When this has been done for all subsystems, any project - no matter how complex - can be simplified into achievable tasks.

Having the activities decomposed into bite-size pieces, is the first step to figuring out how much a project would cost. As mentioned, no matter how complex a project is, once it is decomposed into small packages it is manageable and workable. Ask a number of experts to estimate the cost of a highly complex and unique infrastructural project, the answers you will get will probably have a large spread. Ask those same experts to estimate what each and every manageable work package would cost and they will probably be able to come to estimations that are closer together and more importantly closer to the actual cost of the project. This is the exact manner in which a CBS is created, hanging price-tags on all work packages and aggregate them to from the total project cost.

The question that arises from this however is, how specific should one go to make and keep it manageable? A project manager should still be able to overview all of these work packages, so one cannot account for every wooden beam or nail. According to du Bois et al. (2017) one should go to a level of detail *"...wherein the resources (plant, labour, materials and subcontractors) to accomplish the work are readily distinguishable and discernible"*.

As can be seen in the quote from du Bois et al., four types of resource based cost elements should be used to determine the cost of one single cost item. This adds an extra level of detail to the estimation, compared to an estimate based on one probability distribution for an item. As these four cost elements are individually uncertain and are independent, they should all have an independent distribution from which their value will be drawn.

4.2.1 Cost Elements

According to du Bois et al. there are four cost elements that are needed in order to go from a WBS to a CBS. These four elements are as follows: *plant, labour, materials & subcontractors*. The summation of these four elements will be the cost for a particular cost item. Each of these elements are dissected even one level further as they are all split it a quantity and a unit rate element. What this split means for every cost element, will be looked at below. The split of these elements is shown in a CBS format in Figure 4.4

The first element that will be looked at is *plant*. To ensure clarity as to what this cost element is, it will be called the *equipment* element from here on out. This name clarifies what costs fall under this umbrella, it is all the hardware that is needed to execute the work at hand. In theory this could go from a screwdriver to a tower crane, and everything in between. In practise the larger equipment such as tower cranes, excavators and pile driving equipment will be put under this cost element. Each type of machinery has their own unit cost per hour or per action (e.g. cost per driven pile), which includes general repairs and consumables. As the WBS is based on work packages, these individual rates should be aggregated into one unit price per quantity unit for any given activity.

The second element that du Bois et al. mention is *labour*. As mentioned all elements use a quantity and a unit rate element in order to generate the element cost. For labour however, this quantity is not necessarily the dimensions of the work package. The quantity in this case is the hours worked on that work package (Dukers, 2002). For the unit rate, the hourly rate for someone working that work package should be used.

Materials is the next element that should be used. The way in which this element is split up is the exact same as is the case for equipment. As mentioned before not every screw can be accounted for within a cost estimation, which means that there should be a rough estimate on what the unit rate would be per quantity unit. The issue with material however, is that it is the most volatile of the cost elements (Azhar et al., 2008; Olatunji et al., 2018). Azhar et al. state that issues such as raw material and produced material cost fluctuation are two of the top contributors to construction cost overruns. Olatunji et al. mentions that all other cost elements are highly volatile as well, it is however also mentioned that the fluctuation in material cost can account for a large part of the variability in item cost.

The fourth and final element is *subcontractors*. For this element again a similar build up can be used as for both material and equipment. It is not uncommon however to specify a work package specifically to a subcontractor. This means that the quantity unit might be '1 element' with a given price, in stead of 'x amount of product y' which constitutes for a clear unit rate. It will happen that the latter type of quantity will be used for subcontractor work as well.

Now that all four of the cost elements have been specified into their individual segments, one common denominator shows up in three out of four elements, *quantity*.

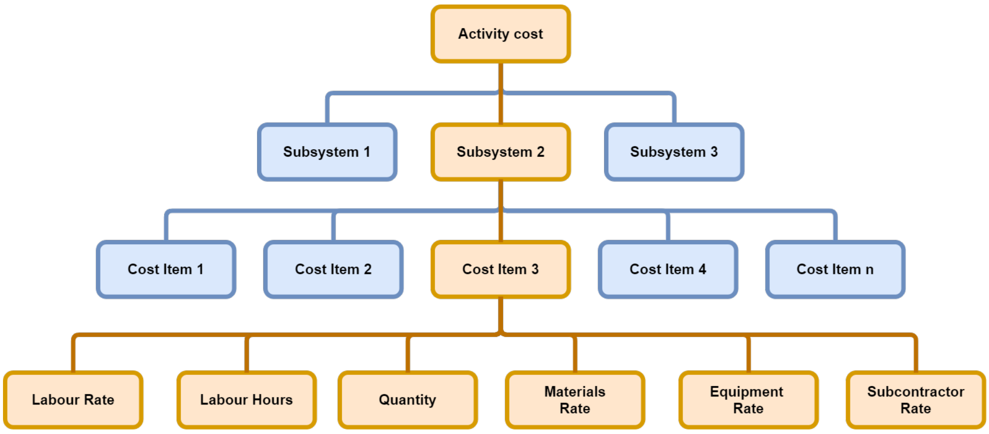

Figure 4.4: Example of a CBS

For the material, equipment and subcontractor elements, quantity has been defined in the same way for all three elements. For labour however, this is not the case as the unit for quantity there will be time related, in stead of activity related. The fact that quantity can be generalised for material, equipment and subcontractor costs leads to Equation 4.1.

$$C_n = LR_n * LH_n + Q_n * (Mat_n + Eq_n + Sub_n) \tag{4.1}$$

In which:

C_n	=	Cost for item n
LR_n	=	Labour Rate per hour for item n
LH_n	=	Labour Hours for item n
Q_n	=	Quantity for item n
Mat_n	=	Material unit rate for item n
Eq_n	=	Equipment unit rate for item n
Sub_n	=	Subcontractor unit rate for item n

In order to simulate the uncertainty that is present in real world situations, all of the above mentioned elements should be stochastic values, drawn from a Beta-PERT distribution. This process is data intensive, as all these estimates have to be made. It will however generate an estimation that will be more realistic than using one distribution per cost item.

4.2.2 Opportunities and Threats

Given the quantification of the cost items, a similar process must be done for the opportunities and threats that are involved in a project. In order to do this, the definition of risk from section 4.1 must be used. In this definition three main concepts were used: *potential event, likelihood & consequence*. The main priority for the quantification for the risks are the likelihood and consequence. As both opportunities and threats are risks and have the same build up, no difference will be made between the two here. The consequence of the risks are relatively straightforward, as a value will be drawn from a Beta-PERT distribution, given a three-point estimate as parameters.

The effect of a risk on the financial outcome of a project mainly depends on the fact whether the risk fires or not. In a real life project this would be easy as a project manager would see this happening and would notice the consequence. Within a simulation the situation should be similar. To achieve this a Bernoulli distribution will be used to 'fire risks'. This way either a risk fires or it does not, completely dependent on the likelihood that the risk event would take place in a real world situation.

Any risk should have their likelihood defined during the risk analysis of a project. Based on this likelihood [p], a random value [1 or 0] from a Bernoulli distribution will be drawn. If the random number is equal to 1 then the risk has fired in that simulation of the project, if the drawn number is equal to 0 then the risk has not fired. For this to happen the Probability Mass Function for a Bernoulli distribution is defined as can be seen in Equation 4.2 (Dekking et al., 2007).

$$f(p_X) = \begin{cases} p & : \ x = 1 \\ 1 - p & : \ x = 0 \end{cases} \tag{4.2}$$

Now that both the way in which likelihood and consequence will be dealt with are known, an equation can be set up to show the impact of risk on the total project cost. Similar to how the cost for all cost items are summed up, so will all risk effects also be summed up.

$$R_T = \sum_{i=1}^{j} RC_i * X_i \tag{4.3}$$

In which:

R_T	=	Total effect of all risks
i	=	The i^{th} risk
j	=	Total number of risks
RC_i	=	Drawn consequence for risk i
X_i	=	Drawn value Bernoulli distribution for risk i [0,1]

4.2.3 Total Project Cost

Based on Equation 4.1 and 4.3, an equation that describes the total project cost (TPC) can be defined. To come to the total project cost, one should sum all cost items and risks together. By doing this, all parts of the project that have an impact on the project cost are included. As the consequences of threats and opportunities have different signs (threats are positive, opportunities negative), a summation will provide the required result. The complete version can be found in Equation 4.4. Within this equation m stands for the total amount of cost items within the CBS.

$$TPC = \sum_{n=1}^{m} LR_n * LH_n + Q_n * (Mat_n + Eq_n + Sub_n) + \sum_{i=1}^{j} RC_i * X_i \quad (4.4)$$

As the above mentioned Equation 4.4 is the summation of two elements (cost items and risks), it can be boiled down to a more elegant equation. In this more elegant equation, 4.5, both elements are described by one variable, in stead of restating both Equation 4.1 and 4.3.

$$TPC = R_T + \sum_{n=1}^{m} C_n \quad (4.5)$$

4.3 PROJECT MANAGERS' CONTROL

Thus far the focus was put mostly on how to come to a realistic cost estimator. This has all been necessary to understand what project cost is based on. As the main aim of this study is to find a way in which project cost can be steered with effectively, it should be clear what this cost is built out of. This is required to find effective manners in which project results can be influenced.

For this study, the risk management process falls outside of the scope. Therefore the assumption is made that the risk register that is present, is one that has already been cleaned up as much as possible by either reducing, eliminating or transferring risks. This would normally be a way in which project result could be adjusted. But as it already is common practice within the construction industry, it can be assumed that any project manager has already done this as effective as possible.

With this falling outside of the scope of this study, there is only one way left that can be used. This is by adjusting the cost elements in such a manner that is possible for a project manager. This is why it has been as important to understand the building stones of the total project cost. In the following section, this manner of influencing the project's financial state will be further elaborated upon.

4.3.1 Areas of control

Knowing that the cost elements are the controls that can be used in order to reduce project cost, throws up the question of how this can be done. In theory any cost could be reduced by negotiating new prices for materials and services by subcontractors. In practice though, this is not a viable option, especially not one that will reduce overall project cost (e.g. due to contractual obligations). The same goes for hourly rates for employees, a project manager cannot decide to pay them less than minimum wage in most countries in the European Union. Below certain examples will be given for how certain cost elements can be controlled, in order to reduce cost.

As mentioned, a project manager cannot simply go to their supplier to renegotiate the prices for materials. If this would still be possible then the preparation for the project has not been done adequately. In order to reduce the material rate for a certain cost item, one needs to be more creative in how the buy-in decisions are made. A possibility would for example be to delay acquiring materials until a point in time where they are needed, this could help reduce material costs by buying at a lower price (Meng et al., 2018). In this way a project manager is working with the supply chain to ensure an ideal situation.

Where a project manager is very unlikely to reduce hourly labour rates, they might be able to adjust the amount of hours that are being worked. By reducing the amount of hours that have to be worked on a building site, one of the biggest cost elements of a project can be reduced. Labour cost constitutes to 25% - 40% of total project cost (Laufer and Jenkins, 1982). By adjusting the manner in which certain activities are being executed, could reduce the time spent on that activity. It would take extra time to prepare the activity or potentially even increase material costs slightly (Proverbs and Holt, 2000). If that would mean that the total cost of that activity would go down, if would be a useful tool to use as a project manager.

Controlling the expenses of an activity can also be done in a way where extra work needs to be done. A good example of this is that, prior to driving piles, extra soil samples are taken to map the soil on a site. This could lead to unexpected soil strengths that either let a project manager proactively add piles to ensure no damage will be done to the structure. It could on the other hand also lead to less piles being needed as there will be less surprises in the soil that need to be accounted for through over-engineering. By potentially reducing the amount of piles needed, the quantity element of the cost item can be reduced.

Another way to ensure that costs are more manageable as a project manager is by making sure that all activities are done to the expectation and requirements that are set. This is especially important when dealing with subcontractors. As they are an external element within the project environment, they might have different priorities than the project manager. As re-works account for a considerable percentage of the whole project cost (Love et al., 2004), it is important to make sure that they are kept to a bare minimum. Love et al. state that quality management and project coordination are vital in this process. If it is possible to guarantee that subcontractors stick to their brief and execute it well, costs can be controlled through the subcontractor element.

The final way in which costs can be controlled is by maintaining a high efficiency with regards of equipment. Projects will mostly use certain heavy machinery for multiple activities during their timeline. By ensuring that certain activities are planned in such a way that this optimises equipment usage, would reduce the equipment element. A good example for this is by maintaining a good equipment flow within a lean construction environment (Thomas et al., 2002). When the flow of equipment through the processes of a project are kept clear, one could achieve reductions in equipment rates here as well, due to less machinery being present on site.

Downside of Control

It might sound ideal to reduce project cost in ways that seem relatively easy. As with most things in life, this also comes at a cost. The tricky part in this is that there is no financial cost to these mitigations, otherwise they would not be effective. So if costs should be reduced, what should be given up in order to make this happen? If one looks at the very well known *triple constraints triangle*, as depicted in Figure 4.5, there would be two options. The triple constraint model prescribes that if the performance of one of the three has to be improved, that at least one other's performance should worsen (Dobson, 2004). Given the fact that most large construction projects have a public function to fulfil, the performance constraint is one that cannot diminish. As a result of this, the downside of cost reduction within construction projects will be time.

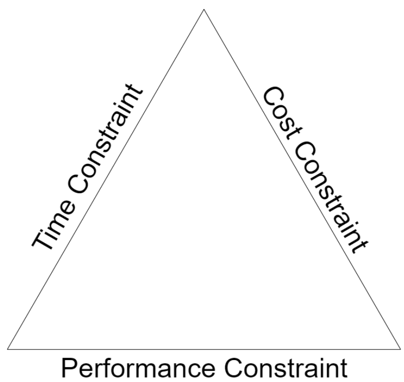

Figure 4.5: Triple Constraints of Project Management (Dobson, 2004)

Mitigation Measures

The measures that have been mentioned in this section are only a few of the options that a project manager has to steer a project's finances. In order to make adjustments that will affect the project outcome, a multitude of these mitigating measures are needed. Each of these mitigating measures should be a realistic and executable measure. In order to use mitigating measures, several elements should be clarified. Each measure should be given a name, cost reduction (and on what cost element) and a negative side-effect (being the delay). In Table 4.1 a hypothetical set of mitigating measures can be found.

As can be seen in Table 4.1, the cost reduction per mitigating measure is not clear when defining the effects. This is the case as all mitigating measures have an effect of a cost element level, which are not all measured in a monetary value. To find out what the reduced costs are for any given measure, the original cost element value must be reduced by the *element reduction* in Equation 4.1. The difference between this new value and the original item cost, is the cost reduction for that particular measure.

Mitigating Measures

Name	Impact on	Element Reduction	Delay	Linked Activity
Sampling soil prior to driving piles	Quantity	6 piles	8 days	25
Maintaining good Equipment Flow	Equipment	30%	21 days	13
Changing construction technique	Labour Hours	400 hours	18 days	66
Quality control on subcontractors	Subcontractors	€ 500/unit	5 days	12
Flexible Material acquisition	Materials	10%	7 days	46

Table 4.1: Example of Quantified mitigating measures

4.3.2 How to chose strategy

With the mitigating measures being defined and their respective cost reduction being defined, a choice must be made which of the measures to use. As project cost is the objective that is being focused on, an ideal situation would be to utilise all mitigating measures to ensure that the cost is as low as reasonably possible. This, however, is not a realistic situation as a project cannot be delayed indefinitely, which would happen if all mitigating measures would be used. This shows that there is a scarcity in time as well as in financial resources. This scarcity demands a certain decision rule that is based on both the benefits and the 'cost' of each measure.

As has been dealt with in subsection 4.1.2, it can be assumed that a project manager doesn't have a fully unbiased view of a project. Even though this bias is mostly based on the subconscious mind of the project manager, it can still impact the outcome of a project drastically. This subjectivity from a project manager should be removed from the equation as much as possible, especially as a project manager is more likely to choose for what they know over what might rationally be the most advantageous strategy (Samuelson and Zeckhauser, 1988). To remove this bias from the decision-making process, a automated process should be opted for. Through automating this process, given certain parameters, a relatively unbiased mitigation strategy could be chosen.

An automated process would help with selecting the best mitigation strategy given the parameters of the project, as it will take away the personal preference of the project manager within the decision-making process. When making a rational choice there should always be a certain level of *dominance* within the preferences of the decision-maker, which should align with the goal in mind (Tversky and Kahneman, 1989). When looking at the goal at hand (reducing project cost) it is clear that the mitigation strategy with the highest cost reduction would have this dominance over other strategies. If dominance would be based on the personal preference of the project manager, there would be no match between the goal and the way to obtain that goal. For this type of rational choice problems, the dominance will always be linked to the utility that a certain measure brings.

Due to the fact that in this type of problems one should keep in mind the scarcity of both financial resources and time, these should both be taken into account as well when defining the utility of a measure. To do this a Benefit-Cost ratio can be used, which will show the financial gain per time unit of delay (e.g. *€ per day*). This ratio is equal to the utility of mitigating measures, which can be calculated using Equation 4.6 (specific version of equation 3 by Schwab and Lusztig (1969)).

$$R_p = u(p) = \frac{CR_p}{\alpha * D_p} \tag{4.6}$$

In which:

R_p	=	Benefit-Cost Ratio for mitigating measure p
$u(p)$	=	Utility for mitigating measure p
CR_p	=	Cost Reduction for mitigating measure p
α	=	Constant to compensate for trailing zeros
D_p	=	Delay for mitigating measure p

Mitigation Effectiveness

Name	Cost Reduction	Project Delay	Utility
Sampling soil prior to driving piles	€ 5 000	8 days	0.625
Maintaining good Equipment Flow	€ 17 000	21 days	0.809
Changing construction technique	€ 20 000	18 days	1.111
Quality control on subcontractors	€ 6 000	5 days	1.200
Flexible Material acquisition	€ 9 000	7 days	1.285

Table 4.2: Utility for mitigating measures (with $\alpha = 1000$)

Using Equation 4.6 for all mitigating measures their utility can be calculated. This has been done in Table 4.2 for the five hypothetical mitigating measures. Here it can be seen that the highest cost reduction does not constitute to the highest utility automatically. This way the most effective mitigating measures can be chosen, over the measures that have the highest absolute cost reduction. This will ensure that more cost can be reduced for the same project delay, which will in place lead to a higher likelihood of the project staying within budget.

As mentioned previously, the goal of a project manager within this study is to reduce project cost by the maximum amount possible, given the maximum delay that a project can deal with. The utility optimisation problem in this situation can be formulated as Equation 4.7 (Board, 2009). This equation shows the utility function on the left, where the major constraint is shown on the left. The set of values for $[x_1, x_2, ..., x_p]$ will denote the strategy that should be chosen given the parameters of the utility maximisation problem.

$$\max_{x_1, x_2, ..., x_p} u(x_1, x_2, ..., x_p) \quad \text{subject to} \quad \sum_{i=1}^{p} D_i * x_i \leq \text{Maximum Delay} \tag{4.7}$$

4.4 CHAPTER SUMMARY

This chapter has focused on the ways in which project cost can be influenced. The first of these ways are risks, that was defined as: *"Risk is the positive/negative consequence of a potential event (with a given likelihood) on the financial outcome of a project"*. Within this study it is also assumed that all risks (both threats and opportunities) are treated as well as possible, which leads to risks management being outside this study's scope.

The idea of risk however has a major impact on how project managers act within a project. Any project manager has a subconscious bias of some sort, which influences their behaviour. It was discussed that this risk perception and attitude could have a deteriorating effect on the likelihood of a project staying within budget. This is why there is a need for a tool that selects certain ways in which a project manager can influence a project.

These ways of influencing the financial outcome of a project have been defined as being mitigating measures. These measures can affect certain cost elements (which are the building blocks for the cost items) in order to reduce the total cost for that item/activity. These cost elements are visualised in Figure 4.4. These measures will reduce project cost from the bottom up.

All mitigations should be defined using an expected effect on such a cost element and a negative side-effect (project delay). Based on these two parameters an effectiveness will be defined for all mitigating measures, which will be the basis for the optimisation problem which maximises the utility of a strategy without going over the maximum project delay.

Part III

SYNTHESIS

5 DEVELOPING OF METHOD

Based on the insights that were found in chapters 3 & 4, this chapter will look at the development of the novel method. The method has been developed in three clearly divided into two parts. The first of which is the cost estimator that provides the context in which a project manager can be active, this will be focused on in section 5.1. Secondly comes the optimisation of the decision-making process, which will be focused on in section 5.2. Finally the development of a singular mitigation strategy will be looked at in section 5.3. It is important to note that all graphs in this chapter are solely used to illustrate what the final results will look like in chapter 6, these figures will therefore not be interpreted.

5.1 COST ESTIMATOR

In order for the strategy optimisation to be an option, a realistic and effective cost estimator should be used first. In order to ensure that this is the case for this study, an estimator will be developed based on the specifics that were mentioned in chapters 3 and 4.

For a probabilistic cost estimator, one of the most important elements is the probability distribution that is used in order to draw the values within the estimator. In subsection 3.2.2 a choice was made to use the Beta-PERT distribution for all values that are defined by a three point estimate (cost elements, risk effect). The fact whether a risk is going to fire, will be determined through a Bernoulli distribution with a given likelihood (p), as was defined in subsection 4.2.2.

The level to which all cost items are supposed to be dissected has been discussed in subsection 4.2.1. This section speaks about the need to specify the underlying parameters for the four major cost elements (*labour, materials, equipment & subcontractors*) into their unit rate as well as a quantity. The quantity element for material, equipment and subcontractors opened up the possibility to combine these with a single quantity variable, where labour cost has its own division into labour hours and labour rate (€ per hour). As mentioned, all of these cost items are defined by a three-point estimate that will define the Beta-PERT distribution from which the values will be drawn.

In order to come to an initial cost estimate, MCS will be used. During these simulations a simple mathematical model will be used to estimate the project cost for each iteration. Within the MCS a value will be drawn for all cost elements, risk effects and occurrence of risk. Once these values are drawn, they are combined into the project cost for that iteration using Equation 4.4. This process will be repeated for n iterations, after which the S-curve will be plotted and the project estimate at a probability of 70% will be defined. This whole process is visualised in Figure A.1 in Appendix A.

The output of this cost estimator is of vital importance for the following steps of this study. The output that is needed is not only the S-curve and the P70 estimate, but also the drawn values for each cost element for each iteration. This information will be used in the mitigation process that will be discussed in the next section (section 5.2). Based on the P70 value that can be seen in Figure 5.1.

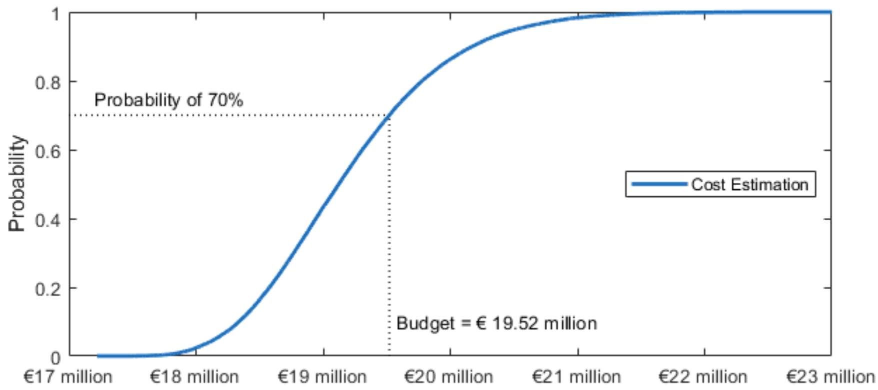

Figure 5.1: Cost Estimation with P70 Value

5.2 OPTIMISATION

The cost estimation that is described in section 5.1 can be seen as the initial estimate that defines the project budget prior to the construction phase. If during the project it appears that the project would still be headed to a 70% probability to stay within budget, then nothing needs to be done. However, the fact that this happens is small as once a threat fires, its probability within the estimation shoots up to 1 (meaning that it is always going to fire within the simulations). If this happens the probability of staying within budget diminishes rapidly. In order to steer back to a 70% probability the optimal mitigation strategy for each iteration should be found.

For all mitigating measures that are included in the model, certain elements have to be defined as discussed in subsection 4.3.1. These elements are:

- Mitigation name
- Cost element(s) that it has en impact on
- Reduction of that element
- Delay that is associated with the measure
- Activity it has an impact on

One element that should still be looked at is the effect of the mitigating measures. It has already been mentioned that the effect of the mitigating measures should also be drawn from a Beta-PERT distribution. These effects however do not have a three-point estimate that can be used in order to describe such a distribution. Moreover, as could be seen in Table 4.1, the effects of mitigating measures can either be absolute (amount of piles needed) or relative (percentage reduction of material cost). The latter can easily be solved by splitting the mitigation effect into both a constant (albeit stochastic) and a relative reduction of the cost element.

To resolve the issue regarding the variability of the mitigation effects, one should take a look at the variability of the activity that is affected. In order to ensure a realistic effect of the measure, its estimates will be based on the variability of the affected activity. To calculate this for all mitigations Equation 5.1 is used.

$$ME_{p,min/max} = ME_{p,ML} * \left(1 - \frac{CE_{n,ML} - CE_{n,min/max}}{CE_{n,ML}}\right) \tag{5.1}$$

In which:

$ME_{p,min/max}$	=	Minimum or Maximum mitigation effect for mitigation p
$ME_{p,ML}$	=	Most likely mitigation effect for mitigation p
$CE_{n,ML}$	=	Most likely cost value for activity n linked to mitigation p
$CE_{n,min/max}$	=	Min or Max cost value for activity n linked to mitigation p

5.2.1 Optimisation Problem

Now that the last issues regarding the effect of mitigating measures are resolved, a closer look can be taken at how the optimisation works. Previously in subsection 4.3.2 the basis of the optimisation problem was mentioned in Equation 4.7. In this section this equation will be expanded on. To refresh the memory, Equation 4.7 is restated below.

$$\max_{x_1,x_2,...,x_p} u(x_1, x_2, ..., x_p) \quad \text{subject to} \quad \sum_{i=1}^{p} D_i * x_i \leq \text{Maximum Delay} \quad \text{(4.7 revisited)}$$

As has been mentioned previously Equation 4.7 is the first step towards defining the optimisation problem that is central to this study. The most important element of this equation is the maximising of utility ($\max_{x_1,x_2,...,x_p} u(x_1, x_2, ..., x_p)$), as this element will ensure that the cost reduction will be as high as possible. As the utility of each mitigation has been defined as being the Benefit-Cost Ratio as described in Equation 4.6, the utility takes the 'cost-effectiveness' into account.

If the optimisation function would not have a number of constraints, there would not be an optimal solution. In order to come to a solution it is important that these constraints are defined. In Equation 4.7 one of these constraints is already defined as the delay of the selected strategy may not be higher than the maximum allowed delay that is defined prior to the optimisation. This is one of the most important constraints for this optimisation problem.

There are two other constraints that are relatively obvious but they still bear a certain level of importance in order to come to a realistic solution. The first of which is all mitigations can only be used once or not at all. There can not be any situation in which a fraction of a measure is used, nor can there be a situation that any mitigation is used more than once.

The second constraint is a bit more complicated. The constraint is that the mitigated project cost (original project cost - total mitigation effect) is lower than the project budget. This constraint is pretty straight forward when in isolation, however when combined with the constraint that includes the scarcity in time it can come to situations where no solution can be found. This means that due to the time constraint it is not possible to reach the budget value. In that case it is still desirable that the best solution is used, even without reaching the target at the budget value. For this a variable is added to this constraint (Δ), which will be the distance between the budget and the lowest value after mitigation. This can be seen in scenario 3 in Figure 5.2, where the green line is the maximum reduction through mitigation. This variable will only be used if there is no solution that can reach the target cost. Now that all constraints are clear, the full optimisation problem can be defined as Equation 5.2

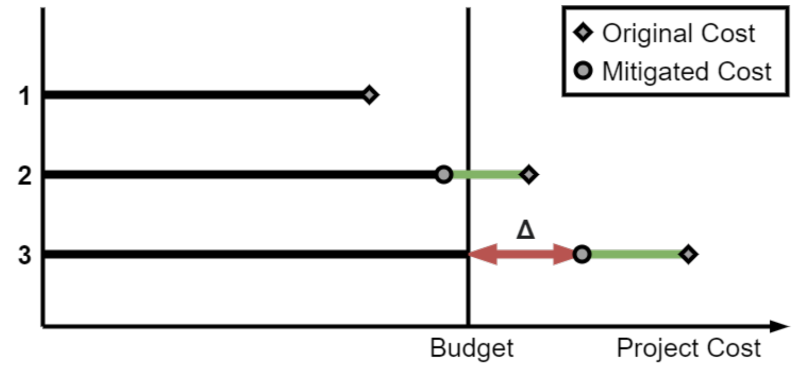

Figure 5.2: Scenarios for optimisation solution

$$\max_{x_1,x_2,...,x_p} u(x_1, x_2, ..., x_p)$$

$$\text{Subject to: } \begin{bmatrix} \sum_{i=1}^{p} D_i * x_i \leq \text{Maximum Delay} \\ x_i \subset \mathbb{Z} : 0 \leq x_i \leq 1 \\ TPC - \left(\sum_{i=1}^{p} CR_i * x_i \right) - \Delta \leq \text{Target Cost} \end{bmatrix} \tag{5.2}$$

The whole process that the optimisation element of the model goes through is visualised in Figure A.2 in Appendix A. As is also visible in Figure 5.2, the optimisation is not activated if an iteration does not breach the budget. This ensures that no cost reductions are made where they are not needed, as that would mean that a project delay would also follow. The result of this is that the S-curve for the optimised strategy shoots up from the budget value towards the S-curve of a situation where all mitigations would be used. This can be clearly seen in Figure 5.3.

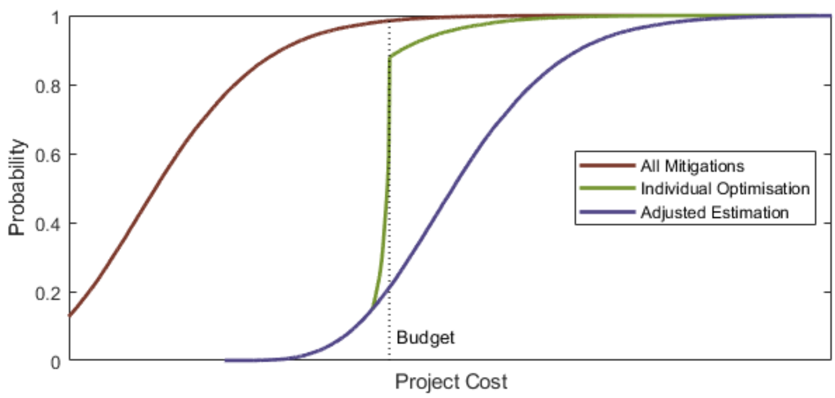

Figure 5.3: Optimisation Results

5.3 DEFINING STRATEGY

The optimisation in section 5.2 acts on the premise that a project manager can adjust whenever they notice that the project will go over budget and will only act then. The optimisation also works for every single iteration individually, which means that every potential project outcome will get a strategy tailored to the situation. As the optimisation is done after knowing all values for both risks and the variability in cost items, this is not a realistic situation. One more step is needed in order to see what strategy would be advisable for a project manager.

This step looks at the usability and effectiveness of all mitigating measures. This is done by tallying up for all mitigating measures how often they have been used. This gives all mitigating measures a score as it were, the more often it was used the higher its score will be. Due to the fact that the mitigation controller simulates many scenarios, it is most likely that the most used measure is the most usable and effective given the current situation. From these results a project manager can choose their own mitigation strategy that is fitting with the current situation.

It is very possible that the mitigation that had the highest Benefit-Cost Ratio is not among the highest performing mitigating measures. This could be the case if the mitigating measures with the highest ratio had a very small cost reduction which would lead to not being able to comply to the 3^{rd} condition in Equation 5.2.

In order to visualise the best performing mitigating measures, a plot will be generated which will show the measures that have been used most often. An example of such a plot can be found in Figure 5.4. Within this figure the mitigating measures have been sorted based on the amount of times that they were used. The top 10 measures have been highlighted in red to identify the top-10 performing mitigating measures.

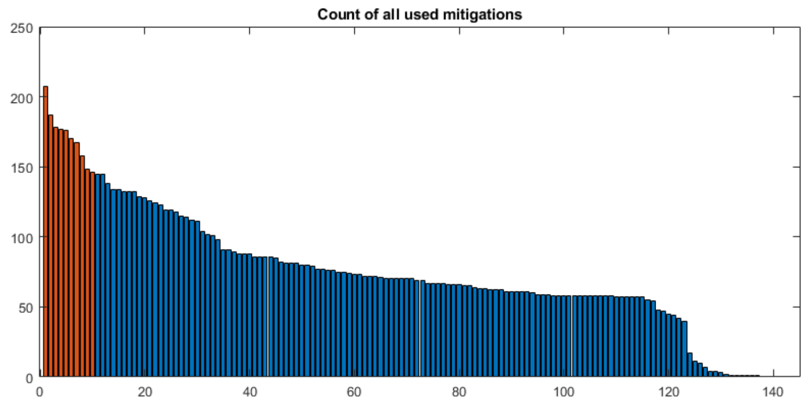

Figure 5.4: Sorted mitigating measures on frequency used

It has been said before, but Figure 5.4 shows the mitigating measures that perform the best given the current context. The mitigation controller has been designed in order to give the project manager the best possible tool to select their mitigation strategy. By running a simulation, a large portion of the subconscious bias has already been eliminated.

This tool provides data that will help a project manager make an informed decision, it is however not designed to give a singular mitigation strategy that will 'solve' the project manager's problem. It seems attractive to go an extra step and advise the project manager on what mitigation strategy they should choose, however this goes against the idea that is behind the mitigation controller. On multiple occasions within this thesis it has been said that a construction project has a dynamic nature. If a singular mitigation strategy would be advised, the dynamic nature of a construction project will be disregarded.

The goal of the optimisation keeps on changing during the duration of the project and so does the context of the project. In order to keep up with this, the mitigation controller should be used continuously to see what at any given point in time are the best performing mitigating measures. The project that is being looked at should not only be affected by the mitigating measures that are used, but also by external contextual changes to the project. This way a continuous learning cycle is generated, which will generate more valuable outcomes. This learning cycle is a double-loop learning system , in which both the actions within the system has an effect on the goal of the optimisation, but also the goal is changed as needed (Argyris and Schön, 1978). This way of dealing with the system, creates a situation where the goal that is worked towards is always the actual and up-to-date goal.
In order to evaluate the mitigation controller however, such mitigation strategy should be defined. This is the case as current practitioners work in a more single-loop manner, where when they come to the realisation that the project will be over budget a single plan is set up to ensure the project stays within budget. In order to do this, the highest performing mitigating measures will be combined into a mitigation strategy, with keeping the maximum project delay in mind. This will be used later on in the evaluation phase, details on how this is done can be found in Figure A.3 in Appendix A. These mitigation strategy will be made permanent as it is assumed that this is current practise. This will also lead to a new S-curve which accommodates for the current standard visualisation of this type of data within the construction industry.

5.4 CHAPTER SUMMARY

In this chapter the mitigation selector has been developed. This tool is built up from three elements, as has been previously discussed. The first of which is the cost estimator, this element provides the rest of the process with the input data for all cost items and risks. Together the risks and cost items generate the cost estimation that is used as the budget in this study.

The second element is the optimisation of individual iterations within the MCS. This optimisation is based on the utility based on the ratio between cost reduction and project delay. The aim of the optimisation process is to maximise this utility. The optimisation is limited by certain constraints however. The first is that the maximum project delay may not be breached, the second is that mitigating measures can be used either once or not at all. The final constraint is that the final project cost should be as close to the budget as possible.

Based on the optimisation for individual iterations, the tool counts how often a measure has been used. Using this count, a project manager can define which mitigating measures are most useful at the moment that the simulation was run. This process however should be done continuously during the construction phase to ensure that the simulation is based on the current situation within the project.

Part IV

EVALUATION

6 PERFORMANCE EVALUATION

A model is only as good as its output. For this reason this chapter will have a look at evaluating the computer model that has been developed in the previous chapter. As mentioned in subsection 2.2.3, the evaluation of the proposed method requires a case. The specific case that has been used for this study will be briefly introduced in section 6.1. After the case has been introduced, a closer look will be taken at what the more theoretical and statistical side of the model. This includes the output of the model, given the case input. All of this will be presented in section 6.2. Once this has been done, the most important step of the evaluation will be done, the empirical validation (in section 6.3. In that section the model will be tested against behaviour in the real world.

6.1 CASE

In subsection 2.2.3 it was mentioned that the requirements for the case to be used in this phase would become clear in the analysis phase of this research. The requirements for such case have presented themselves in the form of the required input data for the model, as discussed in depth in chapter 4. In short the required information would be:

- Cost Estimator
  - Dissected cost items into cost elements (see: Figure 4.4)
  - Quantified risk register (Risk event, likelihood & risk effect)
- Optimisation
  - Defined Mitigation measures (see: subsection 4.3.1)

Based on the required information stated above, a case was found. The project that will be used for the evaluation of this research study is an element of the new Roggebot bridge, located on the N307 near Kampen. This project has an important role in the connection between Flevoland and Overijssel as it is the only bridge connecting the two provinces. On a larger scale it also adds to the connectivity of the West of the Netherlands to the East, linking North Holland to Overijssel (in combination with the Markerwaarddijk).

Through the choices that are made with regards to the design of the new bridge, a choice has been made to separate the three traffic-flows that pass this bridge, in order to improve the situation that is currently in place, as can be seen in Figure 6.1. In the new design three traffic lanes will be created going both ways; separate for cyclists, agricultural vehicles and other traffic. This way congestion will not have as much of an impact as it has now, due to the different types of traffic on the bridge.

The replacement of the current situation at the Roggebot lock, would also mean that the Vossemeer and Drontermeer are no longer separated by the lock, meaning the ecological situation in the area would also improve massively. Given the new design of the movable bridge, it allows for ships up to 7m to pass under the bridge in a closed state. This will ensure that the traffic flow will be influenced less by the opening of the bridge (Provincie Flevoland, nd).

(a) Current Situation

(b) New Situation

Figure 6.1: Change in Roggebot Situation

The data that is required in order to evaluate the model, can be seen as confidential financial information for any given organisation. For this reason the values within the original cost estimation and risk register have all been manipulated using a single constant factor. This constant factor is not known by the researcher in order to ensure the confidentiality of the internal rates used within the estimates. By using a single constant factor however, the internal proportions within the project have not been compromised.

As the mitigating measures are often not defined in such an in depth manner that an extensive list is set up. In order to obtain an extensive list of potential actions that could be taken by a project manager, a brainstorming session has been held with the project manager and cost estimators involved with this project. This has again been done in order to keep the results as realistic as possible, in order to ensure a tool that is useful for realistic cases such as the Roggebot case.

6.2 RESULTS

This section will look at the results that have come from the model whilst using the case that has been described in section 6.1. To ensure clarity, the same steps will be followed as was done in chapter 5. subsection 6.2.1 will look into the cost estimation, on which the budget will be based. Once the budget is defined, subsection 6.2.2 will look into the optimisation process which will be applied on the case. After the optimisation has been completed, the final mitigation strategy will be created in subsection 6.2.3.

6.2.1 Cost Estimation

In order to have a target value that can be worked towards, the cost estimation must be made first. Based on the data provided to the researcher for this study the cost estimator resulted in the S-curve as shown in Figure 6.2. In this figure can be seen that the P70-value for this project would be just over €19.5 million. For this study this value will be seen as the budget of the project.

Within the original cost estimation that was done by the project team working on the Roggebot project, the cost estimation was closer to €19.4 million. For both instances this value constitutes to the cost of the cost items as well as the risks that this project has. The fact that these two estimations are not exactly the same can be explained by the fact that the bandwidths for the cost items was done differently. For the original data, a product-type based bandwidth was used, whereas for the data set that was provided for this study the bandwidths were based on the WBS activities. The small difference in approach in this process, could lead to this difference of $\pm$ 0.5%.

The idea behind the budget that can be seen in Figure 6.2 is that if all risks adhere to their likelihoods and all cost items centre around their expected value, that there would be a 70% probability that the project cost would be lower or equal to €19.52

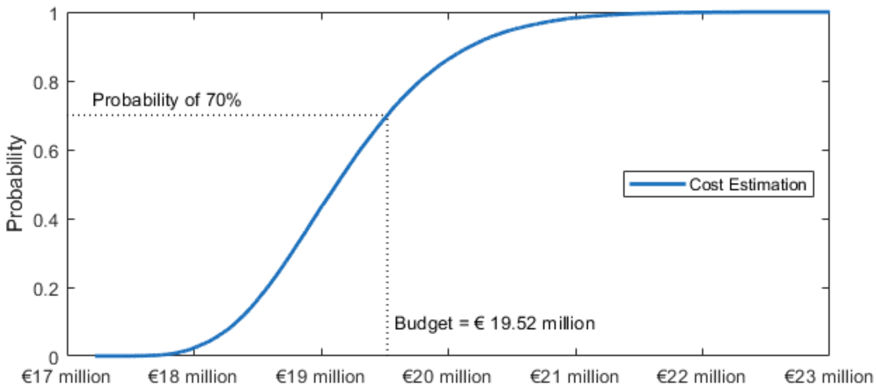

Figure 6.2: Roggebot Cost Estimation

million. If this stays the situation any project manager would try and maintain this without steering the project cost too much, as this would introduce project delay which is also unwanted.

The truth for most projects however is that due to the uncertainty in the design and the context of a project, is is very likely that something will happen that will change this value. In this case two threats with relatively low likelihoods (7.5% and 17.5%) fired where an opportunity with a likelihood of 50% did not happen.

These three risks were all identified as being linked to the beginning of the project. With the project only just starting, the project manager already sees the likelihood of staying within budget shrink drastically. The cost estimation is adjusted, as is visualised in Figure 6.3. As the budget has been set prior to the project, this value will not change easily. As the project only has a 21.2% probability of staying within budget after these three risks played out this way, the project manager will have to act in a way that will ensure that this probability will get closer to the initial value of 70%. The aim would be to maximise this probability to be more resilient, were more threats occur.

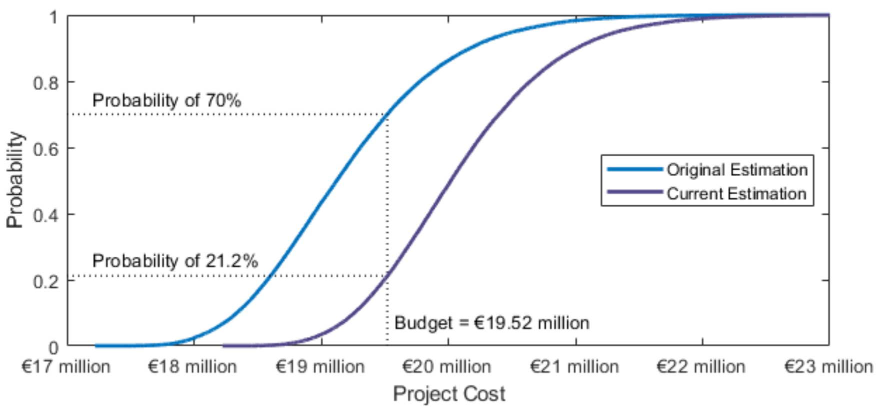

Figure 6.3: Roggebot Estimation During Construction

6.2.2 Optimisation

Now that the likelihood of staying within budget has drastically dropped down to around 20%, the optimisation tool that has been described in section 5.2 should use the mitigating measures to see what the ideal situation would be. On order to see that the list of mitigating measures is sufficient to increase the probability, Figure 6.4 shows the probability that can be reached if there were no scarcity in time. Given that situation, the probability of staying within budget could rise all the way up to 98.5%, as this would mean that all mitigating measures would be used once the project would go over budget.

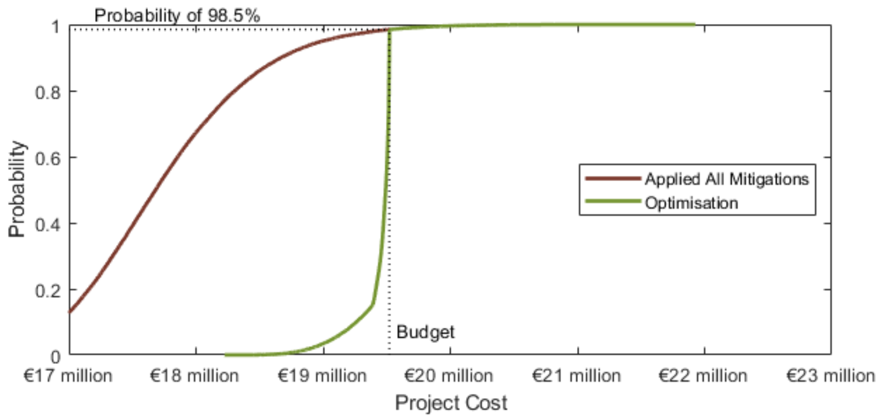

Figure 6.4: Optimisation Without Time Constraint

As previously discussed in subsection 4.3.1 however, any project has both a scarcity in finances as in project time. Due to this scarcity in time, a maximum delay is defined by the project manager. This delay was set at approximately 11% of the total project duration at 4 months. The total delay that would be possible, were all mitigating measures used, would be ± 12 months.

Given this maximum delay, the optimisation finds the mitigation strategy that is most effective for all individual iterations. In the run that has been visualised, this means that for 50,000 iterations, the ideal combination of mitigating measures has been found to reduce project cost back to the budget. This leads to increasing the probability of finishing the project within the pre-set budget to 87.9%. The S-curve for this individual optimisation can be seen in Figure 6.5. As mentioned in subsection 5.2.1, the optimisation is only activated when a project ends up over budget.

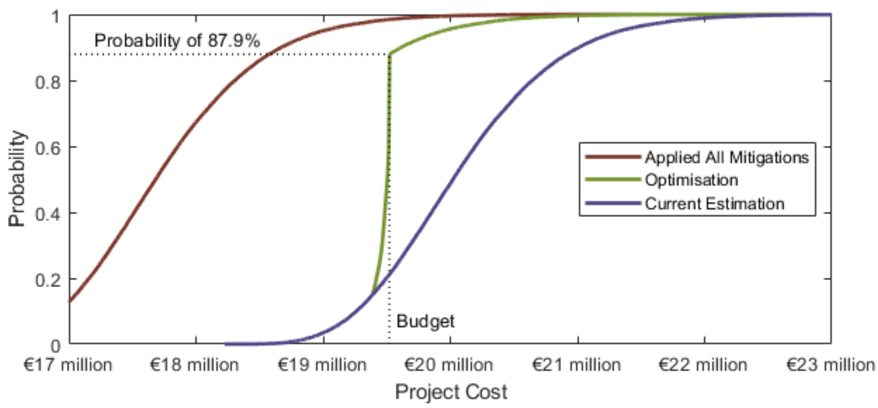

Figure 6.5: Optimisation Including Time Constraint

6.2.3 Defining Strategy

As mentioned in section 5.3 the next and final step of the mitigation controller is tallying up all the times that all mitigating measures have been used. This in order to show the project manager what their most effective mitigating measures are, at that current moment in time. In Figure 6.6 the amount all mitigating measures are used has been visualised. Within this bar chart, the best performing mitigating measures have been highlighted. Which these mitigating measures are, will become clear in subsubsection 6.2.3.

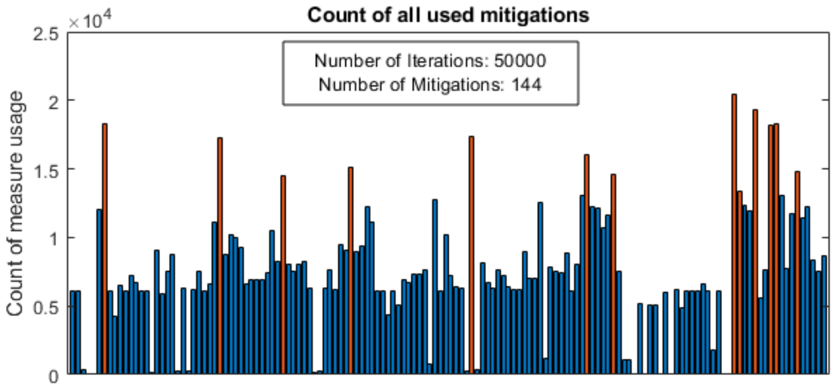

Figure 6.6: Frequency Used Mitigation Measures

As can be seen in Figure 6.6, there are certain mitigating measures that are clearly chosen more often than most. The project manager would be advised to look at these mitigating measures in order to take action concerning the current financial situation for the project. One should note that these mitigating measures are only the top-performers given the current context. A project manager should not rely on one run of the mitigation controller, but should continuously run the model in order to have current and valid results.

Evaluation Strategy

With the top performers presented, all elements within the mitigation controller have been completed. As mentioned in section 5.3 an evaluation strategy will be defined. The aim of this strategy is to mimic the behaviour of current practitioners. This is in regards to the permanent nature of the applied mitigating measures. This section will define the strategy that will be used for this purpose.

Figure 6.6 already gives away which mitigating measures will be added to this evaluation strategy. The top-13 performing mitigating measures have been added to this strategy as these are the most frequently used mitigating measures after running the mitigation controller. Together they use up the complete maximum allowed project delay that was defined for the optimisation. In Table 6.1 the mitigating measures can be seen that were used most frequently.

As has been stated already, the mitigating measures in Table 6.1 will be used as permanent interventions. This means that they will be chosen at this current moment in time and will all be implemented, whatever happens. Based on this strategy, Figure 6.7 shows what the new S-curve would look like. It is worth noting that the probability of staying within budget for this evaluation strategy is above 70%, which means that this strategy would bring the project to a better probability of staying within budget than at the start of the construction phase. Again the issue with this is that this assumes that the project context will not change and with that would not need a different approach in its mitigation strategy.

Number	Mitigation Name	Times Used	Average Reduction
127	Change Bridge Protection	20 400	€263 865
131	Re-Engineer Beam	19 336	€76 686
135	Renegotiate Subcontractor Contract	18 281	€64 045
7	Optimise Mortar Ratio	18 263	€60 582
134	Optimise Steel Thickness	18 189	€52 551
77	Re-Design Concrete Thickness	17 316	€44 953
29	Optimise Mortar Ratio	17 311	€49 191
99	Redesign Thickness Concrete	16 002	€43 470
54	Adjust Piling Technique	15 156	€37 759
139	Renegotiate Subcontractor Contract	14 793	€32 558
104	New width formwork	14 592	€32 203
41	Soil probing for piles	14 455	€33 263
128	Re-Engineer Beam	13 387	€191 027

Table 6.1: Evaluation Mitigation Strategy

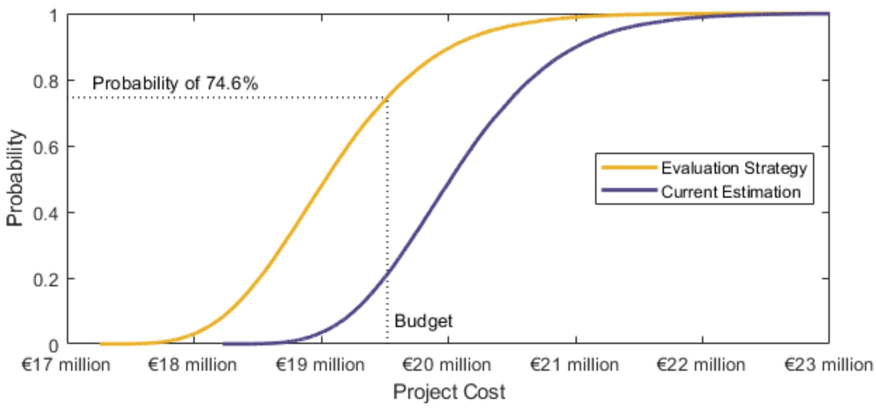

Figure 6.7: Result Evaluation Strategy

6.3 MODEL VALIDATION

Now that the output of the model has been looked at, it is time to see how the proposed method holds against the behaviour of a real project manager. In order to do this, an experiment has been conducted to compare the choices that would be made in real life with those that are made by the proposed method. The experiment will be explained in subsection 6.3.1, after which the results will be discussed in subsection 6.3.2.

6.3.1 Method for Evaluation

The goal for the experiment that will be described here, is to see whether the proposed method is able to come to a mitigation strategy that outperforms a project manager that works with real-world projects. In order to compare these results, both the project manager and the model should work with the same amount of information as well as with the same context. To ensure that this is true, the Roggebot case will be used.

An issue with using this real-life case is the confidentiality of the financial data that has been used for the cost estimator. Even though the data has been altered, a competitor might be able to deduce the constant that was used in order to alter the data. For this reason, no information on the project or the cost estimation part of the model has been communicated. The project is reduced to a budget (or target for this experiment) and a current situation.

The second element are the mitigating measures, which have also been modified. These changes have not been made to maintain the confidentiality of the project, as the mitigating measures would not give away much about the internal prices and the project. They were made to minimise the subconscious bias from the project manager. The first alteration that has been made is only giving the number of the mitigating measure, in stead of the name of the measure. This ensures that a project manager cannot chose their preferred type of mitigation.

The second alteration was done to take risk perception out of the equation. This was done by making the project delay values for the mitigating measures abstract. Through this alteration a project manager should not be influenced by their perception of a real delay. For example if a project manager only works on small projects, a delay of 1 week could be seen as large, whereas another project manager might not even consider this a significant delay. By changing the delays to values ranging from 0.25 to 1000, the idea of time should be taken out of the equation whilst keeping the proportion per measure intact.

The case that has been described above can be found in Appendix B. Within Appendix B the breifing that was given to all project managers is shown (Figure B.1) as well as the data needed to complete the experiment (in Figure B.2, B.3 and B.4). A group containing project managers was asked to fill out the form. They were asked to find a mitigation strategy that would get the project cost back to a value lower than the budget as well as staying below the maximum delay. They were also asked to describe their decision rule that they used to define their mitigation strategy. Based on the answers that were provided through this exercise, a comparison can be made between real world practitioners and the proposed method.

6.3.2 Results Empirical Evaluation

In order to come to the results that will be presented in this section, a number of project managers were asked to figure out a mitigation strategy in such a way that they believed it was the best possible strategy. This was done after explaining the idea behind the experiment as well as behind the mitigation selector. Considering the schedules of all project managers that were involved, they were left with the assignment after the explanation, so that they could do this at their own pace.

A total of 10 project managers were initially involved in the process of this experiment. After the briefing surrounding the idea behind the exercise, two of those already said that they would no longer participate due to the potential time investment that was needed. In the end of the remaining eight project managers, four found the time to work on the exercise. These four will then also be taken into account when looking at the results.

The group of respondents consists of four practitioners with different levels of experience within different parts of the construction industry. Two of the respondents have less than 5 years experience within project management, whereas the other two have more than 10 and 20 years experience. The project managers are all in different organisations, two of which are among the top-10 largest contractors in the Netherlands, one owns a medium-sized business specialised in residential construction and the final project manager works for a large player in the public sector. This mixture of experience and areas of expertise gives a good idea of how practitioners in the market are likely to behave in this situation.

In order to compare the project managers' strategies to the output of the mitigation selector, they have been combined into one 'strategy'. This has been done my implementing all strategies for all iterations, after which the mean of the four reduced project costs per iteration has been taken. This has lead to the S-curve that can be seen in Figure 6.8. This shows that the combined strategy of the four project managers increases the likelihood of staying within budget from 21.2% to 69.1%. This means that this strategy ensures that the probability of staying within budget is nearly at the same level as it was prior to the construction phase. However, the practitioners do not outperform the mitigation selector (with a probability of 74.6 %).

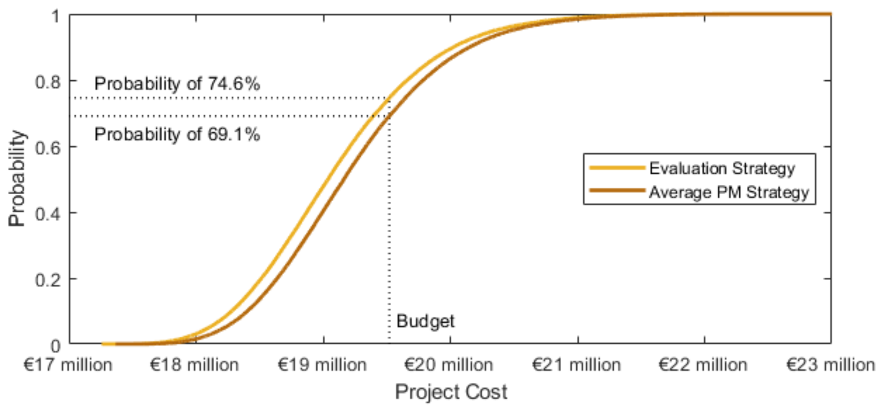

Figure 6.8: Results Evaluation and PM Strategies

Table 6.2 shows that three project managers are very close to each other where the fourth project manager is considerably lower. With three project managers reaching such similar results (the first two even the exact same probability at 70.28%), it seems like they are using a similar method to come to their mitigation strategy. As they are all from different organisations, this may be a market standard within the larger contractors. This potential 'market standard' would be a good method to test against. For this reason a new aggregation of strategies has been made, with only the three top-performers.

The S-curve that was computed based on the combined strategy can be seen in Figure 6.9. It can be seen that the probability of staying within budget have increased by 1.2%, to 70.3%. Without the lowest performing mitigation strategy taken out of the equation, the original probability of 70% has been reached once again. This still is not enough to perform similarly to the mitigation selector. In the next section, this difference will be looked into statistically.

Project Manager	Total # Mitigating Measures	Probability
PM 1	67	70.3 %
PM 2	16	70.3 %
PM 3	17	70.2 %
PM 4	65	65.3 %

Table 6.2: Strategies by project managers

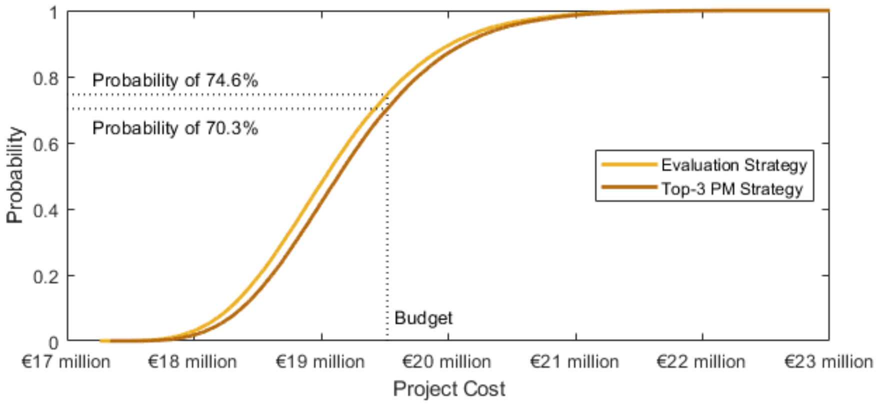

Figure 6.9: Results Evaluation and Top-3 PMs

6.3.3 Statistical Analysis

Given the fact that the difference between the two strategies is 4.3%, it looks like the mitigation selector outperforms the practitioners in the field. This difference however should also be looked at in a more statistical manner. As the sample size is quite large (50 000) a paired t-test will always conclude that there is a significant difference between the two interventions. This is why the effect size should be considered. For this the effect size metric of *Hedges' g* will be used.

Through the use of the g-statistic for both the project managers'strategies and the mitigation selector tool, the effect of both interventions will be standardised using the combined standard deviation of the two distributions. This way it is possible to compare the two interventions without worrying about the distributions that lie at the basis of this statistic. The difference between the two means (pre- and post intervention) will be expressed in the fraction of standard deviation (see: Equation 6.1 (Hedges, 1985)). A g-statistic value of 1 means that the mean after the intervention is 1 times the standard deviation lower than the mean prior to the intervention.

$$g = \frac{M_A - M_B}{s} \tag{6.1}$$

In which:

g	=	Hedges' g-statistic
M_A	=	Mean of distribution prior to intervention
M_B	=	Mean of distribution post intervention
s	=	Pooled standard deviation for both distributions

Using Equation 6.1, the g-statistic can be determined for the interventions that were defined for both the mitigation selector and the project managers. Based on the data from Table 6.3, the g-statistic can be determined for both interventions. For the project managers' strategy a value for g was found of 1.23. This means that the mean of the project cost after the project managers' intervention is 1.23 times the standard deviation lower than prior to the intervention. For the mitigation selector a value for g of 1.41 was found.

Based on the two values for the g-statistic that were found it can be said that the mitigation selector performs better than the practitioners in the field. The magnitude of the performance should not be focused on too heavily as this statistic is mainly aimed at comparing two interventions to each other, regardless of the values for the standard deviation within the distributions. As the standard deviation for all distributions are similar in this context, it can be said that

Distribution	Mean	Standard Deviation
Adjusted Estimate	€ 20.09 million	€ 695 123
Project Managers	€ 19.23 million	€ 694 974
Mitigation Selector	€ 19.11 million	€ 694 122

Table 6.3: Statistics for Hedges' g-statistic

6.3.4 Qualitative Results

This section will review the process that surrounded the experiment with the project managers. There are several things that came up whilst discussing the strategies and results. Throughout the conversations two main points stick out, these will be discussed below.

The first point is that not knowing what all mitigating measures did and meant was seen as a large issue by the project managers. Even though it was mentioned that project scope was a non-negotiable, it was mentioned that in order to make a good decision about what measures to select, they needed to know what the measures did. It was deemed more important to know what each measure did rather than knowing how it affected the financial picture as well as the planning of a project.

The other remark that came back was the fact that certain project managers were wary of using measures with a lower cost reduction, even if they were very cost effective. Main reason for this was that due to its low yield, many small measures had to be taken which would lead to more issues regarding time. Even though two project managers looked at the effectiveness of the measures, they tended to steer away from these measures due to the issues they assumed to be related to these.

One project manager mentioned that one should never have to adjust certain elements of a project because another element was more expensive than expected. This was specifically true if that was the case due to the uncertainty in unit rates for materials. They stated that a project should not be adjusted to the planning or budget, but that this should be the other way around. Any project can take more time or money, as long as it is finished.

Overall it was clear that the project managers that were involved in this process are very used to a single way of finding their mitigation strategy. They felt uneasy when the bias was partially taken away during the process of selecting their mitigation strategy. This only clarifies the need for the mitigation selector further, as project managers are very used to their bias, that they see it as a positive element, even if they ignore highly effective mitigating measures.

6.4 CHAPTER SUMMARY

Within this chapter the results of the mitigation selector have been presented based on the Roggebot case which was also introduced. The same three steps have been followed as was the case in the development of the tool.

The cost estimation for this study was made based on the estimates from the Roggebot case. Including risks this estimation on the 70% probability came to €19.52 million. This estimate differed slightly from the original estimation due to a different use of bandwidths in the three-point estimates. After the construction phase had started, risks occurred which lead this probability to drop to 21.2%.

To mitigate this drastic drop in probability the optimisation was started for all iterations that went over budget. After this was done the probability went up to 87.9%, based on the optimisation from the mitigation controller. As the final results of the mitigation controller, the most frequently used mitigating measures have been reported.

Based on these most frequently used mitigating measures, an evaluation strategy was defined in order to compare the mitigation controller to real-world practitioners. This evaluation strategy generated a probability of staying within budget of 74.2%, whereas the top-3 performing project managers that took part in the experiment came to a probability of 70.3%. This means that the mitigation controller generates an advice that outperforms industry practitioners.

Part V

CONCLUSION

7 CONCLUSION

In this chapter the development statement (as posed in section 1.3) will be discussed. This will be done after revisiting the sub-questions that were formulated in the same section. After this is done recommendations will be given so that further research can build on this study.

7.1 SUB-QUESTIONS

In section 1.3, four sub-research questions have been formulated in order to being able to answer the main research question. In the previous chapters these questions have been implicitly answered, this section aims to clarify these answers.

What type of cost estimation is fitting for this tool?

There is a multitude of types of cost estimating methods, as described in chapter 3. For this study it was found that a probabilistic approach in which a bottom-up estimation was combined with three-point estimations for all required values. Computing a Beta-PERT distribution based on the three-point estimations from which values will be drawn using MCS. Based on the results of the simulation a budget is set at a value that is estimated to have a 70% likelihood of happening.

In what ways can a project manager control project cost?

The control that a project manager has on project cost, lies mostly in how to influence individual item's prices. As mentioned in chapter 4, it is assumed that traditional risk management has already been done to the best of a project manager's abilities. A project manager can tamper with the building blocks of cost items, in order to reduce that item's cost. Most influence can be exercised on: labour hours, material rate, subcontractor rate, equipment rate or the quantity of a certain item.

How can the selection process of a mitigation strategy be optimised?

Chapter 5 looks at the manner in which the process of selection a mitigation strategy can be optimised. This has been done by computing the utility that all mitigating measures bring, which is the ratio between the cost reduction and the associated delay. The utility of a mitigation strategy will be optimised given the optimisation problem (see: Equation 5.2). To come to the final mitigation strategy, the most frequently used mitigating measures are combined into a strategy that does not exceed the maximum allowed project delay.

How do the results of the proposed method compare to current practise?

The final sub-question has been answered in chapter 6. Through an experiment conducted with current practitioners a mitigation strategy was defined that represents the current practise. This strategy led to a probability of staying within budget of 70.3%, where the mitigation selector reached a probability of 74.6%. After accounting for a potential difference in standard deviation between the distributions, it can be concluded that the proposed method outperforms the current practise.

7.2 DEVELOPMENT STATEMENT

With the sub-questions of this study being answered in the previous section, the development statement will be dealt with in this section. This development statement is as follows:

"To develop a software tool that automates the process of finding the optimal cost mitigation strategy to enhance the probability of construction projects staying within budget"

Throughout this study it has become clear that one single optimal mitigation strategy does not exist within a construction project. This is why the current strategy of selecting one mitigation strategy and not reevaluating this strategy during the project is not advisable. A construction project is dynamic in nature and will therefore show an ever-changing picture. In order to speed up the process of constant evaluation of the project's status and possible mitigation strategy, the mitigation controller should be used.

By using the mitigation selector to determine a mitigation strategy, the subconscious bias from a project manager is taken away from the decision making process. Through the simulation of having hindsight knowledge, this tool is capable of optimising for each simulation. Based on these optimisations it is possible to formulate a mitigation strategy that will have the highest likelihood of reducing project cost in order to stay within budget. This as mentioned only holds for that moment in time, as again a construction project is ever-changing.

7.3 RECOMMENDATIONS

Based on the research that has been done, certain elements that were deemed outside this study's scope should be considered for future studies into this topic. If these recommendations are executed the mitigation selector will only increase in usability and realism.

1. **Incorporate project planning into a more holistic tool**
   This study is based on the assumption that project cost is the only focal point of a project. In reality there is a fine balance between project cost and project duration, as mentioned by one of the project managers.

2. **Add financial penalties for project delay**
   Certain types of contracts within the construction industry warrant fines when a project goes over budget. Adding this parameter to the optimisation could take away the need for a maximum allowed delay, by optimising the gains from a delay given such a penalty.

3. **Integrate historical data into the cost estimation**
   To reduce the level of bias even further within the cost estimation and mitigation selection process, it is important to reduce the level of bias within the three-point estimates. The perception of risk and uncertainty is ever present in the input estimations. If the unit rates would be based on the analysis of historical data, a portion of that bias would be reduced.

4. **Include risk management into research scope**
   By adding the element of risk management into the scope of this tool, a stronger mitigation strategy can be found through larger interventions that are useful project wide, in stead of activity or cost item specific. Certain risk management actions could also change the cost of certain items, by including these the tool may become more realistic.

5. **Let mitigating measures affect multiple cost items**
   In the current situation a mitigation is linked to a single cost item. There can be mitigating measures that can be used that will automatically affect multiple cost items. Through this type of mitigating measures it might be possible to reach an even more advantageous mitigation strategy.

7.4 DATA AVAILABILITY STATEMENT

In order to maintain reproducibility for this research, all resources that are not referred to in the bibliography have been made available online. This includes the code for the mitigation controller as well as the case that has been used for this study. As mentioned in section 6.1, the data that has been used from the Roggebot case have been anonymised in order to keep to the agreement that was made with the organisation that has provided the author with said financial data. The repository in which all this information can be found is located at: https://github.com/ravandijk/MitigationController.

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Part VI

APPENDIX

A FLOWCHARTS MODEL

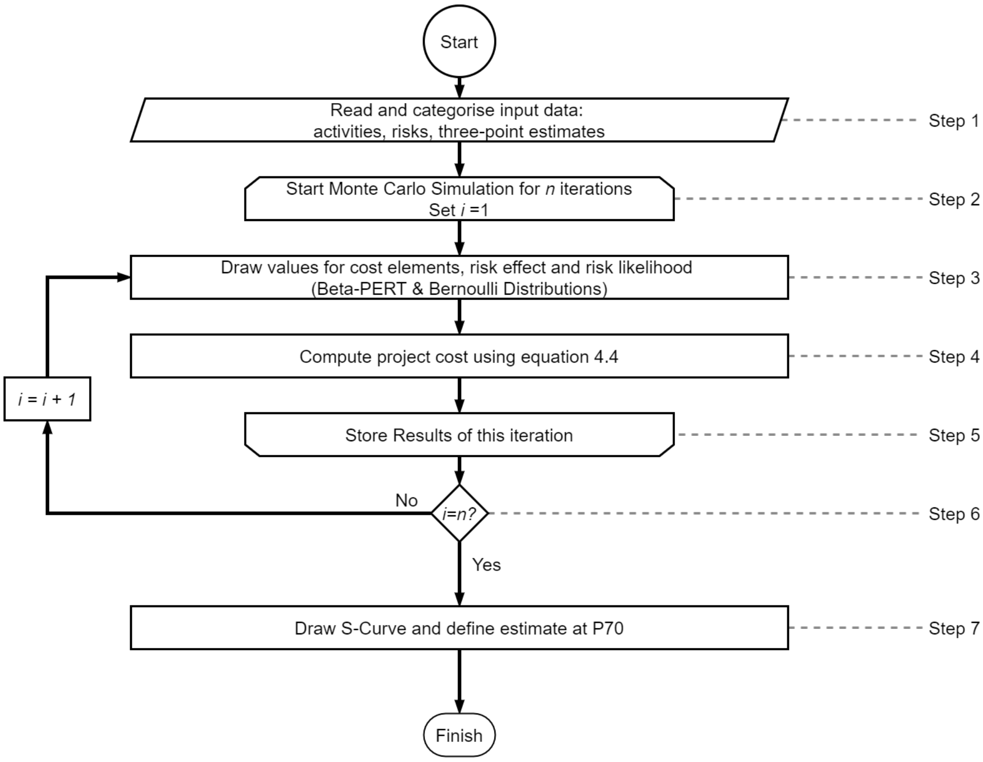

Figure A.1: Flowchart of cost estimation process

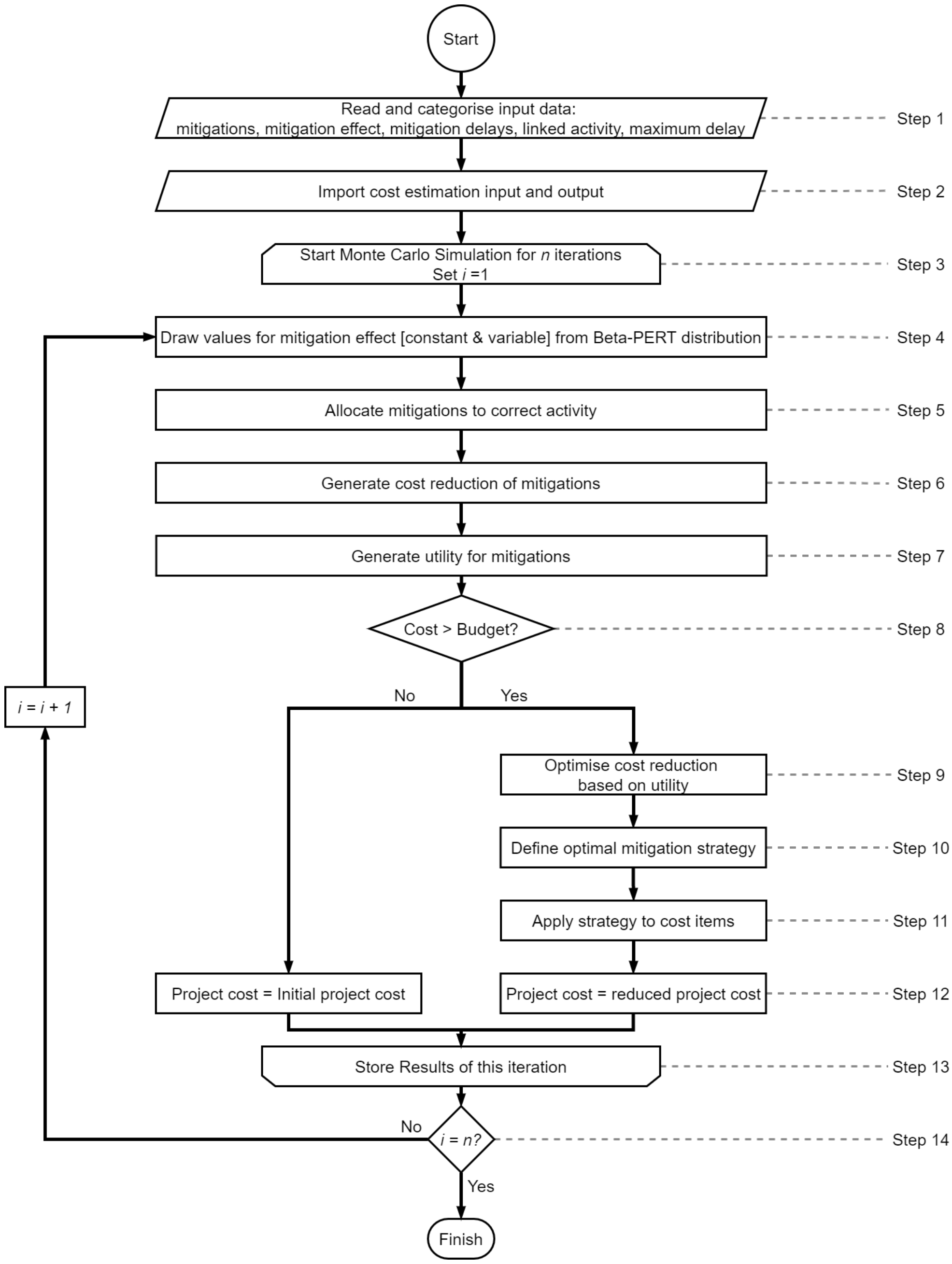

Figure A.2: Flowchart of mitigation strategy optimisation process

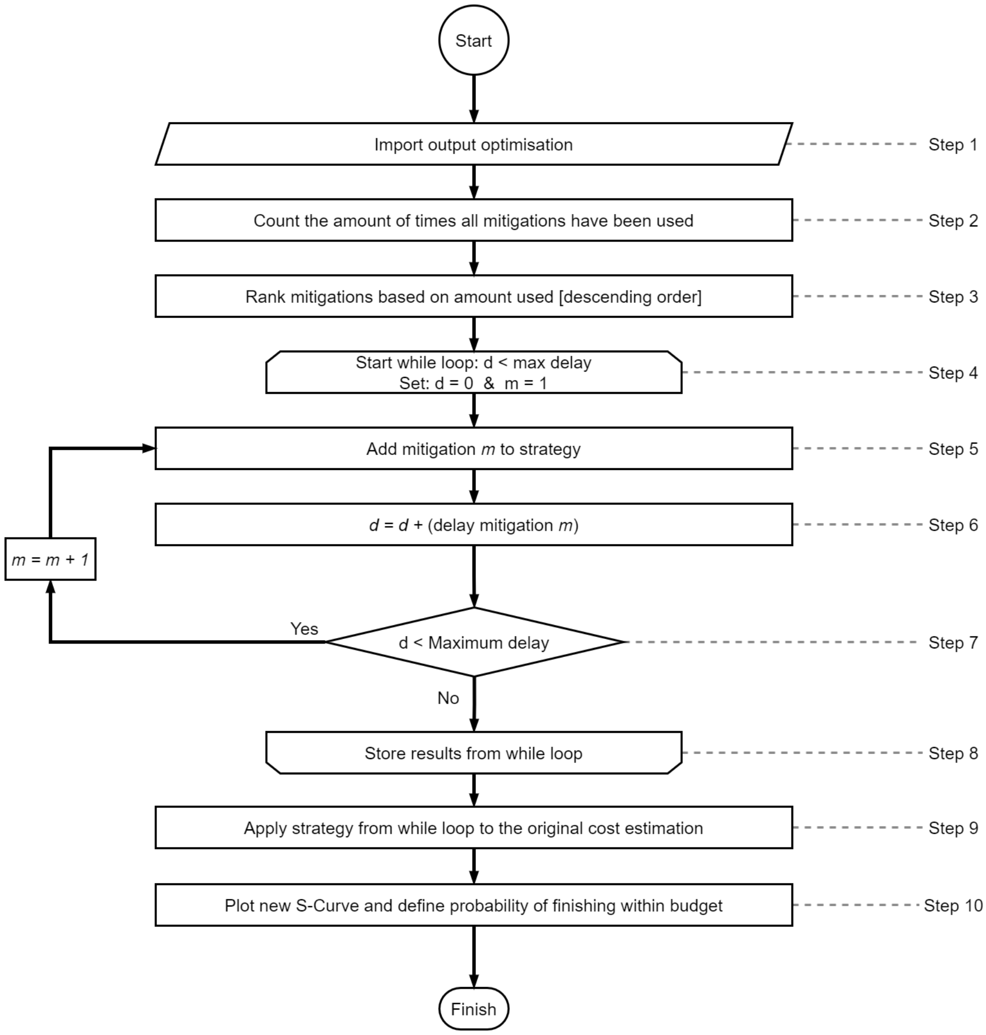

Figure A.3: Flowchart of defining singular mitigation strategy

B PROJECT MANAGER EXPERIMENT

This appendix holds the experiment that has been conducted with the project managers. As mentioned in chapter 6 it has only been used to evaluate the mitigation controller to current day practitioners. The data that is included into this form, are the average cost reductions for each and every mitigation.

Name:	
Employer:	

Current Estimation:	€ 20,433,182
Budget:	€ 19,555,380
Result of exercise:	€ 20,433,182
Delta to budget:	€ 877,802
Project Delay:	0
Max accepted delay:	2500

Used Time	
	Minutes

Strategy:	Please elaborate here how your strategy has come to exist. What decision rule did you use or what were specific things you were looking out for?

Briefing	During the early stages of a project, a couple of risks have fired. This lead to the expected cost of the project to have risen far higher than the budget The goal for this exercise is to get the project cost down as close to the budget as possible. This can be achieved by typing something in the blue column behind the mitigating measure, this automatically reduced the project cost. Each measure also has an associated delay, for each selected measure its associated value is added to the total project delay. This value cannot exceed 2500.

Figure B.1: Briefing for Experiment with project managers

Measure	Expected Effect		Delay	Selected
1	€	264,434	1000	
2	€	191,391	750	
3	€	187,813	650	
4	€	135,624	650	
5	€	76,579	193	
6	€	68,394	261	
7	€	64,113	104	
8	€	60,558	150	
9	€	52,571	121	
10	€	49,176	80	
11	€	44,904	90	
12	€	43,466	70	
13	€	37,776	55	
14	€	34,642	94	
15	€	33,263	40	
16	€	32,564	47	
17	€	32,245	43	
18	€	23,173	32	
19	€	22,094	43	
20	€	21,871	52	
21	€	21,372	41	
22	€	20,463	40	
23	€	20,011	29	
24	€	19,209	29	
25	€	19,154	15	
26	€	19,147	30	
27	€	18,826	28	
28	€	18,789	30	
29	€	18,728	34	
30	€	18,171	26	
31	€	17,952	27	
32	€	17,892	29	
33	€	16,999	31	
34	€	16,115	26	
35	€	15,718	31	
36	€	14,682	27	
37	€	14,260	14	
38	€	14,131	26	
39	€	13,303	8	
40	€	13,180	15	
41	€	12,599	17	
42	€	12,563	25	
43	€	11,994	22	
44	€	11,807	16	
45	€	11,771	20	
46	€	11,563	24	
47	€	11,239	13	
48	€	11,173	22	

Figure B.2: Mitigating Measures 1-48

Measure	Expected Effect		Delay	Selected
49	€	11,159	22	
50	€	9,985	9	
51	€	9,970	21	
52	€	9,946	20	
53	€	9,780	20	
54	€	9,714	24	
55	€	9,614	19	
56	€	9,235	15	
57	€	8,623	18	
58	€	8,465	21	
59	€	8,195	6	
60	€	8,077	21	
61	€	7,880	10	
62	€	7,336	17	
63	€	7,323	15	
64	€	7,320	23	
65	€	7,173	20	
66	€	7,163	16	
67	€	6,940	14	
68	€	6,935	15	
69	€	6,843	14	
70	€	6,817	12	
71	€	6,789	13	
72	€	6,661	14	
73	€	6,660	6	
74	€	6,581	16	
75	€	6,551	14	
76	€	6,535	12	
77	€	6,369	11	
78	€	6,329	10	
79	€	6,058	13	
80	€	5,895	12	
81	€	5,885	13	
82	€	5,875	5	
83	€	5,746	15	
84	€	5,746	13	
85	€	5,462	17	
86	€	5,239	12	
87	€	5,219	14	
88	€	5,191	13	
89	€	5,042	6	
90	€	5,008	12	
91	€	4,976	14	
92	€	4,952	13	
93	€	4,897	16	
94	€	4,897	15	
95	€	4,883	12	
96	€	4,883	5	

Figure B.3: Mitigating Measures 49-96

Measure	Expected Effect		Delay	Selected
97	€	4,880	17	
98	€	4,806	24	
99	€	4,667	4	
100	€	4,564	21	
101	€	4,533	12	
102	€	4,212	11	
103	€	4,180	4	
104	€	4,088	7	
105	€	3,913	8	
106	€	3,852	9	
107	€	3,027	6	
108	€	3,000	5	
109	€	2,813	4	
110	€	2,591	3	
111	€	2,357	4	
112	€	2,307	4	
113	€	2,216	3	
114	€	2,041	3	
115	€	2,040	4	
116	€	1,963	3	
117	€	1,689	4	
118	€	1,631	3	
119	€	1,577	7	
120	€	1,206	2	
121	€	1,188	3.5	
122	€	1,070	3	
123	€	959	2	
124	€	944	2	
125	€	830	1	
126	€	780	2	
127	€	698	3	
128	€	673	0.5	
129	€	589	2.5	
130	€	516	3	
131	€	468	2	
132	€	408	1	
133	€	363	0.5	
134	€	362	0.5	
135	€	357	0.5	
136	€	348	0.5	
137	€	319	0.5	
138	€	319	1	
139	€	287	2.5	
140	€	287	2	
141	€	284	2.5	
142	€	252	4.5	
143	€	208	0.5	
144	€	202	0.25	

Figure B.4: Mitigating Measures 97-126

COLOPHON

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