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Flexibility and Uncertainty in Infrastructure Investment Valuation

A roadmap for valuing bridge life cycle investments taking flexibility and uncertainty along

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A roadmap for valuing bridge life cycle investments taking uncertainty and flexibility along

K.J.B. Harleman

in partial fulfilment of the requirements for the degree of

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This thesis is confidential and cannot be made public until 8 March 2018.

PREFACE

Before you lies the master thesis "Flexibility and Uncertainty in Infrastructure Investment Valuation", the basis of which is a roadmap for valuing bridge life cycle investments taking uncertainty and flexibility along. The report has been written in partial fulfilment of the requirements for the degree of MSc Construction, Management & Engineering at Delft University of Technology.

The research in this report was performed at the request of Ingenieursbureau Amsterdam, the organisation where I undertook a graduation internship. Although the research has been a rollercoaster with ups and downs, I look back upon the graduation period in satisfaction. In order to understand flexibility valuation principles one must first learn the fundamentals of financial engineering. The following statement taken form the book "Principles of Corporate Finance" by Brealey et al. (a must read in my opinion) gives a good impression of the journey I made.

Chapter 20, p. 519:

"If you have managed to reach this point, you are probably in need of a rest and a stiff gin and tonic. So we will summarize what we have learned so far and take up the subject of options again in the next chapter when you are rested (or drunk)."

It was a long journey, but I have enjoyed it and certainly learned a lot. Without the help of my supervisors at the university and municipality I would not have been able to conduct this research. Therefore I would like to thank all members of the thesis committee: Martine van den Boomen, Harro Temmink, Rogier Wolfert and Mathijs Spaan. Special thanks go to Martine and Harro for regular supervision, you kept me motivated and helped to overcome daily struggles. Furthermore a note of thanks goes to my family and friends since their help and support during the past months has, as always, served me well.

Koen Harleman
Amsterdam, March 2018

ABSTRACT

Internal and external uncertainties like structural integrity, load, demand, weather conditions and spatial planning have an impact on Infrastructure assets. Incorporating uncertainties and flexibility to decisions by means of more information becoming available, adds value to new investments, life time extended maintenance and replacements. The traditional way to evaluate such projects, the Life Cycle Cost Analysis (LCCA) based on traditional Net Present Value (NPV) techniques fails to incorporate flexibility, and hence ignores extra value from expected future information. Decision Tree Analysis (DTA) and Monte Carlo Analysis (MCA) can actually allow for valuing flexibility in investments.

If investments are subject to non-diversifiable uncertainties, investors should be compensated for associated risks by using time dependent risk adjusted discount rates for valuation practices. A discussion is taking place on difficulties that occur if this principle is applied to infrastructure investments. Conducted literature research shows that current techniques to correct for non-diversifiable cannot be applied directly to most engineering valuation problems.

A MCA on investment alternatives regarding to the replacement of a bridge in the municipality of Amsterdam demonstrates how expected investment values can be calculated taking along multiple uncertainties and flexibility. Although the value of flexibility is always equal or greater than zero, case study results show that incorporating uncertainty and flexibility in the analysis can also affect the NPV negatively.

SUMMARY

This report aims to provide a method for infrastructure investment valuation taking multiple uncertainties and flexibility into account. In the context of the research flexibility is defined as the opportunity to optimimise for expected investment value by exercising optimal investment options that come with deferral of infrastructure investment. From this definition the value of flexibility can be described as the expected Net Present Value (NPV) taking uncertainties and multiple investment options into account minus the expected NPV taking only uncertainties along and excluding investment options for preventive asset replacement interventions. In literature two methods are suggested to include flexibility in the valuation process, namely the Decision Tree Analysis (DTA) and Monte Carlo Analysis (MCA). Where DTA is generally applied to optimize and visualize investment strategies, MCA can be very useful for complex analysis to determine expected investment values.

Depending on uncertainty characteristics DTA and MCA can be performed using fixed or time dependent risk adjusted discount rates. Infrastructure investments are generally subject to both diversifiable uncertainties (endogenous) as well as non-diversifiable uncertainties (exogenous). In order to compensate investors for risk associated with non-diversifiable uncertainties, one could adjust discount rates to changing risk profiles over time. This principle is based on the financial option pricing theory and often referred to as Real Options Analysis (ROA). To perform ROA the analyst should construct a portfolio that replicates the investment option payoffs and subsequently discount the portfolio value with time dependent risk adjusted discount rates. Since the adjustment of discount rates over time is very difficult and time-consuming ROA provides an alternative technique that gives identical valuation results, namely the risk-neutral probability approach. The approach risk-adjusts probabilities of specific cash flows occurring at specific times and simulates a risk-free world by composing a risk-free hedge portfolio. This allows to use a fixed risk-free rate to obtain the value of certain investment options.

A discussion is taking place on difficulties that occur if ROA techniques are used for infrastructure investment valuation. As mentioned these investments are subject to both exogenous as well as endogenous uncertainties, which makes it hard to construct portfolios that perfectly replicate option pay-offs in every state of nature over the time to maturity. For exogenous market uncertainties related to material price levels it is likely that a replicating portfolio can be constructed. Since materials are priced on markets and traded as world commodities it possible to replicate option payoff schemes using commodity share values. Endogenous uncertainties like for example asset user demand are not priced or traded on markets, forcing the analyst to find a financial surrogate that has the same cash pay-outs as the investment options for a particular asset in every possible future state over the duration of the deferral period. If not impossible, this task seems to be highly ambitious.

As discussed an alternative to correct for non-diversifiable risk would be the risk-neutral probability approach. The approach uses binomial trees to incorporate uncertainty into the analysis. In order to consider multiple uncertainties trees should be constructed for each uncertainty and subsequently combined to a single binomial tree. Formulas to calculate probabilities for up- and downward uncertainty movement in trees assume that uncertainty development follows a random walk, also referred to as Brownian Motion (BM). This motion follows a series of steps, where each step is a created by a random shock which can take positive and negative values. In particular endogenous uncertainties around infrastructure investment do not always follow BM, causing that formulas associated with the risk-neutral probability approach cannot be applied 1-on-1 to construct (sub)trees for these uncertainties. For these reasons standard ROA techniques cannot be blindly used to correct for non-diversifiable risk in infrastructure investments which makes this task difficult and credible results are not guaranteed due to the level of complexity.

In order to demonstrate the valuation for process for infrastructure investments taking multiple uncertainties and flexibility into account, a case study is conducted on the replacement of a fixed road bridge in the city centre of Amsterdam. Uncertainties that affect investment option payoffs and therefore the expected NPV are determined by conducting a sensitivity analysis on bridge life cycle cost variables. Results show high sensitivity to investment cost for actual bridge replacement which are mainly driven by the dimensions of the new build bridge, material cost and labour cost. Therefore uncertainties around bridge user demand, a car-free city centre and price levels for concrete, steel and labour are incorporated in the analysis. Furthermore, NPV is sensitive to investment timing due to time value of money. Because the maximum period to defer replacement is limited by settlement of the bridge, uncertainty around this event to occur is also taken into account. Both preventive as well as corrective 1-on-1 and scaled down bridge replacement options are considered as they react to uncertainty development and therefore affect the expected NPV of the investment alternative to defer replacement.

Since the focus in this research is on calculating expected investment values and not to find optimal investment strategies, MCA is applied to solve the case study valuation problem. Furthermore MCA is favoured since the method can handle complex analysis by means of including multiple investment options and uncertainties that follow different motions. The probabilistic model optimizes for the expected NPV related to deferred investments taking risk of corrective replacement and opportunities for preventive interventions along. Expected NPV is defined as the average of investment values associated with simulated optimal investment options under possible uncertainty developments. Because considered uncertainties form a mix of endogenous, exogenous and hybrid (endo-/exogenous) factors and uncertainty development regarding to a car-free city centre and bridge settlement deviate from BM, standard ROA valuation techniques cannot be applied directly or easily. As literature does not provide a suitable solution to correct for non-diversifiable related to infrastructure investments the model in the case study works with a fixed discount rate.

Analysis results show that flexibility adds value to the deferral investment alternative, however the NPV outcome taking multiple uncertainties and flexibility into account is slightly negative relative to results obtained with a traditional deterministic LCCA approach. This can be explained by the fact that negative impact on NPV caused by adding multiple uncertainties to the analysis overrules the positive effect that comes with flexibility. Therefore, comments in literature about the underestimation of investment alternatives if valued using traditional NPV because it fails to capture the value of flexibility should be treated carefully. Furthermore the importance of including all relevant uncertainties that may affect NPV outcomes is demonstrated by comparing MCA based on single and multiple uncertainties. Results show differences in sampled scenarios and associated investment values. Consequently expected NPV for the deferral investment alternative differs significantly under single and multiple uncertainty conditions.

From research results it can be concluded that exact valuation of infrastructure investments taking multiple uncertainties and flexibility along is highly complex as current techniques to correct for non-diversifiable risk are based on financial option pricing theory and cannot be applied directly to most engineering valuation problems. Furthermore an important research finding is the relevance of including multiple uncertainties to the infrastructure investment valuation process. Whereas current flexibility valuation practices generally incorporate only a single uncertainty that can be controlled by exercising certain investment options, this approach may provide misleading results if the analyst pursues to calculate the expected NPV of an infrastructure investment alternative. In general flexibility valuation is considered to be very useful as it forces the analyst to determine risks sources and define investment options that can be used to control uncertainty impact.

As mentioned the proposed Monte Carlo Simulation (MCS) model works with a fixed discount rate which means investment cashflows are not corrected for non-diversifiable risk. Although this could affect the expected NPV results generated by the model, the relevance of compensating investors for risk related to investments in public infrastructure seems to be questionable. Further research is recommended on hybrid valuation methods that can be used to value investments subject to both exogenous as well as endogenous uncertainties. Moreover research on bridge replacement decisions at network level and their effect on expected NPV outcomes would be a logical next step to improve infrastructure investment valuation practices. Finally, inter-dependencies between different uncertainties and incorporation of non-quantifiable costs/benefits could be interesting research topics.

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ABBREVIATIONS

BM = Brownian Motion
DTA = Decision Tree Analysis
GBM = Geometric Brownian Motion
IBA = Ingenieursbureau Amsterdam
LCCA = Life Cycle Cost Analysis
LM = Lattice Model
MCA = Monte Carlo Analysis
MCS = Monte Carlo Simulation
NPV = Net Present Value
ROA = Real Options Analysis
V&OR = Verkeer & Openbare Ruimte

1 INTRODUCTION

The following sections provide information on the research problem, research objective and the methodology applied to achieve intended research goals.

1.1 Problem Description

The municipality of Amsterdam has to manage a portfolio consisting of circa 1,900 bridges. Whereas 280 of these bridges are centrally maintained by the Traffic and Public Space Department (Verkeer & Ordelijke Ruimte, V&OR), management of the remaining 1,420 bridges is assigned to local city districts. The municipality constantly seeks to improve bridge life cycle management as safety and accessibility of the city are highly sensitive to the functioning of these infrastructure objects (Neves Cordeiro & Hauwert, 2015).

In 2013 the municipality of Amsterdam conducted safety assessments for circa 10% of the bridge population and discovered that the majority does not meet minimum safety requirements. For these bridges managers have to compare cost, risks and expected performance related to maintenance strategies to characteristics of replacement alternatives. In order to perform this task, the municipality currently applies Life Cycle Cost Analysis (LCCA) based on traditional Net Present Value (NPV) techniques. LCCA is a static approach, as expected cash flows and therefore NPV results are based on a fixed future scenario (Neves Cordeiro & Hauwert, 2015)

However, the future is highly uncertain and the application of a dynamic approach could provide additional insights. According to general valuation rules infrastructure investments should be rejected if the expected NPV is negative. Identification and valuation of options for flexibility can compensate for the negative balance and turn investments into profitable alternatives. Furthermore investment alternatives with a positive expected NPV may benefit from flexibility valuation as extra value increases the yield on investment. (Bos & Zwaneveld, 2014) .

1.2 Research Objective

Based on the described problem it would be interesting to conduct research on the valuation of infrastructure investments taking uncertainty and flexibility along. From literature review (appendix B) it is concluded that current flexibility valuation practices generally include a single uncertainty source to determine expected NPV and the value of flexibility. It seems to be unlikely that including a single uncertainty will generate credible valuation results as the expected NPV for deferred investment alternatives are mostly influenced by multiple uncertainties under real life conditions. Therefore this research focuses on achieving the following objective:

Identify a method that can be used to evaluate infrastructure investments taking flexibility and multiple uncertainties along.

Research Question

In order to achieve the intended goal a research question is defined and eventually answered. The main question to be answered in this study is:

How can infrastructure investments be evaluated taking multiple uncertainties and flexibility along and to what extent does flexibility valuation affect investment decisions in bridge life cycle management?

Furthermore sub-questions are defined that will provide guidance in finding an answer to the central research question:

a) Which methods are available to evaluate and compare infrastructure investment alternatives?
b) To what extent can these valuation methods incorporate uncertainty and flexibility?
c) What are the difficulties regarding to infrastructure investment valuation taking flexibility and multiple uncertainties along?
d) To what extent deviates analysis outcome obtained with traditional deterministic valuation methods from results obtained with methods that incorporate flexibility and uncertainty?

1.3 Research Methodology

In order to perform research in a structured way a research methodology is designed. The study in this report can be divided in three phases that need specific methods to finalize each phase.

1. The first phase focused on examination of current valuation methods. It provided insights into difficulties that occur if infrastructure investments are evaluated taking uncertainty and flexibility along. For this phase the methodology "literature research" is considered to be useful, as the focus is on acquiring general information and not case-specific knowledge.
2. Literature research provided insight into data and knowledge needed for infrastructure investment valuation. In order to translate these insights to case-specific situations interviews are conducted with experts from the municipality of Amsterdam. These Interviews have a semi-open structure as valuable information is often gathered during informal open discussions.
3. Finally, a case study is performed on the replacement of a fixed road bridge in the city centre of Amsterdam. A single case study provides possibilities to demonstrate preferred valuation methods and test research findings. For the case:
    - Multiple relevant uncertainties are identified and incorporated
    - Different investment options are identified and incorporated
    - A valuation Monte Carlo Simulation (MCS) model is designed and tested

2 BRIDGE LIFE CYCLE MANAGEMENT

Bridges are important infrastructure objects as network safety and accessibility are highly sensitive to the functioning of these elements. When bridges approach the end of their lives, managers compare cost, risks and expected performance related to maintenance strategies to characteristics of replacement alternatives. In order to make a trade-off between these investment alternatives LCCA is commonly used to as a decision support tool for valuation practices. Unfortunately LCCA often miscalculates expected investment values since the method fails to incorporate flexibility, and hence ignores extra value from expected future information. In this chapter general concepts of Bridge Maintenance Management, LCCA and Flexibility Valuation in Bridge Life Cycle Management will be described.

2.1 Bridge Maintenance Management

Bridge maintenance can be defined as all activities and services that aim to retain or return an asset to the optimal state in which it can perform its function properly. In general, there exist three maintenance categories in which activities can be classified:

- **Small Maintenance** entails daily activities that focus on temporary conservation of the bridge. These activities will not contribute to lifespan optimisation or preservation of the assets quality on the long term.
- **Major Maintenance** such as preventive maintenance activities will be performed to preserve and improve the lifespan of a bridge. Major maintenance makes deferral of bridge replacement possible and aims to decrease cost for small maintenance.
- **Deferred Maintenance** are delayed maintenance activities. Delay of maintenance is often caused by budget exceedance or redistribution of expenses. It can cause capital destruction if early replacement is necessary because bridges do not meet their expected lifespan.

Apart from maintenance activities that contribute to quality conservation and optimisation, bridge management covers activities that reduce risk and preserve the functionality of the asset during its life. This includes monitoring, conducting inspections and redesigning in the case of changing user preferences. The life cycle of a bridge can be divided in three phases: the initial, middle and final phase. During the initial phase acquisition, design and construction of the bridge followed up by small maintenance activities will be covered. In the middle phase major maintenance activities will be added to the maintenance program and focus will shift to conservation and optimisation of the assets lifespan. The final life cycle phase is characterized by more and more component failures which at the end will result in the decision to replace the bridge. In figure 1 the initial phase is depicted on the left, since functionality and quality of the bridge is 100% just after construction. As shown by the grey line quality of the asset will decrease in time until minimum safety standards are exceeded, and replacement of the bridge is inevitable. Although major maintenance activities will increase bridge quality during this period, total recovery can only be reached by replacement. The red line shows that deferral of maintenance activities will accelerate the deterioration process which results in a shorter bridge life-cycle (Neves Cordeiro & Hauwert, 2015).

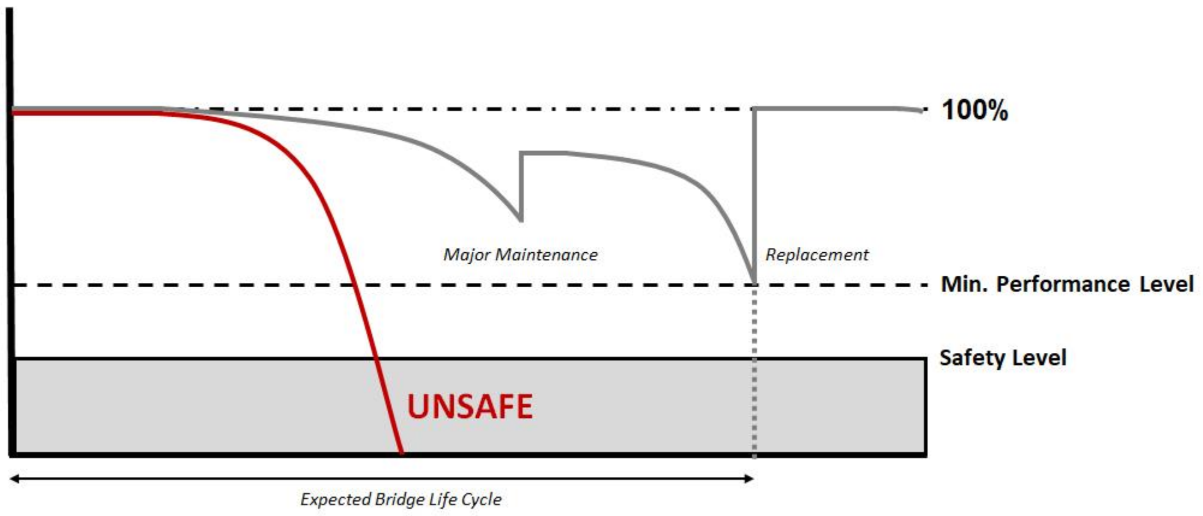


Figure 1, Bridge Life Cycle & Maintenance Management (Neves Cordeiro & Hauwert, 2015)

2.2 Traditional Life Cycle Cost Analysis

When a bridge approaches the end of its life, cost, risks and expected performance related to restoration should be compared to characteristics of the replacement strategy. To make a trade-off between these investment alternatives LCCA is commonly used as a decision support tool. This method identifies all significant cost sources that occur during an asset life cycle and subsequently quantifies cost by applying the NPV technique. An extensive elaboration on the principles and application of this valuation technique can be found in chapter 3. As mentioned earlier the life cycle of a bridge starts when acquisition is taken into consideration and ends when the asset is taken out of service for demolition. Leland Blank & Anthony Tarquin give the following definition for LCCA (Leland Blank & Anthony Tarquin 2012):

> *"Life-cycle cost (LCC) analysis utilizes AW or PW methods to evaluate cost estimates for the entire life cycle of one or more projects. Estimates will cover the entire life span from the early conceptual stage, through the design and development stages, throughout the operating stage, and even the phaseout and disposal stages. Both direct and indirect cost are included to the extent possible, and differences in revenue and savings projections between strategies are included"*

A shorter definition is given by David Woodward (Woodward, 1997):

> *"The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life"*

Graham Harvey describes a general procedure that can be used to perform LCCA. The first step in the analysis is to define cost elements of interest. In other words, the analyst should start with defining all cost parameters that occur during the life of the asset. The second step consist of defining cost structures to identify potential trade-offs. If there are many cost parameters grouping of these variables is necessary to identify trade-offs and achieve optimum LCC. Examples of cost groups are engineering cost, production cost and operating cost. When cost parameters are defined and grouped the development of actual cash flows during the life of an asset should be estimated. The analyst tries to extract cost estimating relationships from historical data. Cost estimating relationships are linear, parabolic or for example hyperbolic functions that describe the cashflow as a function of one or more independent variables. Finally, the asset's LCC should be evaluated using NVP techniques.

LCCA gives analysts the possibility to assess the economic worth of an investment by identifying and discounting all future cash outflows. The following elements are suggested to consider in order to achieve credible LCCA results (Woodward, 1997):

- **Initial Capital Cost** are expenses related to purchasing, acquisition and installation of the asset.
- **Life of The Asset** is the expected lifespan of an asset. Functional, physical, technological, economic, social or/and legal life can be determinants of this element.
- **The Discount Rate** is an interest rate that should be used for discounting future cash flows and calculating present values. The selection of an appropriate discount rate is important for LCCA results. Low discount rates have a positive effect on the value of investment alternatives with long lifespans, high capital cost and low recurring cost. High discount rates favour alternatives with opposite characteristics.
- **Operating & Maintenance Cost** are all expenses to keep the asset fulfilling its function during its life
- **Disposal Cost** are expenses related to demolishing, scrapping or selling the asset.
- **Information & Feedback.** To perform LCCA, financial, time related, information is needed. For example, information on the capital cost of acquisition is essential for proper analysis. Furthermore, data on the asset's performance should be collected during operation. Data capture and feedback systems help to forecast failure rates, spares demand and maintenance requirements.
- **Uncertainty & Sensitivity Analysis** reveals the sensitivity of results to changes in input. LCCA results are highly dependent on input variables. Because information and data is often collected by monitoring asset performance during operation, initial input is based on assumptions and estimates. Sensitivity analysis is a deterministic technique that is often used to take uncertainty along in LCCA. Without requiring additional resources or information, the analysis can produce a single-point estimate of how input variables affect the LCCA results.

2.3 The Concept of Flexibility

Traditional methods like LCCA evaluate investment strategies based on a single-line future scenario. Although sensitivity analysis incorporates uncertainty into the analysis, the approach is still deterministic as future scenarios are fixed. Each scenario produces a single-point estimate of how uncertain input data affect the analysis outcome. However, in real life coincidence plays an important role which requires the use of a stochastic valuation method to generate credible results.

Even though uncertainty is often linked to downside risk it can also provide conditions for upside flexibility opportunities. In literature the concept of flexibility is often described as the possibility to adapt investment strategies to deviations in expected future developments caused by uncertainty. Implementing this so-called managerial flexibility creates value as downside risk can be reduced and upside opportunities increased. It is the relative ease to make changes in the investment strategies or technical changes in the asset/system itself. The strategy to start production on a small-scale and to expand whenever product demand rises contains this managerial flexibility. If demand stagnates or even decreases, the manager can choose to defer expansion or abandon production at relatively low cost. Furthermore, managerial flexibility always comes with deferral as infrastructure investments made today are irreversible.

In the context of this research flexibility is defined as follows:

Flexibility is the opportunity to optimimise for expected investment value by exercising optimal investment options that come with deferral of infrastructure investments.

NPV methods prescribe that investment alternatives with a negative value should be rejected. The extra value flexibility creates can compensate a negative expected NPV and turn the alternative into a profitable investment. Furthermore investment alternatives with a positive expected NPV can also benefit from flexibility valuation as extra value increases the yield on investment. From the definition and in the context of this research the value of flexibility can be described as the expected Net Present Value (NPV) taking uncertainties and multiple investment options into account minus the expected NPV taking only uncertainties along and excluding investment options for preventive bridge replacement interventions. The following example will show the concept of flexibility and its value.

Flexibility Value Example: A Simple Deferral Option (obtained from Copeland & Antikarov (2001))

In this example an investor has to choose between two investment strategies: invest 2,000 euro in a production line today or defer the investment 1 year. All investments are assumed to be irreversible and depreciation of the system will be compensated by future replacement investments of equal magnitude. If the investor decides to invest today he/she will make a direct profit of 300 euro. What the profit on investment will be one year from now is uncertain. There is a 50% chance that it will go up to 500 euro and a 50% chance that it will decrease to 100 euro. Profit changes in the first year are assumed to be permanent, in other words the yearly profit will stay at a constant level. Therefore, Long-term expected profit will be 300 euro/year. Finally, the cost of capital is assumed to be 10.0%. It is suggested to forecast expected cash flows and discount them at the cost of capital. Subsequently this amount can be subtracted from the initial investment. For the two investment strategies this will result in the following values:

- <u>NPV Direct investment:</u>

  $= -2{,}000 + \sum_{t=0}^{\infty} 300/(1.1)^{t} = -2{,}000 + 3{,}300 = 1{,}300$ euro

Note: expected cash flows of 300 euro is based on 50/50 chance of a permanent 500 or 100 euro price level

- <u>NPV defer investment 1 year:</u>

  $= 0.5 \text{ MAX } [(-2{,}000 / 1.1) + \sum_{t=1}^{\infty} 500/(1.1)^{t};\ 0\ ] + 0.5 \text{ MAX } [(-1{,}500 / 1.1) + \sum_{t=1}^{\infty} 100/(1.1)^{t},\ 0]$
  $= 0.5 \text{ MAX } [(-2{,}000 + 5{,}500) / 1.1,\ 0\ ] + 0.5 \text{ MAX } [(-2{,}000 + 1{,}100) / 1.1,\ 0]$
  $= 0.5\ [3{,}500 / 1.1] + 0.5\ [0] =$ 1,591 euro

If the analyst chooses to defer the investment 1 year, he has the possibility to follow the development of the profit uncertainty. A profit decrease results in cash flows with a total present value of 1,100 euro at the end of year 1. Because the initial expenses are 2,000 euro the investment has a negative NPV and the investor will reject the investment. On the other hand, when profit goes up to 500 euro, the total value of cash flows will be 5,500 euro at year 1. The value of future cash flows exceeds the initial investment and after discounting this results in a positive NPV. If this scenario evolves it is suggested to take the investment along. Assuming a 50 percent chance for each of the scenarios to happen, the weighted present value from today's point of view of deferring the investment 1 year will be 1,591 euro. As 1,591 > 1,300 this investment strategy to defer investment with one year is favoured. The value of flexibility in this example is the difference between the two investment alternatives, namely 1,591 – 1,300 = 291 euro

Without uncertainty there is no incentive for managers to use investment options during the deferral period and therefore the value of flexibility becomes zero. Since certain future developments do not exist one could argue that flexibility will always add value. However, if options to defer, phase or scale an investment are lacking it is obvious that the valuation of flexibility is worthless. Therefore, flexibility is not only positively correlated to uncertainty, but also to the amount of options that become available due to deferral of investments.

Although the value of flexibility is greater than or equal to zero implementing investment options will not always affect the value of investment strategies positively. Sometimes initial expenses should be made to make deferral of investments possible and therefore to enable flexibility. Although the option to postpone replacement may be desirable for optimal bridge life cycle management, this often comes with major and expensive maintenance activities. The value of flexibility enabled by postponement does not always outweigh the pre-investments (Bos & Zwaneveld, 2014). In order to determine expected investment value and therefore taking into account the value of flexibility literature suggests to follow the steps shown in figure 2.

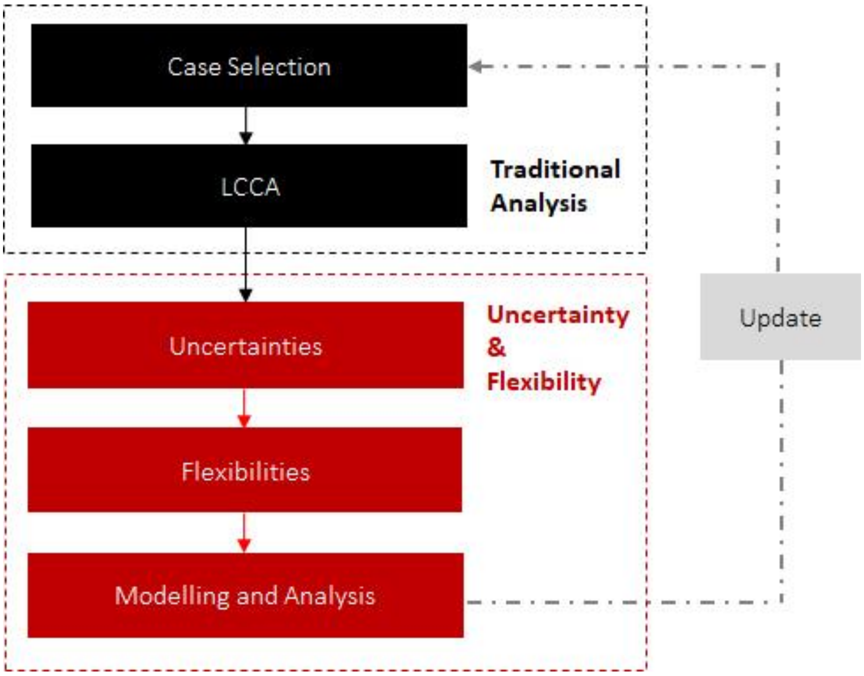


Figure 2, Investment Valuation Process (own figure, 2018)

Before the actual valuation process starts the analyst should select a case for the analysis. A few questions are important to take into consideration regarding to the case selection (Bos & Zwaneveld, 2014; Bräutigam, Esche, & Mehler-Bicher, 2003; Tahon et al., 2014):

1. **Is the future surrounding the asset uncertain?** The value of flexibility increases with the amount of uncertainty surrounding assets. Without uncertainty flexibility is worthless.
2. **Are there investment options available during deferral periods?** Flexibility comes with investment options during deferral periods for infrastructure investments. Availability of these options is necessary to reduce risks or increase opportunities associated with uncertainties.
3. **Are there no regret solutions?** Flexibility will not add value to expected NPV if certain investment options are favoured for all considered future conditions.

4. **Are investments irreversible and do they lead to sunk cost?** If investor can reverse investment decisions the availability of investment options will be redundant and hence flexibility worthless.
5. **Are asset payoffs asymmetric under risk?** If asset payoffs are not asymmetric under risk the influence of uncertainty development on the expected investment value will be zero. Therefore the impact of risk cannot be controlled by exercising investment options during the deferral period
6. **When do I have to decide?** Flexibility only exists if investments can be deferred. Furthermore, the value of flexibility increases with time as more information becomes available and investors can make better investment decisions.

When the case is selected a LCCA based on traditional NPV techniques should be performed. This analysis provides a clear understanding of the assets value if uncertainties and flexibility are not taken into account. The next step is to identify and incorporate relevant uncertainties and investment options. Finally the analyst should choose a valuation method that can be used to determine expected investment values taking along investment options and uncertainty development in a probabilistic way. In literature the Decision Tree Analysis (DTA) and Monte Carlo Analysis (MCA) are suggested methods to perform the final step. The choice of valuation method for infrastructure investments will be elaborated extensively in chapter 3. Because valuation results are dependent on uncertainty development estimates the analysis should be revised when more information becomes available and midcourse investment decisions are made.

2.3.1 The Identification of Relevant Uncertainties

The identification and incorporation of uncertainties is an important step in the valuation process. Uncertainty around for example product prices or user demand drive investment option values and therefore affect expected NPV outcomes. Lin describes three groups in which uncertainty sources can be classified (Lin, 2008):

- **Endogenous Uncertainties:** Endogenous uncertainties are embedded in the technical system itself. Engineering knowledge is required to identify, actively manage and reduce these uncertainties. An example is system failure uncertainty.
- **Exogenous Uncertainties:** Managers cannot directly control or reduce these uncertainties. Although impact can be managed by proactive or reactive response, it is impossible to reduce the risk at the source. Examples are market uncertainties as interest rates and price levels.
- **Hybrid Uncertainties:** This type is always a combination of endogenous and exogenous uncertainties. Decision makers can to some extend control these uncertainties. Examples are labour cost, schedule and contractual uncertainties.

In literature Lessard proposes five uncertainty layers as shown in figure 3. The influence of decision makers on the uncertainty types decreases from the upper to the lower box. The box on top corresponds with endogenous uncertainties, whereas the three lowest uncertainty types reflect exogenous uncertainties. Uncertainties in the second layer can be classified as hybrid uncertainties. Neely and de Neufville (2001) divide uncertainties in diversifiable project uncertainties (endogenous) and non-diversifiable market uncertainties (exogenous). They describe project uncertainties as uncertainties associated with the asset itself. On the other hand, market uncertainties result from market forces. These uncertainties are not unique to one asset, but have impact on the value of all assets with similar system designs (Neely & de Neufville, 2001).

Figure 3, Uncertainty Layers (Lessard & Miller, 2001)

Bridge Life-Cycle Uncertainties

Since the case study in chapter 4 concerns the replacement of a fixed road bridge in the city centre of Amsterdam, bridge life-cycle uncertainties that affect expected NPV of replacement investment alternatives are relevant in the context of this research. An Ishikawa diagram, also known as a cause-effect diagram or a fishbone diagram, can be used to determine uncertainties in a clear and effective way. In literature the diagram is often constructed to find bottlenecks and improve efficiency of asset performance or production processes. Ishikawa describes three general steps which should be followed in order to create a cause-effect diagram: Identification of the main problem/goal, identification of main causes and finally the identification of detailed causes.

An overview of uncertainties around bridge replacement can be found in appendix A. The presented Ishikawa diagram is based on main uncertainties that affect expected NPV outcomes and detailed causes that define these main uncertainties. The LCCA elements and uncertainty sources mentioned in section 1.2.2. are taken as a starting point for the identification of main uncertainties and detailed causes. A literature research and interviews with four experts from the municipality of Amsterdam provided more insights on possible relevant uncertainties for the bridge life cycle valuation problems.

2.3.2 Investment Options to Control Uncertainty

In order to control the impact of uncertainty developments on the value of investment alternatives, uncertainty management should be carried out. Literature provides three approaches to control uncertainty (Lin, 2008):

- **Control Approach:** This uncertainty management type can be described as direct risk reduction. Uncertainty will be controlled directly during system operation and modifications on the system/asset are not necessary. An example is controlling customer demand by adjusting product price or quality.

- **Passive Approach:** Uncertainty management is called passive if managers do not actively seek to reduce downside risk or use upside opportunities during system operation. This approach controls uncertainty by designing robust systems will. Robust designs can fulfil their function despite changes in the environment or within the system. Therefore, robustness of a system can be measured by its functional sensitivity to environmental changes.
- **Pro-Active Approach:** Pro-active uncertainty management is performed by designing and exercising investment options in order to adapt to uncertainty developments. Since this description corresponds with the definition for flexibility in context of this research, the pro-active approach will be examined in the remainder of the report.

Investment Options

One of the most common investment options to control uncertainty development is the deferral option. It gives managers the possibility to alter an investment until more information comes available and better investment decisions can be made. Instead of replacing a bridge at the end of a life cycle managers can "buy time" by performing major maintenance activities. This gives a manager the possibility to analyse uncertainties and decide later whether the bridge should be replaced or not depending on for example user demand developments. Reservation of space next to a bridge creates flexibility as future expansion possibilities are left open. Initial capital cost will be higher, but the option to expand may result in extra social benefits in the future. Trigeorgis (1996) did research to general investment options in infrastructure and distinguished the following main categories (Trigeorgis, 1996):

- **The option to defer:** This option gives managers the possibility to alter investments. The option has value if there is a possibility that future conditions are preferable compared to the present situation.
- **The option to stage:** This option gives managers the possibility to stage investments. Staged investments subsequently create abandon and growth options at each stage.
- **The option to alter operating scale:** This option gives managers the possibility to scale if market conditions change. For example, asset demand may change over time and therefore scaling asset capacity can be valuable
- **The option to abandon:** This option gives managers the possibility to abandon investments if expected returns are too low.
- **The option to switch:** This option gives managers the possibility to shift investments. Managers may for example have the option to switch production and invest in products with a higher market value.
- **The growth option:** This option gives managers the possibility to easily growth in the future by conducting pre-investments.
- **The interacting option:** Combination of previous options.

Cardin and de Neufville describe two approaches to identify ivestment options. The indirect approach suggests that analysts should gather data and information in order to find design variables and subsequently design options for investment flexibility themselves. The direct approach involves discussions in which designers and experts are directly asked to identify and design investment opportunities (M.-A. Cardin & de Neufville, 2009).

2.4 Conclusion

Bridges are important infrastructure objects as network safety and accessibility are highly sensitive to the functioning of these elements. When bridges approach the end of their lives, managers compare cost, risks and expected performance related to maintenance strategies to characteristics of replacement alternatives. In order to make a trade-off between these strategies LCCA is commonly used as a decision support tool for valuation practices. This method identifies all significant cost sources that occur during an asset life cycle and subsequently quantifies cost by applying NPV techniques.

Traditional methods like LCCA evaluate investment strategies based on a single-line future scenario. Although sensitivity analysis incorporates uncertainty into the analysis, the approach is still deterministic as future scenarios are fixed. Each scenario produces a single-point estimate of how uncertain input data affect the analysis outcome. However, in real life coincidence plays an important role which requires the use of a stochastic valuation method to generate credible results. Furthermore traditional valuation methods fail to incorporate flexibility, and hence ignores extra value from expected future information. In the context of this research flexibility can be defined as follows:

Flexibility is the opportunity to optimimise for expected investment value by exercising optimal investment options that come with deferral of infrastructure investments.

An important first step to determine the “real” expected NPV of deferred investment alternatives is the identification of relevant uncertainties. These uncertainties can be divided in endogenous, exogenous and hybrid uncertainties. Endogenous uncertainties are embedded in the system itself and can be controlled directly, whereas managers are not able to influence exogenous uncertainties. From literature research and interviews with four experts at the municipality of Amsterdam a set of bridge life cycle uncertainties is subtracted and shown in appendix A.

Uncertainties can be managed in three different ways, namely following the control, passive or pro-active approach. In this research the pro-active uncertainty management approach, which entails designing and exercising investment options in order to optimise expected NPV of deferred investment alternatives, will be examined. Investment options can be classified in options to defer, stage, scale, abandon, switch or growth. Moreover, combinations of these option types, known as interacting options, exist. Analysts can identify these options by asking experts directly about investment option opportunities, or indirect through collecting information on system components and subsequently design investment options for flexibility themselves.

3 INFRASTRUCTURE INVESTMENT VALUATION

In literature DTA and MCA are suggested methods to evaluate infrastructure investments taking flexibility and uncertainty along. Depending on uncertainty characteristics DTA and MCA can be performed using fixed or time dependent risk adjusted discount rates. In this chapter the main principles and differences between traditional NPV analysis, DTA and MCA will be described. Furthermore, difficulties regarding to the adjustment of discount rates to correct for non-diversifiable risk are presented. The principles behind these valuation methods and techniques will be demonstrated with examples based on option valuation practices by Copeland & Antikorov (2003). In the examples an investor has to decide today on pre-commitment for an investment of 125 euro next year that will generate 50/50 140 euro or 80 euro. The alternative is to exercise an option to defer investment decisions, which gives the analyst the right but not the obligation to wait with the investment until the end of the year. This option creates value as the investor is now able to analyse uncertainty development around investment payoffs and make better investment decisions. The examples show how different valuation methods and techniques can be applied to determine option value and expected NPV of investment alternatives taking flexibility and uncertainty along.

3.1 Comparing Net Present Value, Decision Tree and Monte Carlo Analysis

Regarding the valuation steps presented in figure 2, actual infrastructure investment analysis starts with a LCCA based on traditional NPV techniques. This analysis provides a clear understanding of the assets value if uncertainties and flexibility are not taken into account. Although traditional NPV analysis fails to incorporate flexibility, methods like DTA and MCA heavily rely on NPV valuation techniques. Therefore this section will firstly describe the main principles of NPV, followed by an elaboration on DTA and MCA methods.

3.1.1 Net Present Value Analysis

NPV analysis relies on a known capital outlay and from there on calculates the expected cash flows. The next step in analysis is to correct the future cash flows for depreciation of currency, also known as time value of money. A risk-adjusted rate can be used to discount the cashflows and determine present values. A relevant risk-adjusted discount rate entails the weighted average cost of capital (WACC) plus a premium for risk associated with the investment. WACC consist of the company's cost of equity and debt and can be defined as the interest a company has to pay for every dollar it finances. If the sum of all discounted cashflows is larger than zero, the investment is profitable and should be taken along. A negative NPV generally results in rejection of the investment. If NPV shows around zero valuation of flexibility can be very useful as adding extra value can prevent the investor from rejecting the investment alternative (Copeland & Antikarov, 2001).

As mentioned the most important disadvantage of NPV analysis is that the method assumes pre-committed investment decisions. This means that it fails to incorporate flexibility that comes with the availability of investment options during the deferral period for infrastructure investments. Furthermore, NPV analysis is based on a single scenario that is obtained by averaging possible future developments. It assumes that evaluating an investment around average conditions gives correct results. This assumption holds if all relevant relationships are linear, otherwise the so-called flaw of averages will affect analysis outcomes (Neufville & Scholtes, 2011).

NPV Example: Deferral Without Flexibility (obtained from Copeland & Antikarov (2001))

	Twin Security Payoff (t=1)	*Twin Security Cost (t=0)*	*Investment Payoff (t=1)*	*Investment Cost (t=1)*
Cash Flow Up (V_{up})	€ 35	€ 25	€ 140	€ 125
Cash Flow Down (V_{Down})	€ 20	€ 25	€ 80	€ 125

Risk-Free Rate (r_f) 3%
Investment decision at t=0

The following example demonstrates how the traditional NPV method evaluates investments without flexibility. The table above shows a pre-committed investment and a twin security with payoffs that are perfectly correlated (1/4 Investment Payoff = Twin Security Payoff). Because they are perfectly correlated it is assumed that the twin security has the same risk as the investment. Therefore cashflows of the investment strategy and the twin security can be discounted with the same rate. As the value of the twin security (V_0) and the expected cash flow one year from now ($0.5*V_{up}+0.5*V_{Down}$) are known, is easy to find an appropriate risk-adjusted discount rate (k):

- $NPV_{security}$ $= (q(V_{up}) + q(V_{Down})) / (1 + k)$
  25 $= (0.5*(35) + 0.5*(20)) / (1 + k)$
  k $= 10.0\%$

Now the value of the investment can be obtained by discounting the cash flows at 10.0%:

- $PV_{investment,\ cash\ flows}$ $= (q(V_{up}) + q(V_{Down})) / (1 + k)$
  $= (0.5*(140) + 0.5*(80)) / 1.10$
  = 100 euro

Since the investment costs are not uncertain (an assumption in this example following from the pre-commitment) and will be 125 euro 1 year from now, this cash flow should be discounted at the risk-free rate:

- $PV_{investment,initial\ costs}$ = 125/1.03 = 121.36 euro

The NPV of the investment without flexibility (pre-commitment) is $PV_{investment,\ cash\ flows}$ - $PV_{investment,\ initial\ costs}$:

- $NPV_{investment}$ = 100 – 121.36 = -21.36 euro

Because the expected NPV of deferred investment is negative, investors will generally reject this alternative.

3.1.2 Decision Tree Analysis

DTA combines NPV techniques to discount expected investment cashflows with scenario analysis in order to incorporate uncertainty and flexibility. The analysis starts with the translation of uncertainty development into possible future states with proportional weighted discretised probabilities to happen. In the decision trees each future state is succeeded by a decision moment that entails multiple investment options. A combination of successive investment decisions under possible future states forms a strategic pathway, also known as an investment strategy. DTA determines the value of these strategies by calculating expected cashflows and subsequently discounting to correct for the time value of money. Furthermore decision trees function as decision roadmaps for managers and provide a clear overview on optimal investment options under possible future conditions. Therefore this valuation method is generally used to optimize investment strategies (Guthrie, 2009).

Although DTA can be very useful to evaluate investment alternatives taking uncertainty and flexibility along, literature describes some main flaws regarding to the implementation of the method. Firstly, a limited amount of investment options and uncertainties can be incorporated as trees tend to get complex and fuzzy easily due to increased strategic pathways. For this reason it is not recommended to apply DTA for complex infrastructure investment valuation taking along multiple investment options and uncertainties. Furthermore, uncertainties are translated towards discretised probabilities instead of using continues probability distributions. Therefore inaccurate estimations of these probabilities could have great impact on analysis outcome (Wang & De Neufville, 2005).

DTA Example: Deferral with Option to Reject (obtained from Copeland & Antikarov (2001))

	Investment Payoff (t=1)	*Investment Cost (t=1)*	*Net Investment (t=1)*	*Reject Option (t=1)*
Cash Flow Up (V_{up})	€ 140	€ 125	€ 15	MAX[15,0]
Cash Flow Down (V_{Down})	€ 80	€ 125	€ -45	MAX[-45,0]

Risk-Free Rate (r_f) 3%
Investment decision at t=1

A common use of DTA, includes the option for the analyst to defer an investment until the end of the year. Now the analyst can follow the developments of uncertainties that drive the payoffs of the investment. If the state of nature turns out to be low at the end of the year the net value of pre-commitment to the investment is negative (-45 euro) and therefore the analyst will reject the investment. If the state of nature turns out to be high at the end of the year the net value of pre-commitment to the investment is positive (15 euro) and therefore the analyst will probably invest. The NPV of these decisions in all possible scenario's will determine the value of the deferral investment strategy. Also in this example each scenario has a 50% chance to evolve:

- $NPV_{security} = (q(V_{up}) + q(V_{Down})) / (1 + k)$
  $= (0.5*(15) + 0.5*(0)) / (1 + 0.10)$
  $= 7.5 / 1.10$
  $= 6.82$ euro

By adding the option to reject the investment in t=1, NPV has increased from -21.36 euro (result NPV example) to 6.82 euro. Consequently, the value of this option and therefore flexibility is 6.82 - (-21.36) = 28.18 euro. Note: although adding flexibility changes the risk profile of the investment, DTA uses the same discount rate (10.0%) as the NPV analysis without flexibility (1st example).

3.1.3 Monte Carlo Analysis

MCA is an analytical tool that can be used to imitate real-life situations. With computer programmes that support MCA, analysts can generate output for uncertain input variables in a random manner. The method models uncertainty development as a series of future states, where each state is created by random sampling from probability distributions that reflect possible future uncertainty conditions. Common distribution types like discrete, normal, triangular, uniform or lognormal distributions can be obtained using assumptions and estimates based on historical data. For simulated future scenarios investment option values will be calculated and with programmed decision rules the computer finally exercises optimal investment options at each decision moment. This process will be repeated until the average of all simulations becomes constant (Mun, 2002).

MCA can provide solutions for a wide range of valuation problems. With MCA the analyst can include multiple uncertainties and customize models for each uncertainty development (Wang & De Neufville, 2005). Furthermore, MCA can be intuitive for engineers as they are often more familiar with this method compared to purely financial valuation tools. Finally, analysis can be updated easily as it takes little effort to change input values and repeat the simulation. For these reasons MCA can be very useful for complex analysis regarding to expected investment valuation taking multiple uncertainties and investment options along.

The method also has a number of flaws and disadvantages. Most important is that an analysis performed with MCA lacks structure and overview. MCA does not provide a clear overview on optimal investment strategies under different future conditions. If investments are deferred and information about uncertainty development becomes available it is difficult for managers to link real life developments with simulation iterations and associated optimal solutions. Furthermore, MCA does not provide clear insights into relationships between variables. Key drivers can be determined by conducting sensitivity analysis, but a clear understanding on the reasons why certain drivers are important is missing. (Wang & De Neufville, 2005).

3.2 Correcting for Non-Diversifiable Risk

Depending on uncertainty characteristics DTA and MCA can be performed using fixed or time dependent risk adjusted discount rates. If investments are subject to endogenous uncertainties the use of static risk adjusted discount rates (WACC + Risk Premium) is preferable. Endogenous uncertainty concerns uncertainties associated with the asset itself. Their uniqueness to an asset gives managers the opportunity to diversify investments. Diversifying results on average in compensation for unexpected losses in one project by unexpected gains in others. Oil companies can spread their investments among oil fields in different regions, which will result in lower risks concerning the total oil reserves. Because endogenous uncertainties can be avoided or diversified, it is not required to compensate managers for investing in riskier projects (Neely & de Neufville, 2001).

On the other hand, exogenous uncertainties are associated with for example market forces. These uncertainties are not unique to one asset but have impact on the value of all assets with similar system designs. Take the example of the oil companies, who cannot guard themselves against a crash in market price for oil. This crash will have impact on the value of all their oil products and diversification by for example geographical origin does not remove the risk. In order to compensate investors for risk associated with non-diversifiable uncertainties, one could adjust discount rates to changing risk profiles over time. This principle is based on the financial option pricing theory and often referred to as Real Options Analysis (ROA) (Neely & de Neufville, 2001). Since the adjustment of discount rates over time is very difficult and time-consuming ROA provides an alternative technique that gives identical valuation results, namely the risk neutral probability approach. In the next sections the replicating portfolio and risk-neutral probability approach will be examined.

3.2.1 Replicating Portfolio Approach

The replicating portfolio approach is based on the principle that option payoffs can be replicated by composing a portfolio of shares and a risk-free loan. It is assumed that the value of an investment with certain options is equal to the known value of a portfolio that generates identical cash flows. Furthermore portfolios with identical payoff schemes as the investment are associated with the same level of risk. These assumptions only hold in a perfect market with no arbitrage opportunities. Suppose there are portfolios with identical payoffs and risk but different values. Now arbitrage opportunities do exist as investors can buy the lower valued portfolios and short sell the portfolios with higher values without taking any risk. In a perfect market demand drives value and a rush on the cheap portfolio's will directly result in value increase of the portfolio. Market forces tend to make portfolios with identical risk levels and payoff schemes equilibrate in value and therefore remove possible (long-term) arbitrage opportunities. Only under these conditions the assumption that portfolios with identical payoffs also have identical values will hold even though portfolio compositions may differ (Mun, 2002).

Replicating Portfolio Example: Deferral with Option to Reject (obtained from Copeland & Antikarov (2001))

	Twin Security Payoff (t=1)	*Twin Security Cost (t=0)*	*Investment Payoff (t=1)*	*Investment Cost (t=1)*	*Net Investment (t=1)*	*Reject Option (t=1)*
Cash Flow Up (V_U)	€ 35	€ 25	€ 140	€ 125	€ 15	MAX[15,0]
Cash Flow Down (V_D)	€ 20	€ 25	€ 80	€ 125	€ -45	MAX[-45,0]

Risk-Free Rate (rf) 3%
Investment decision at t=1

In this example the option payoffs will be replicated by creating a portfolio that exists of "m" twin securities and 'B'risk-free bonds of 1 euro each. The option payoffs are 15 euro (MAX[15,0]) in the up state and 0 euro (MAX[-45,0]) in the down state. Therefore the replicating portfolio pay-outs can be written as:

- *Replicating Portfolio pay-out in the up state:* $m(35) + B(1+r_f) = 15$ *euro*
- *Replicating Portfolio pay-out in the down state:* $m(20) + B(1+r_f) = 0$ *euro*

Solving these equations for the unknowns results in:

- *m* = 1 *(shares of the twin security with price € 25)*
- *B* = -19.42 *euro (a loan of 19,42 risk-free bonds of € 1 each)*

Now the NPV of the replicating portfolio becomes:

- *NPV Replicating Portfolio* $= m(25) + B(1)$
  $= 25 + (-19.42)$
  $= 5.58$ *euro*

Since option and portfolio payoffs are identical and arbitrage opportunities are assumed to be removed by a perfect market conditions the NPV of the investment strategy "defer investment to t=1" with flexibility is the same as the value of the in replicating portfolio, namely 5.58 euro. The (flexibility) value created by adding the option to reject investment in t=1 is equal to the difference between NPV without flexibility (1st example) and NPV with flexibility: 5.58 - (-21.36) = 26.94 euro.

3.2.2 Risk-Neutral Probability Approach

The risk-neutral probability approach is based on the principle that investments can be valued using the risk-free interest rate if a risk neutral world can be created. In a risk neutral world, investors do not care about risk which means that they do not require a higher return on investment to compensate risk. Since the approach aims to create a perfect hedge portfolio that poses risk-free payoffs the adjustment of discount rates in time in no longer necessary, as investors can use the risk-free interest rate to discount all cashflows (Brealey, Myers, & Allen, 2011). Although this differs from real life where required returns on investments are positively correlated with risk, the option value calculated in a risk neutral world can also be used in the real world. Risk on investments can be neutralized using risk-adjusted probabilities on cash flows generated by the investment. This means that the probabilities of different outcomes are calculated assuming that the world is risk neutral. With these risk-neutral probabilities the expected option payoff can be determined and subsequently discounted at the risk-free rate of interest. Note that risk-neutral probabilities are not equal to actual probabilities that provide chances on the occurrence of an event under real life conditions (Hull, 2012).

Risk-Neutral Prob. Example: Deferral with Option to Reject (obtained from Copeland & Antikarov (2001))

	Twin Security Payoff (t=1)	*Twin Security Cost (t=0)*	*Investment Payoff (t=1)*	*Investment Cost (t=1)*	*Net Investment (t=1)*	*Reject Option (t=1)*
Cash Flow Up (V_u)	€ 35	€ 25	€ 140	€ 125	€ 15	MAX[15,0]
Cash Flow Down (V_D)	€ 20	€ 25	€ 80	€ 125	€ -45	MAX[-45,0]

Risk-Free Rate (r_f) 3%
Investment decision at t=1

From the twin security we know that an up move (U) is given by a factor 35/25 = 1.4 and a down move (D) by 20/25 = 0.8. We assume these values applicable to our investment (marketed asset disclaimer assumption). In a risk-neutral world we compose a risk-less hedge portfolio consisting of one share of the twin-security and x shares in a short position of the option being prices (Copeland & Antikarov, 2001). With such a portfolio an investor is indifferent for risks. The riskless hedge portfolio is composed as follows:

$$V_0 - xC_u = DV_0 - xC_d$$

$$V_u - xC_u = V_d - xC_d$$

$$= 140 - x(15) = 80 - x(0)$$

Where, investment pay-off in upstate = $UV_0 = V_u = 140$ (note that V_0 must be 100 because U = 1,4); investment pay-off in down-state = $DV_0 = V_d = 80$; x is the number of shares in a short position of the option being priced; the option pay-off in the upstate = $C_u = 15$ and the option pay-off in the downstate is $C_d = 0$. Solving for x results in 4 shares of a short position of the option being priced. The option C_0value is now directly calculated from:

$$(V_0 - xC_0)(1 + r_f) = V_u - xC_u$$

$$(100 - 4C_0)(1 + 0.03) = 140 - 60$$

Solving for C_0 yields 5.58 euro. Reworking these two equations results in a well-known formula that defines the so called the risk-neutral probabilities:

$$n_u = \frac{(1 + r_f) - D}{U - D} = \frac{(1 + 0.03) - 0.8}{1.4 - 0.8} = 0.38$$

And $$n_d = 1 - n_u = 1 - 0.38 = 0.62$$

The NPV of the investment alternative with the option to defer is given by:

$$C_0 = \frac{n_u C_u + n_d C_d}{(1 + r_f)} = \frac{(0.38)(15) + (0.62)(0)}{1.03} = 5.58 \text{ euro}$$

Because the deferred investment alternative in the example has a short time span uncertainty development can be modelled relatively easy. As the analysis includes only one decision moment the analyst has to determine just two possible uncertainty states at that node. If deferred investment alternatives have long timespans and multiple decision moments the amount of possible future states growths significantly. For these valuation problems the risk-neutral probability approach can be combined with the binomial lattice model. The model is based on a tree that visualizes possible future uncertainty states that have impact on the value of investment paths. By translating continuous developments into discrete steps LM can reduce a large set of future conditions to a manageable size. Therefore, the tool provides a clear understanding and overview of possible future states under which management must make decisions regarding to investment strategies.

The first node in a lattice (t=0) represents the current situation and therefore conditions are certain. Next the standard binomial lattice assumes that uncertainties that drive the value of an investment (option) can develop into two possible future states per time step, namely up and down. The risk neutral probability approach converts actual probabilities to risk neutral probabilities that reflect the chance of up and down movement. Finally, the analyst has to determine option values for all possible future states at each decision moment. Combining the highest option values for each future state with the risk-neutral probability that the future state will be reached gives the analyst not only cashflows but also investment strategies for different future conditions.

The number of time steps or decisions moments between the first node and the end of the investment period can be determined by the analyst. More time steps will result in more possible future states and a higher accuracy of the analysis as the tree converges to a continues model. This can be compared with increasing the amount of iterations when uncertainty developments are simulated with the help of computational forces. Although accuracy increases with the number of timesteps the analysis also gets more complex and time consuming to solve. Because the standard binomial tree assumes two possible uncertainty development paths per time step, the number of possible outcomes grows exponentially (2^n) with the number of time steps (n). In order to minimize the number of outcomes nodes can be recombined. This reduces the amount of possible future states and therefore simplifies the analysis. Although generally standard binomial trees with recombining nodes are applied for valuation of investment strategies, the analyst can opt to use trinomial or even larger trees in order to correctly represent uncertainty development. Both Copeland & Antikarov (2001) and Guthrie (2009) elaborate on the application of lattice models.

3.3 Infrastructure Valuation Difficulties

In literature a discussion is taking place on difficulties that occur if ROA techniques like the replicating portfolio or risk-neutral probability approach are used for infrastructure investment valuation. The key assumption of financial option pricing theory and therefore ROA is the possibility to replicate option payoff schemes. Generally infrastructure investments are subject to a mix of endogenous and exogenous uncertainties, which makes it hard to construct portfolios that perfectly replicate option pay-offs in every state of nature over the time to maturity. For exogenous market uncertainties related to material price levels it is likely that a replicating portfolio can be constructed. Since materials are priced on markets and traded as world commodities it possible to replicate option payoff schemes using commodity share values. Endogenous uncertainties like for example asset user demand are not priced or traded on markets, forcing the analyst to find a financial surrogate that has the same cash pay-outs as the investment options for a particular asset in every possible future state over the duration of the deferral period. Whereas financial options generally have a short time to expiration (months), investments alternatives and associated options for engineering systems may have last for years even decades. The use of historical data to estimate investment payoffs is only relevant for the near future as on de long-term market conditions can change drastically due to for example an economic crisis. Therefore, estimations on replicating portfolio payoffs for investments on the long term and with long option durations are often not credible (Neufville & Scholtes, 2011).

Furthermore, Geltner and de Neufville (2012a) make a clear distinction in models that can handle endogenous and exogenous uncertainties. Engineering models provide solutions to valuation issues concerning project risks. They are sensitive to important details, which requires in-depth analysis and inclusion of asset specific endogenous uncertainties. Economic models like the risk-neutral probability approach operate on a whole different level and often rely on simplifying assumptions that form the basis for mathematical solutions used in option pricing (Geltner & Neufville, 2012a). The risk-neutral probability approach uses binomial trees to incorporate uncertainty into the analysis. In order to consider multiple uncertainties trees should be constructed for each uncertainty and subsequently combined to a single binomial tree. Formulas to calculate probabilities for up- and downward uncertainty movement in trees assume that uncertainty development follows a random walk, also referred to as Brownian Motion. In other words, the uncertainty follows a series of steps, where each step is a created by a random shock which can take positive and negative values. In particular endogenous uncertainties around infrastructure investment do not always follow BM, causing that formulas associated with the risk-neutral probability approach cannot be applied directly to construct (sub)trees for these uncertainties.

Finally, payoff structures of investment options associated with engineering systems are not clear neither stable. Contractual documentation of a fixed expiration date often doesn’t exist for these options. For example the option to expand a bridge will not have a clearly defined expiration date as the owner of the reserved area around the bridge will not lose the right to expand until he sells the space. Not only clear expiration dates are missing, also well-defined exercise prices and exercise decision rules cannot be determined. An important reason for instability is that the exercise of investment options in engineering systems often changes system characteristics which may affect investment benefits. For example, capacity expansion of a bridge can make a certain route more attractive for traffic and may cause higher user demand (Brealey et al., 2011).

For these reasons standard ROA techniques cannot be blindly used to correct for non-diversifiable risk in infrastructure investments which makes this task difficult and credible results are not guaranteed due to the level of complexity.

3.4 Conclusion

An important objective of this research is to find a method that can be used to determine expected infrastructure investment values taking multiple uncertainties and investment options along. In literature NPV analysis, DTA and MCA are suggested methods to evaluate infrastructure investments. The traditional way to evaluate such projects, the Net Present Value (NPV) approach fails to incorporate flexibility, and hence ignores extra value from expected future information. DTA can actually allow for valuing flexibility in investments, but has the disadvantage that a limited amount of investment options and uncertainties can be incorporated as decision trees tend to get complex and fuzzy easily due to increased strategic pathways. An alternative method to take flexibility into account for investment valuation is MCA, an analytical tool that is often used to imitate real-life situations. With computer programmes that support MCA analyst can generate output for uncertain input variables in a random manner. MCA provides the analyst possibilities to include multiple uncertainties and customize models for each uncertainty development. Therefore MCA is favoured for complex analysis regarding to expected investment valuation taking multiple uncertainties and investment options along.

Depending on uncertainty characteristics MCA can be performed using fixed or time dependent risk adjusted discount rates. In general infrastructure investments are subject to both diversifiable uncertainties (endogenous) as well as non-diversifiable uncertainties (exogenous). In order to compensate investors for risk associated with non-diversifiable uncertainties, one could adjust discount rates to changing risk profiles over time. This principle is based on the financial option pricing theory and often referred to as Real Options Analysis (ROA). A discussion is taking place on difficulties that occur if ROA techniques are used for infrastructure investment valuation. As mentioned these investments are subject to both exogenous as well as endogenous uncertainties, which makes it hard to construct portfolios that perfectly replicate option pay-offs in every state of nature over the time to maturity. For exogenous market uncertainties related to material price levels it is likely that a replicating portfolio can be constructed. Since materials are priced on markets and traded as world commodities it possible to replicate option payoff schemes using commodity share values. Endogenous uncertainties like for example asset user demand are not priced or traded on markets, forcing the analyst to find a financial surrogate that has the same cash pay-outs as the investment options for a particular asset in every possible future state over the duration of the deferral period. If not impossible, this task seems to be highly ambitious.

An alternative to correct for non-diversifiable risk would be the risk-neutral probability approach. The approach uses binomial trees to incorporate uncertainty into the analysis. In order to consider multiple uncertainties trees should be constructed for each uncertainty and subsequently combined to a single binomial tree. Formulas to calculate probabilities for up- and downward uncertainty movement in trees assume that uncertainty development follows a random walk, also referred to as Brownian Motion (BM). This motion follows a series of steps, where each step is a created by a random shock which can take positive and negative values. In particular endogenous uncertainties around infrastructure investment do not always follow BM, causing that formulas associated with the risk-neutral probability approach cannot be applied 1-on-1 to construct (sub)trees for these uncertainties. For these reasons standard ROA techniques cannot be blindly used to correct for non-diversifiable risk in infrastructure investments which makes this task difficult and credible results are not guaranteed due to the level of complexity.

4 AGEING BRIDGE IN THE CITY CENTRE OF AMSTERDAM: A CASE STUDY

In order to demonstrate the valuation process for infrastructure investment alternatives taking multiple uncertainties and flexibility into account, this chapter presents a case study on the replacement of a fixed road bridge in the city centre of Amsterdam. The chapter is introduced by a short case description, where after a base case LCCA will be conducted based on traditional NPV principles. The LCCA functions as a benchmark and starting point for the valuation process that includes uncertainty and flexibility. Since the focus of the research is on calculating expected investment values and not to find optimal investment strategies, MCA will be used to solve the valuation problem in this case study. Analysis results will be used to answer the second part of the main research question, namely "to what extent does flexibility valuation affect investment decisions in bridge life cycle management?".

4.1 Ageing Road Bridge Leading to The City Centre

As presented in figure 2 the first step in the investment valuation process is the selection of a case. The case study presented in this chapter aims to evaluate life cycle investment alternatives for a fixed road bridge that crosses a canal in the city centre of Amsterdam. The bridge is situated in a street that provides an important route to access downtown area. In this street car, taxi and public transport are dominant which means there is little space reserved for pedestrians and cyclists. The municipality of Amsterdam uses the term "plusnetten" to point out which means of transport get high priority at certain routes throughout the city. For the bridge in our case study pedestrian, bicycle and public transport have this status. Vehicles are allowed on this route but don't get the same preferential treatment as provided space, investment budgets and priority at intersections are limited. It is expected that in the near future vehicles will disappear from the street (Gökemeyer, 2016).

The bridge in this case study has a reinforced concrete deck which is supported by two land abutments and two pillars. These bearing elements are constructed with brickwork and founded on wooden piles. The structure is built in 1773, broadened around 1900 and expanded again in 1925. Simultaneously with the second expansion the municipality renewed the deck of the bridge. In 2015 a safety assessment is conducted which concludes that the bridge is in a poor condition. Although damage caused by deterioration is visible, the main supporting structure, bridge deck and brickwork still meet safety standards. Furthermore extra research is conducted on the foundation as normal visual inspections don't show the technical condition of this important element. Both wood samples from piles and geotechnical research showed disappointing results as the quality of these bearing elements is lower than the minimum prescribed safety level. Nevertheless, the structure doesn't show settlement until today and therefore direct major interventions are not considered necessary. On the short-term monitoring measures or bridge replacement should be carried out to lower risk associated with poor bridge conditions. If settlements can be determined in an early stage the municipality will act directly with preparing replacement or reinforcement activities to avoid downtime. Life threatening situations are not expected to occur as bridges don't collapse in an acute manner. Since the city centre of Amsterdam belongs to UNESCO World Heritage the bridge has a monumental status. Therefore the municipality is obliged by law to maintain or recover iconic bridge elements if renovation or replacement takes place (Dirksen & Ha, 2016). In order to check whether flexibility valuation may add significant value to deferred investment alternatives the following questions have to be answered. (Bos & Zwaneveld, 2014; Bräutigam et al., 2003; Tahon et al., 2014):

1. **Is the future surrounding the asset uncertain?** Yes, appendix A shows typical uncertainty sources that may affect the NPV of bridge life cycle cost investment alternatives.
2. **Are there investment options available during deferral periods?** Yes, replacement investments can be deferred, staged or abandoned. Furthermore, in theory the bridge can be expanded or scaled down.
3. **Are there obvious no regret solutions?** No, since uncertainties like for example bridge settlement and associated risk may result in preferred investment alternatives other than maximum deferral.
4. **Are investments irreversible and do they lead to sunk cost?** The replacement of a bridge costs approximately 3-5 million euros, plus bridges have a life span of 100 years.
5. **Are asset payoffs asymmetric under risk?** If asset payoffs are asymmetric under risk uncertainty development will affect the expected investment value. In the past uncertainty development associated with labour cost had great impact on investment cost for bridge replacement and therefore affected investment payoffs.
6. **When do I have to decide?** Form the safety assessment it is concluded that the bridge can be operated safely for the next 15 years if settlements are monitored and normal maintenance is conducted. Therefore it is expected that replacement can be deferred with 15 years.

The answers show that incorporation of uncertainty and flexibility is relevant for the considered case.

4.2 Base Case Life Cycle Cost Analysis

In order to have a clear understanding on investment values if uncertainties and flexibility are not taken into account, LCCA based on traditional NPV techniques should be performed for investment alternatives regarding to bridge replacement. For this base case LCCA two investment alternatives will be evaluated and compared, namely direct bridge replacement in 2018 and postponed replacement in 2033. The maximum deferral period is assumed to be 15 years since safety assessment calculations in 2015 were based on the same time horizon. As described in section 2.2 the main principle of LCCA is to determine all cashflows generated by a certain investment alternative and subsequently discounting these cashflows in order to take the time value of money into account. The following formula will be used to calculate the NPV:

$$NPV = I + \frac{K_1}{(1+r)^1} + \frac{K_2}{(1+r)^2} + \cdots + \frac{K_n}{(1+r)^n}$$

I: *Investments on t = 0*
n: *last year of calculation horizon*
K: *Cash Flow in year n*
r: *discount rate*

NPV results function as a financial parameter to compare the investment alternatives correctly, provided that calculation horizons are equal. Bridges are built with an expected life span of 100 years. Therefore, the life cycle for direct replacement will be 100 years, whereas a deferral period prior to replacement obviously increases the life cycle. These unequal life cycles can be corrected for valuation practices by using infinite calculation horizons. For the investment alternatives considered in this case study infinity is approached by a calculation horizon of 300 years that includes several replacements with successive life cycle costs. Due to the time value of money cashflows generated after this period will barely contribute to expected NPV results.

4.2.1 Input Variables & Underlying Financial Assumptions

During the life cycle of the bridge several cost variables determine yearly cashflows and thereby the expected NPV. As described in section 2.1 there are three maintenance variables for bridge management, namely small maintenance, major maintenance and deferred maintenance. Small maintenance is carried out on a daily base and generates yearly cashflows. Major maintenance can be divided into short term (ST) maintenance every ten years and long-term maintenance with an interval of 30 years. For valuation practices delayed maintenance will not be included in the analysis since it is assumed that the municipality does not deviate from predetermined maintenance programmes. As suggested by the safety assessment report (Dirksen & Ha, 2016) risk lowering measures should be taken when the bridge approaches the end of its life. Therefore, the cost variable "deformation monitoring" is added to the LCCA for the last 15 years of the life cycle. Since the calculation horizon is 300 years and bridges have an expected life span of 100 years, "investment cost" for several bridge replacements are included in the analysis. Table 1 shows the list with all considered cost variables for LCCA.

Table 1 *Input Variables LCCA*

Small Maintenance	€	5,000	/1 Year
Major Maintenance ST	€	43,100	/10 Years
Major Maintenance LT	€	79,500	/30 Years
Deformation Monitoring	€	10,000	/1 Year
Investment Cost	€	4,700,000	/100 years

For the LCCA replacement is defined as rebuilding a bridge with same appearance and equal dimensions. Actual input for the analysis is obtained from the report "LCCA Raadhuisstraat-Rozengracht" (van den Boomen, 2017) and rounded to hundreds. The cashflows that these cost variables generate during one life cycle for the considered investment alternatives are presented in figures 4 and 5.

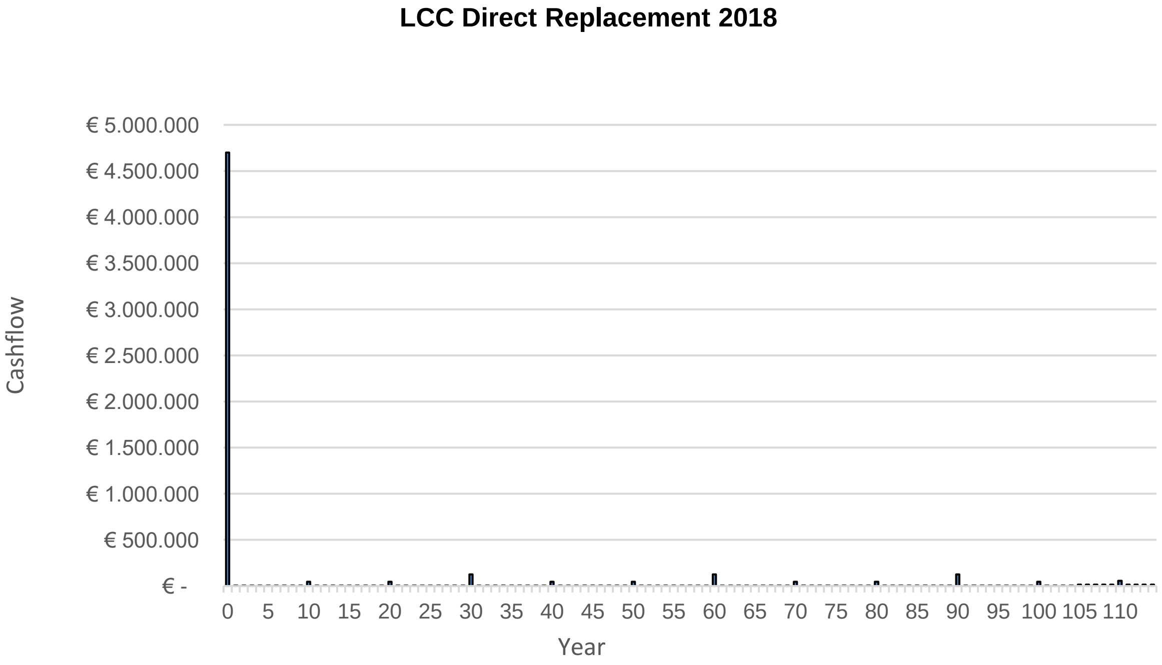


Figure 4, LCC the investment alternative "Direct Bridge Replacement 2018" (own figure, 2018)

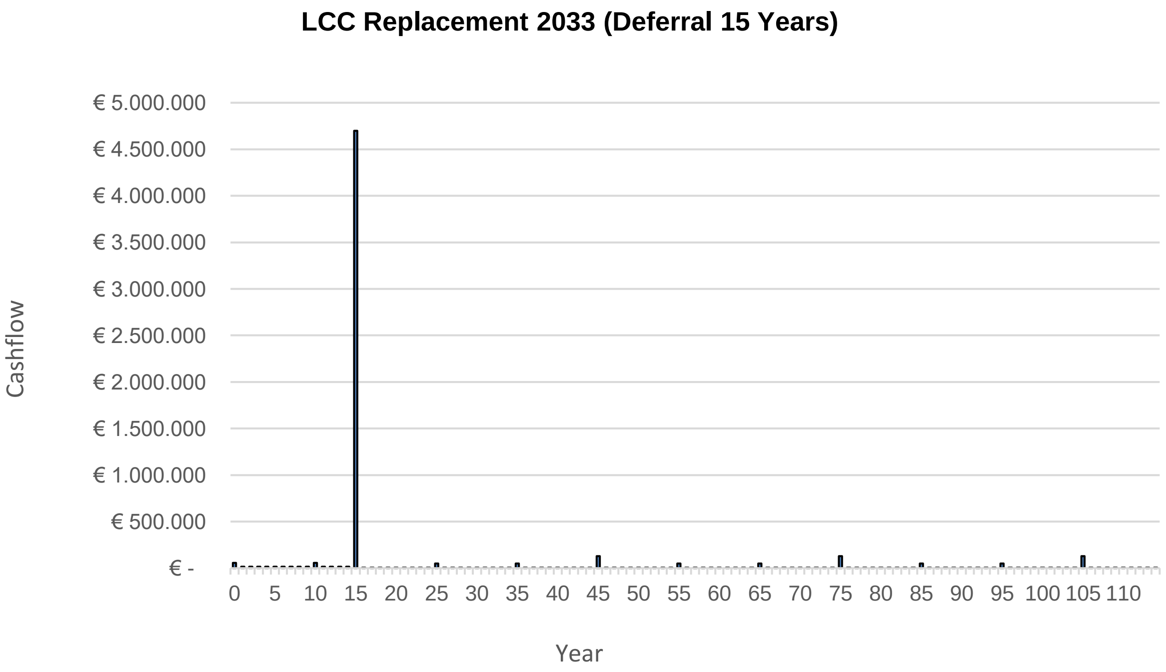


Figure 5, LCC for the investment alternative "Deferred Bridge Replacement 2033" (own figure, 2018)

As mentioned calculations are based on a time horizon of 300. Since input for WACC calculations is difficult to obtain for public organisations like the municipality, the use of a general 4.5% discount rate for infrastructure investments is suggested by Werkgroep Discontovoet 2015 (2015). This rate is inflation-free which means the discount rate is already corrected for price increase due to general inflation. Furthermore, maintenance and operating cost are assumed to be constant as these costs hardly increase over time for bridges. Incorporating a growth factor for this variable increases complexity of the analysis, whereas NPV outcomes will not change significantly. A list of underlying financial assumptions for the base case LCCA can be found in table 2.

Table 2 *Underlying Valuation Assumptions*

Calculation Horizon	300 years (infinity)
Discount Rate	4.5%
Growth Factor Maintenance & Operating Cost	0 (constant)

4.2.2 Life Cycle Cost Analysis Results

In table 3 base case LCCA results for direct and deferred bridge replacement are presented. The NPV of deferred bridge replacement in 2033 is lower compared to direct replacement and therefore deferral will be the preferred investment alternative if valuated with LCCA based on traditional NPV techniques.

Table 3 *Base Case LCCA Results (no uncertainties, no flexibility)*

Investment alternative	NPV
Direct Bridge Replacement 2018	€ 4,948,259
Bridge Replacement 2033	€ 2,795,512

Given the fact that investment cost for replacement are significantly higher than other cost variables and maintenance cost are assumed to be constant over time, this outcome was expected in advance. Due to time value of money postponement of investment will always be favoured, unless increasing cost associated with maintenance or risk compensate this benefit. LCCA results show that the municipality can save approximately 2,152,747 euro if bridge replacement is deferred.

Well known auteurs like Copeland & Antikorov (2001) point out that investments will always be underestimated if valued using traditional NPV because it fails to capture the value of flexibility. This argument is based on the fact that flexibility always has a value equal to or greater than zero. Therefore, including investment options for flexibility will never have a negative effect on the expected NPV of an investment. Although this cannot be denied it is important to keep in mind that optimal expected NPV results will be obtained if future conditions are simulated as realistic as possible. As presented in appendix B current flexibility valuation practices solely focus on including uncertainties on which managers can act by exercising certain options. It is unlikely that including a single dominant uncertainty source will generate credible valuation results as expected NPV for deferred investment alternatives are mostly influenced by multiple uncertainties under real life conditions. In contrast to current valuation practices that include flexibility multiple uncertainty sources will be examined including uncertainties for which relevant investment options cannot be defined.

4.3 Monte Carlo Analysis: Taking Uncertainty & Flexibility Along

The final step is the actual valuation of the deferred investment alternative including uncertainties and investment options. As uncertainty and flexibility comes with deferral, the investment alternative for direct bridge replacement will not be considered in this step. In order to perform the analysis an appropriate method should be selected taking the valuation difficulties as described in chapter 3 into consideration. This section starts with an explanation on the choice of valuation method, namely MCA. The paragraphs that follow elaborate on the identification and incorporation of case-specific uncertainties and investment options. Finally the MCS model will be presented that optimizes for the expected NPV related to the deferred investment alternative taking risk of corrective replacement and opportunities for preventive interventions along. The section ends with a brief description of the obtained valuation results.

4.3.1 The Choice of Valuation Method

Since the focus of this research is on calculating expected investment values and not to find optimal investment strategies, MCA is applied to solve the valuation problem in the case study. Furthermore MCA is favoured as the method can handle complex analysis by means of including multiple investment options and uncertainties that follow different motions. Depending on uncertainty characteristics MCA can be performed using fixed or time dependent risk adjusted discount rates. In this case study investment option payoffs are driven by seven uncertainties presented in table 4. Elaboration on the identification and incorporation of these uncertainties will follow in the next section. A replicating portfolio for option payoffs consist of borrowed money at a risk-free rate and shares in the underlying uncertainties. For endogenous uncertainties like current pile strength and pile strength decrease it is difficult to create replicating portfolios as they are not priced or traded on markets and financial surrogates are hard to find. This also applies to the hybrid user demand uncertainty and exogenous uncertainty around labour cost. For price level uncertainties related to concrete and steel it is more likely that a replicating portfolio can be constructed. These materials are traded and priced on markets which makes it theoretically possible to replicate payoff schemes for investment options.

However, investment cost and therefore option payoffs are driven by multiple uncertainty factors. It is therefore unlikely that buying shares of one underlying uncertainty like steel or concrete with borrowed money at a risk-free rate will replicate the option payoffs perfectly. Furthermore, investment options considered in this case and presented in figure 10 have unclear characteristics and therefore instable payoff schemes. For example, the option to defer doesn't have a fixed "time to maturity" as the maximum deferral period could be shortened due to poor bridge conditions. If early replacement is necessary investment cost will be higher because interventions will be from a corrective instead of preventive nature. 1-on-1 and scaled down replacement option payoffs change, and the initial created replicating portfolio does not match anymore.

Furthermore the formulas associated with the risk-neutral approach and binomial trees cannot be applied 1-on-1 to correct for non-diversifiable uncertainties. In order to perform analysis based on this approach all uncertainties should follow BM. If this assumption holds, risk-neutral probability formulas can be used to construct binomial trees for each uncertainty development. Subsequently the analyst is able to combine these subtrees into a single binomial tree that can be used to determine expected investment and option values. Bridge condition uncertainties cannot be modelled using BM as it is assumed that the condition of a bridge will not improve during the deferral period. Therefore pile strength and deterioration uncertainties follow a series of steps, where each step is a created by a negative shock. It deviates from BM modelling as shocks associated with random walks can take both negative as well as positive values. This also applies to uncertainty around political decisions regarding to a car-free city centre. Since these decisions are assumed to be irreversible during the considered deferral period the principle of a random walk does not hold. Because considered uncertainties form a mix of hybrid, endogenous and exogenous factors and uncertainty development regarding to a car-free city centre and bridge settlement deviate from BM, standard ROA valuation techniques cannot be applied directly or easily. As literature does not provide a suitable solution to correct for non-diversifiable related to infrastructure investments the model in the case study works with a fixed discount rate.

4.3.2 Bridge Integrity, Traffic flow and Price Level Uncertainties

As shown in appendix A there are multiple uncertainty sources that may affect the NPV of investment alternatives regarding to bridge replacement. Incorporating all uncertainties into the analysis would be both very time consuming as well as ineffective since investment payoffs are affected by only a few uncertainties for case specific conditions. Therefore Mun (2002) suggests to determine so called success drivers by conducting a sensitivity analysis on the base case LCCA variables. Sensitivity of LCCA outcome to variables can be determined by adjusting input one by one, provided that the input for other variables remain unchanged. For the sensitivity analysis a typical +/- 10% adjustment is used. Results are presented in figure 6.

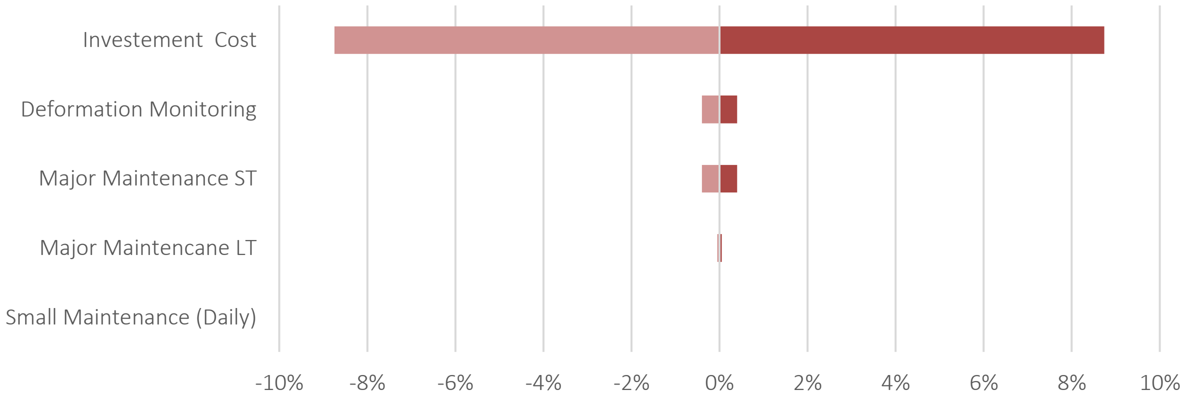


Figure 6, Sensitivity Analysis LCCA Input Variables (own figure, 2018)

The tornado diagram in figure 6 shows that expected NPV results obtained with LCCA are highly sensitive to investment cost levels, since a +/- 10% input adjustment for this variable results in approximately 9% increase/decrease of the expected NPV. Managers will mainly be interested in optimizing investment cost by controlling uncertainties that influence the input for this variable. Figure 7 is subtracted from appendix A and presents important uncertainties that may affect investment cost for bridge replacement and therefore the expected NPV.

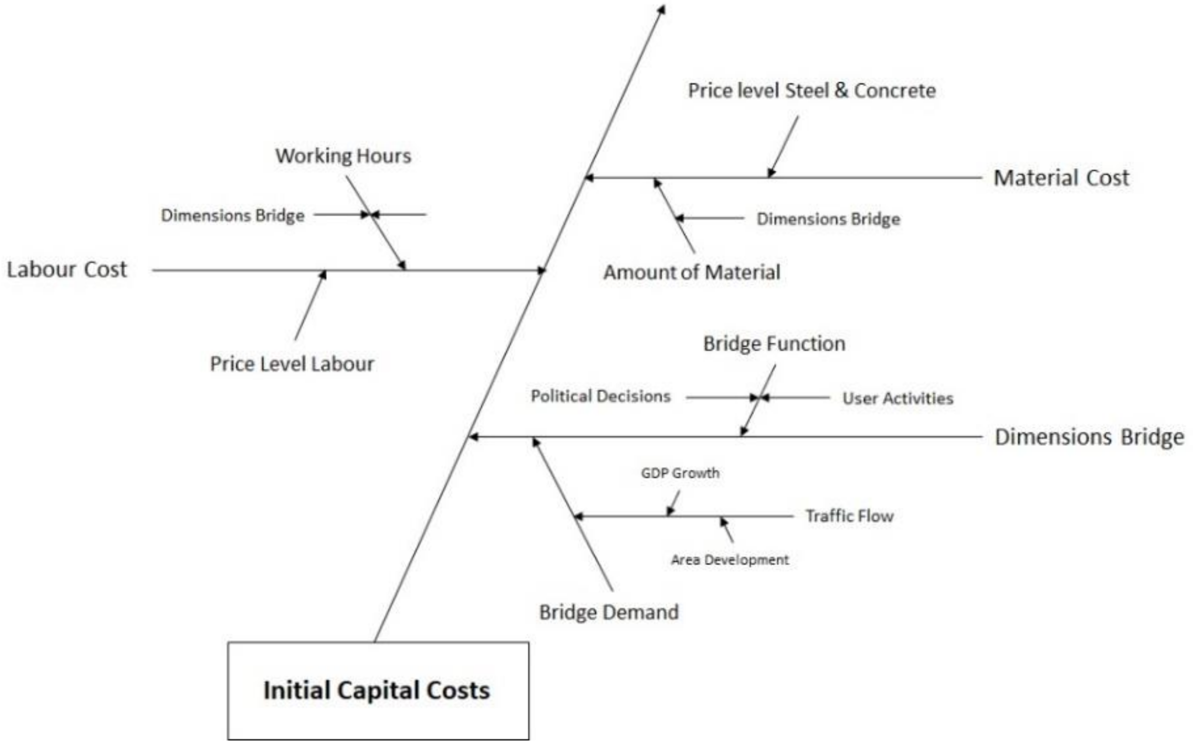


Figure 7, Investment Cost Uncertainties (own figure, 2018)

The figure shows that bridge dimensions, cost for material and cost for labour are main uncertainty sources. Dimensions of the new build bridge will be determined by future traffic flow and asset function. Whether the bridge retains its current function as a point for vehicles, public transport, bikes and pedestrians to access downtown area depends on political decisions. Newspaper articles and policy documents reveal that policy makers are willing to ban vehicles from the city centre in near the future. This is an important uncertainty as cars use considerable space on the bridge and abandonment will make it possible to scale down bridge dimensions. Furthermore, uncertainty development regarding to user demand for the bridge will determine the total traffic flow and therefore preferred bridge dimensions.

From discussions with experts from the municipality it can be concluded that nowadays fixed road bridges with short spans are constructed with reinforced concrete elements. Therefore, material costs are assumed to consist of expenses made for (reinforcement) steel and concrete. Fluctuations in these expenses will be originated by price level uncertainties for steel and concrete. Moreover, the amount of material needed for replacement depends on preferred bridge dimensions which will as explained earlier be determined by uncertainty around political decisions for a car-free city centre and user demand. Working hours needed for replacement and wages paid in the construction industry determine the total labour cost. Input for this variable will mainly be influenced by price level uncertainty for labour and uncertainty around preferred dimensions which is the main uncertainty source that drives the number of working hours needed to replace a bridge.

Finally, it should be mentioned that the expected NPV is not only sensitive to the investment cost itself but also to investment timing as time value of money exist. Future bridge condition states determine the maximum deferral period for replacement and therefore the boundaries for investment timing. Unavailability of the bridge and early corrective replacement are mainly caused by unexpected bridge settlements. Based on expert judgement it is assumed that these settlements only occur if load exceeds pile strengths which subsequently results in pile failure. Pile load is assumed to be deterministic and constant over time as this value is prescribed by safety standards for bridges in the Netherlands. Pile strength on the other hand is uncertain in two different ways, namely its current condition and degradation in the future. Although a safety assessment has been conducted, there is still significant uncertainty around current pile conditions. In order to determine the condition of the piles wood samples were taken from 24 piles and subsequently examined. As the bridge is supported by +/- 500 piles it is highly uncertain whether results obtained with this sample size represent the condition of the total pile population. Geotechnical bearing capacity of the piles is assumed to be constant over time as experts do not expect that degradation will affect this characteristic. In table 4 summarizes all uncertainty sources that are considered in the actual analysis (Dirksen & Ha, 2016).

Table 4 *Case Specific Uncertainty Sources*

NPV Determinants	Main Uncertainties	Detailed Uncertainties	Uncertainty Type
Investment Cost	Traffic Flow (Bridge Dimension)	User demand	Hybrid
		Car-free City Centre Decision	Exogenous
	Material Cost	Price Level Concrete	Exogenous
		Price Level Steel	Exogenous
	Labour Cost	Price Level Labour	Exogenous
Investment Timing	Bridge Settlement	Current Pile Strength	Endogenous
		Pile Strength Decrease	Endogenous

The table also distinguishes for exogenous and endogenous uncertainty types. Current pile strength and pile strength decrease are typical endogenous uncertainties since they are embedded in the technical system itself. With engineering knowledge risk associated with these uncertainties can be identified, actively managed and reduced. For example uncertainty around bridge settlement that may cause downtime can be diversified by replacing a certain number of foundation piles, installing reinforcement elements or building a second bridge nearby.

Price levels for concrete and steel are non-diversifiable market uncertainties. Although impact of these exogenous uncertainties can be managed by reactive response, it is impossible to reduce the risk at the source. Managers can only react to increased price levels for steel and concrete by using other materials for bridge replacement. For the bridge in this case study the option to build with materials other than concrete or steel does not apply because of the monumental status. Labour cost and political decision uncertainties are also exogenous as they cannot be actively controlled by managers. Diversification is not possible since every investment alternative related to bridge replacement nearby the city centre of Amsterdam is exposed to risk associated with labour cost and political decision uncertainties.

Finally, user demand can be classified as a hybrid uncertainty since managers can partly reduce risk associated with this uncertainty. User demand is both determined by exogenous factors like Gross Domestic Product GDP growth as well as endogenous uncertainty sources like area development. Although exogenous factors cannot be controlled actively, managers are able to guide user demand development by increasing asset attractiveness. The next sections will elaborate on the incorporation of defined uncertainties into the MCA.

Uncertainty Modelling for Integrity

In the MCA bridge settlement is modelled using the limit state function Z=R-S. In this formula Z is the limit state, R the pile strength and S the pile load. If Z is negative this means that the load exceeds pile strengths which results in pile failure. The pile load is assumed to be deterministic and constant over time as this value is prescribed by safety standards for bridges in the Netherlands. As calculated in the assessment safety report the loads for this bridge are 113kN for piles under the abutments and 176kN for piles that support the two pillars. Pile strength is determined by random sampling from a dataset that consists of current strength values for 115 wooden piles. The current strength values are normally distributed and obtained from pile research reports for six bridges located nearby the bridge considered in this case study. Yearly pile strength decrease is determined by random sampling from a dataset that consist of expected 30 year pile strength decrease values from the same 115 wooden piles (Dirksen & Ha, 2016). These values are also obtained from the pile research reports and follow a triangular distribution. The datasets and associated distributions are presented in Appendix C. It is assumed that settlement will occur if at least 33% of the piles under a supporting element (abutment or pillar) fails the limit state check or if the sum or pile loads exceeds sum of pile strengths. If this situation occurs the MCS model will return "FAILURE" for the uncertainty bridge condition. The described settlement mechanism is shown in figure 8.

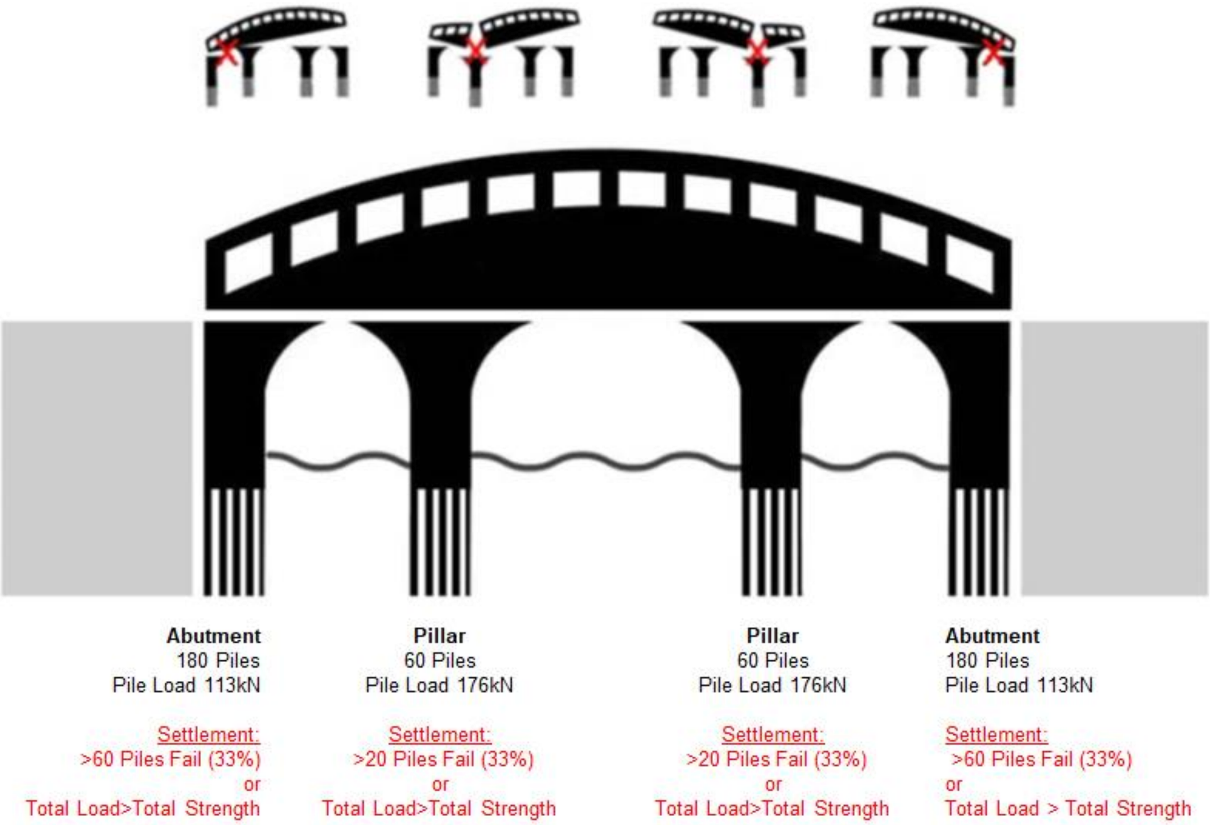


Figure 8, Bridge Settlement Mechanism (own figure, 2018)

Uncertainty Modelling for Traffic flow

Future traffic flow modelled by two detailed uncertainty factors, namely user demand and political decisions regarding to a car free city centre. As presented in appendix D it is assumed that user demand follows a normal distribution with mean values and standard deviations obtained from a traffic prognoses tool (2015) for the city of Amsterdam. Random sampling from these distributions generates input values at decision moments for possible future traffic flow conditions. Furthermore, it is assumed that once in five years policy makers may decide to ban vehicles from the city centre. Estimates for this event to occur are based on newspaper articles and can be found in table 5. Based on these discrete probabilities, the model will select "Vehicles" or "No Vehicles" as at each decision moment. If the model simulates a "No Vehicle" state during the deferral period, user demand values will be overruled, and traffic flow set to zero from that moment.

Table 5 *Probability Distribution "Car-free City Centre Decision"*

	2018	2023	2028	2033
No Vehicles (NV)	0%	20%	40%	60%
Vehicles (V)	100%	80%	60%	40%

Uncertainty Modelling for Price Levels

Uncertainty developments regarding to price levels for steel, concrete and labour are modelled using a Geometric Brownian Motion. This motion adds a certain drift to the standard BM. Therefore GBM can be modelled as a series of steps, where each step is a created by a drift plus a random shock which can take positive and negative values. A small selection of GBM simulation runs for the steel price is presented in appendix E. The annualized drift and volatility that determine price level developments and therefore GBM are obtained from historical index values described in "CROW Indexen Risicoregelingen GWW". In order to determine the drift and the volatility first historical data is converted into relative price levels, where after the natural logarithms of these relative values are calculated. Taking the standard deviation of these natural logarithms will give the price level volatility (σ), whereas the drift (μ) can be found by calculating the average value. Finally, yearly price levels (S_t) can be modelled in excel with the following GBM formula:

$$S_t = S_0 * EXP(\mu + \sigma * NORM.S.INV((ASELECT())$$

In this formula S_0 is the initial price level value for steel, concrete or labour in 2018. Price level developments are linked to investment cost for scaled down and 1-on-1 bridge replacement. These replacement options will be discussed more in depth in the next paragraph. In table 6 the initial investment cost regarding to steel, concrete and labour for both replacement options are presented. It is assumed that 1/3 of the total investment for replacement is determined by labour cost and 2/3 by expenses for material. These material expenses are equally distributed over cost for steel and cost for concrete.

Table 6 *Steel, Concrete and Labour Cost for Bridge Replacement in 2018*

Replacement Option	Labour Cost	Steel Cost	Concrete Cost	Total Investment Cost
1-on-1	€ 1,566,667	€ 1,566,667	€ 1,566,667	€ 4,700,000
Scaled Down	€ 783,333	€ 783,333	€ 783,333	€ 2,350,000

4.3.3 Investment Options for 1-on-1 and Scale Down Replacement

The next step is to determine and incorporate investment options that can be exercised by the MCS model to optimize for expected NPV. Traditional LCCA neglects flexibility since it excludes investment options that become available due to deferred investment for bridge replacement. As described in section 4.2. and presented in figure 9 this results in two replacement scenarios, namely direct bridge replacement in 2018 or postponed replacement in 2033.

Bridge Replacement Scenario		
Preventive	1-on-1	2018
Preventive	1-on-1	2033

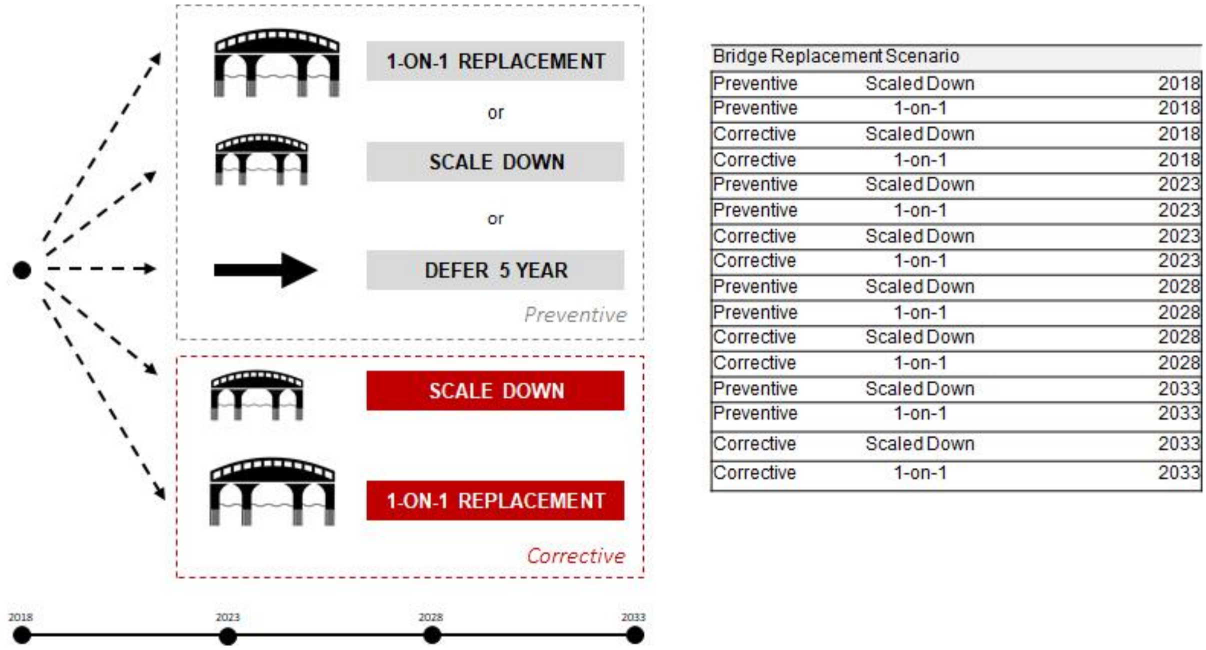
Figure 9, Traditional LCCA: Investment Options and Associated Replacement Scenarios (own figure, 2018)

The traditional approach shown in figure 9 does not represent real-life conditions and therefore it is suggested to add decision moments and associated investment options in the analysis. Relevant options for the case are identified using general investment options presented in section 2.3.2. Although including the option to defer investment seems obvious, the right to exercise this option expires if settlements occur due to pile strength decrease and subsequently pile failures. In case of bridge settlement managers are obliged to perform a corrective bridge replacement directly.

The option to stage investment would mean that bridge elements like the deck, pillars and abutments are replaced one after another. If a certain element does not satisfy minimum safety standards it can be replaced earlier separate from the rest. Replacement of other elements can be deferred as long as possible in order to follow uncertainty development regarding to the degradation of the elements. Because in this case study the foundation is assumed to be dominant for the failure mechanism bridge downtime will only occur if this element fails. This means that staged investment will always start with replacement of foundation piles which is considered as a costly and therefore costly situation. Therefore the option to stage investment is not taken into account in the analysis.

The option to growth provides opportunities to analyse traffic flow development and to expand bridge capacity if user demand increases. Growth options can be created by conducting pre-investments like the reservation of extra space alongside the bridge. Unfortunately, roads connected to the bridge cannot be expanded as the bridge in this case study is situated in a dense area and a fixed city grid. Therefore, bridge expansion will not create the expected benefits and can be considered worthless in this case. On the other hand, the option to scale down can add significant value if user demand decreases and/or vehicles are banned from the city centre.

Furthermore, managers could have the possibility to abandon investment. However, in practice this is not an option as the bridge belongs to UNESCO World Heritage and the municipality is obliged by law to replace the bridge if the current object is removed. For the same reason switching options are not applicable for this case study as they assume temporary investment abandonment. Figure 10 shows investment options that can be exercised by the MCS model at decision moments in 2018, 2023, 2028 and 2033. Based on the exercised investment option the MCS model will return a bridge replacement scenario presented in figure 10. In order to reduce model complexity decision moments are not on a yearly basis, but assumed to occur once in 5 years when political decisions are made on a car-free city centre.



Bridge Replacement Scenario		
Preventive	Scaled Down	2018
Preventive	1-on-1	2018
Corrective	Scaled Down	2018
Corrective	1-on-1	2018
Preventive	Scaled Down	2023
Preventive	1-on-1	2023
Corrective	Scaled Down	2023
Corrective	1-on-1	2023
Preventive	Scaled Down	2028
Preventive	1-on-1	2028
Corrective	Scaled Down	2028
Corrective	1-on-1	2028
Preventive	Scaled Down	2033
Preventive	1-on-1	2033
Corrective	Scaled Down	2033
Corrective	1-on-1	2033

Figure 10, Flexibility Valuation: Investment Options and Associated Replacement Scenarios (own figure, 2018)

Note that replacement is assumed to take place once during the deferral period, which means that 1-on-1 and scale down replacement options will expire after bridge replacement. For the scale down option it is assumed that car tracks will be excluded from the new bridge design which means that bridge dimensions and therefore investment cost can be cut by half. Therefore, this option can only be exercised if the model simulates to ban vehicles from the city centre of Amsterdam. Furthermore the model can return corrective replacement scenarios. Since options are defined as the right but not the obligation to invest, forced corrective replacements fall outside the scope of flexibility. Therefore the model can sample corrective replacement scenarios if flexibility is not taken along in the analysis. Because bridge downtime is longer for corrective replacement the investment cost will increase. In consultation with experts extra cost are estimated to be 2,000,000 euro.

In this case study Microsoft Excel software is used to run the MCA. The designed MCS model simulates developments for each uncertainty and returns bridge settlement, traffic flow, material cost and labour cost uncertainty values at the decision moments in 2018, 2023, 2028 and 2033. Based on these uncertainty conditions 1-on-1, scale down and defer investment options will be valued and compared. Subsequently the model will exercise optimal investment options at each decision moment and finally return a bridge replacement scenario. For the example in figure 11 this is a preventive small bridge replacement in 2033 as the bridge did not fail during the deferral period and cars are banned from the city centre in 2028. The expected NPV for this replacement scenario under simulated price levels for material and labour is determined to be € 1,527,438.

2018		2023		2028		2033	
NO FAILURE	4293057	NO FAILURE	3208587	NO FAILURE	0	NO FAILURE	0

Replacement Scenario	NPV
Preventive Scaled Down 2033	€ 1.527.438

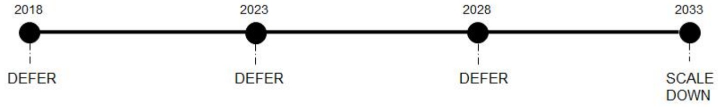


Figure 11, MCS output line (own figure, 2018)

4.3.4 Monte Carlo Analysis Results

The probabilistic model optimizes for the expected NPV related to the deferred investment taking risk of corrective replacement and opportunities for preventive interventions along. For this case study the model sampled ten thousand bridge replacement scenarios and calculated associated present investment values. Table 7 and figure 12 show the MCA sampling distribution of bridge replacement scenarios.

Table 7 *MCA Sampling Distribution of Bridge Replacement Scenarios*

Replacement Scenario			(#) Samples
Preventive	Scaled Down	2018	0
Preventive	1-on-1	2018	629
Corrective	Scaled Down	2018	0
Corrective	1-on-1	2018	1003
Preventive	Scaled Down	2023	440
Preventive	1-on-1	2023	446
Corrective	Scaled Down	2023	92
Corrective	1-on-1	2023	1
Preventive	Scaled Down	2028	1322
Preventive	1-on-1	2028	321
Corrective	Scaled Down	2028	167
Corrective	1-on-1	2028	0
Preventive	Scaled Down	2033	4469
Preventive	1-on-1	2033	895
Corrective	Scaled Down	2033	202
Corrective	1-on-1	2033	13

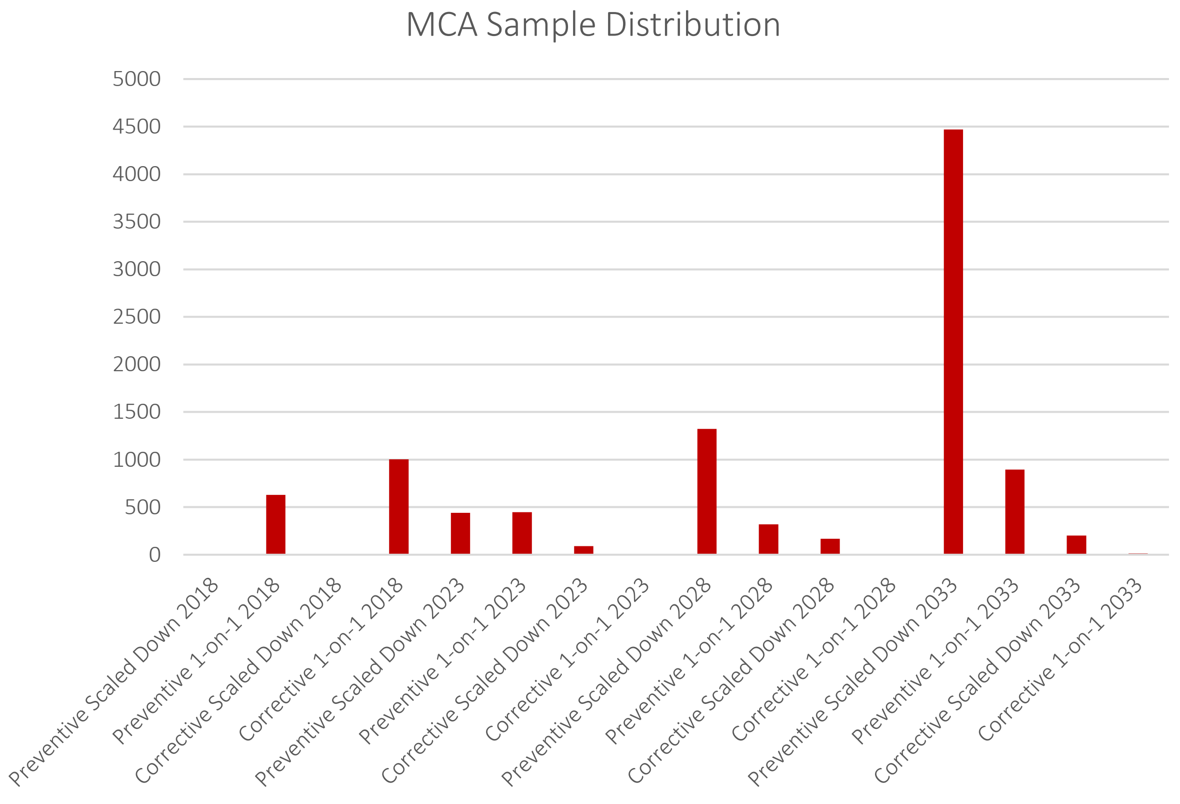


Figure 12, MCA Sampling Distribution of Bridge Replacement Scenarios (own figure, 2018)

The expected NPV for the deferred investment alternative "Bridge Replacement 2033" is determined by taking the average of present investment values associated with the sampled replacement scenarios. This results in a NPV of 3,131,986 euro. Because the NPV for direct bridge replacement in 2018 is 4,948,259 euro (4.2.2, table 2), the alternative to defer investment until 2033 is preferred. It should be mentioned that deferred bridge replacement comes with risk mainly related to early corrective interventions. The model sampled 1,478 corrective replacement scenarios with an average NPV of 5,871,957 euro.

Table 7 and figure 12 show that the scenario "preventive scaled down bridge replacement in 2033" is most likely to occur. Therefore a strategic choice could be to defer bridge replacement with 5 years until the next decision moment. In 2023 uncertainty states should be determined and the analysis repeated using the information that became available during the deferral period. Based on obtained results the analyst can choose to replace the bridge or extend the deferral period. Table 8 compares expected NPV results for the base case LCCA, analysis that includes uncertainty and valuation taking both uncertainty as well as flexibility along.

Table 8 *Comparison of Analysis Results*

Valuation Conditions	NPV Replacement 2018	NPV Replacement 2033	Preferred Alternative
Base Case LCCA	€ 4,948,259	€ 2,795,512	Replacement 2033
+ Uncertainty	€ 4,948,259	€ 4,803,948	Replacement 2033
+ Uncertainty & Flexibility	€ 4,948,259	€ 3,131,986	Replacement 2033

First, it can be concluded that the preferred investment alternative is the same under all valuation conditions, namely deferred replacement in 2033 (< 4,948,259 euro). Furthermore, the results show that taking along uncertainty has a negative effect on the expected NPV for the deferred investment alternative as the expected investment cost increase from 2,795,512 to 4,803,948 euro. If investment options are added to the valuation process the model can optimize for expected investment value by exercising optimal investment options for simulated uncertainty conditions. In this case study flexibility creates a value of 1,671,962 euro as expected investment cost decrease from 4,803,948 to 3,131,986 euro. Therefore it can be concluded that flexibility valuation has a positive effect on expected NPV results for the deferred investment alternative. Although it is demonstrated that flexibility creates value in this case study, the NPV outcome for the deferred investment alternative determined with MCA is slightly negative relative to base case LCCA results that neglect uncertainty and flexibility (3,131,986 > 2,795,512 euro). This can be explained in terms of the negative impact that comes with uncertainty overruled the positive effect of including multiple investment options in the MCA. As in this case traditional LCCA overestimates the deferred investment alternative, comments about the underestimation of investments if valued using traditional NPV because it fails to capture the value of flexibility (Copeland & Antikarov, 2001) should be treated carefully.

The valuation process in this case study focused on including multiple uncertainties, whereas current flexibility valuation practices generally include one uncertainty. As investment options considered in this study mainly react to uncertainty development around a car-free city centre, current flexibility valuation practices would only include this uncertainty type. It is unlikely that including a single uncertainty source will generate credible valuation results as investment option values and therefore the expected NPV for deferred investment alternatives are mostly influenced by multiple uncertainties under real life conditions. Table 9 presents the distribution of sampled replacement scenarios if a single uncertainty is taken into account, namely the uncertainty regarding to a car-free city centre.

Table 9 *MCA Sampling Distribution of Replacement under Single Uncertainty Conditions (Car-free City Centre)*

Replacement Scenario			(#) Samples
Preventive	Scaled Down	2033	8094
Preventive	1-on-1	2033	1906

The table shows significant differences compared to table 7, which presents sampled replacement scenarios if all relevant uncertainties are taken along. Since the model exercises optimal replacement options with the lowest investment cost, differences in sampling distributions are caused by deviations in option payoffs. As sampling distributions for single and multiple uncertainty analysis differ this will also affect expected NPV outcomes. Table 10 shows NPV results for the deferred investment alternative "Bridge Replacement 2033" if valuated under both uncertainty conditions.

Table 10 *NPV for Single & Multiple Uncertainty Analysis*

Uncertainty Condition	NPV Replacement 2033
Multiple Uncertainties	€ 3,131,986
Single Uncertainty (Political Decisions)	€ 1,610,659

Significant deviations in outcomes show the importance of including all relevant uncertainties if the research objective is to determine expected NPV for deferred investment alternatives.

4.4 Conclusion

In order to demonstrate the valuation process for infrastructure investment alternatives taking multiple uncertainties and flexibility into account, this chapter presented a case study on the replacement of a fixed road bridge in the city centre of Amsterdam. Since the focus of this study is on calculating expected investment values and not to find optimal investment strategies, MCA is applied to solve the valuation problem. Furthermore MCA is favoured since the method can handle complex analysis by means of including multiple investment options and uncertainties that follow different motions. The probabilistic model optimizes for the expected NPV related to deferred investments taking risk of corrective replacement and opportunities for preventive interventions along. Expected NPV is defined as the average of investment values associated with simulated optimal investment options under possible uncertainty developments. Because considered uncertainties form a mix of hybrid, endogenous and exogenous factors and uncertainty development regarding to a car-free city centre and bridge settlement deviate from BM, standard ROA valuation techniques cannot be applied directly or easily. As literature does not provide a suitable solution to correct for non-diversifiable related to infrastructure investments the designed MCS model in the case study works with a fixed discount rate.

MCA for the considered investment alternatives, namely “direct bridge replacement in 2018” and “deferred bridge replacement in 2033”, resulted respectively in expected NPVs of 4,803,948 and 3,131,986 euro. Therefore the deferral alternative is favoured above direct replacement based on expected NPV results. It should be mentioned that deferred bridge replacement comes with risk mainly related to early corrective interventions. From ten thousand iterations the model sampled 1,478 corrective replacement scenarios with an average NPV of 5,871,957 euro. Although the case study demonstrates that flexibility creates value, the NPV outcome for the deferred investment alternative determined with MCA is slightly negative relative to base case LCCA results that neglect uncertainty and flexibility. This can be explained in terms of the negative impact that comes with uncertainty overruled the positive effect of including multiple investment options in the MCA.

Furthermore valuation process in this case study focused on including multiple uncertainties, whereas current flexibility valuation practices generally include one dominant uncertainty. As investment options considered in this study mainly react to uncertainty development around a car-free city centre, current flexibility valuation practices would only include this uncertainty source. NPV results for analysis that include the uncertainty around a car-free city centre and valuation taking along all uncertainties considered to be relevant show significant deviations. This shows the importance of including all relevant uncertainties if the research objective is to determine expected NPV for deferred investment alternatives.

5 CONCLUSION & DISCUSSION

In this chapter reflection on the conducted research takes place. The proposed research question will be answered, followed by a discussion on main research limitations and recommendations. As described in the introduction the main question to be answered is:

How can infrastructure investments be evaluated taking multiple uncertainties and flexibility along and to what extent does flexibility valuation affect investment decisions in bridge life cycle management?

In order to provide a structured answer, the research question is subdivided and discussed in two separate sections.

1. *How can infrastructure investments be evaluated taking multiple uncertainties and flexibility along?*

Thorough qualitative research resulted in remarkable insights regarding to this sub question. In literature NPV analysis, DTA and MCA are suggested methods to evaluate infrastructure investments. The traditional way to evaluate such projects, the NPV approach fails to incorporate flexibility, and hence ignores extra value from expected future information. DTA can actually allow for valuing flexibility in investments but has the disadvantage that a limited amount of investment options and uncertainties can be incorporated as decision trees tend to get complex and fuzzy easily due to increased strategic pathways. An alternative method that can be used to take flexibility into account for investment valuations is MCA. MCA is an analytical tool that can be used to imitate real-life situations. With computer programmes that support MCA analyst can generate output for uncertain input variables in a random manner. MCA provides the analyst possibilities to include multiple uncertainties and customize models for each uncertainty development. Therefore MCA is favoured for complex analysis regarding to expected investment valuation taking multiple uncertainties and investment options along.

Depending on uncertainty characteristics MCA can be performed using fixed or time dependent risk adjusted discount rates. In general infrastructure investments are subject to both diversifiable uncertainties (endogenous) as well as non-diversifiable uncertainties (exogenous). In order to compensate investors for risk associated with non-diversifiable uncertainties, one could adjust discount rates to changing risk profiles over time. This principle is based on the financial option pricing theory and often referred to as ROA. A discussion is taking place on difficulties that occur if ROA techniques are used for infrastructure investment valuation. As mentioned these investments are subject to both exogenous as well as endogenous uncertainties, which makes it hard to construct portfolios that perfectly replicate option pay-offs in every state of nature over the time to maturity. For exogenous market uncertainties related to material price levels it is likely that a replicating portfolio can be constructed. Since materials are priced on markets and traded as world commodities it possible to replicate option payoff schemes using commodity share values. Endogenous uncertainties like for example asset user demand are not priced or traded on markets, forcing the analyst to find a financial surrogate that has the same cash pay-outs as the investment options for a particular asset in every possible future state over the duration of the deferral period. If not impossible, this task seems to be highly ambitious.

An alternative to correct for non-diversifiable risk would be the risk-neutral probability approach. The approach uses binomial trees to incorporate uncertainty into the analysis. In order to consider multiple uncertainties trees should be constructed for each uncertainty and subsequently combined to a single binomial tree. Formulas to calculate probabilities for up- and downward uncertainty movement in trees assume that uncertainty development follows a random walk, also referred to as Brownian Motion (BM). This motion follows a series of steps, where each step is a created by a random shock which can take positive and negative values. In particular endogenous uncertainties around infrastructure investment do not always follow BM, causing that formulas associated with the risk-neutral probability approach cannot be applied 1-on-1 to construct (sub)trees for these uncertainties. For these reasons standard ROA techniques cannot be blindly used to correct for non-diversifiable risk in infrastructure investments which makes this task difficult and credible results are not guaranteed due to the level of complexity. As literature does not provide a suitable solution to correct for non-diversifiable related to infrastructure investments this research suggests to discount cash flows with a fixed rate.

2. *To what extent does flexibility valuation affect investment decisions in bridge life cycle management?*

The answer to this sub question is provided using a case study on the replacement of a fixed road bridge that crosses a canal in the city centre of Amsterdam. The study aimed to value life cycle investment alternatives taking along multiple uncertainties and investment options. Whereas the traditional LCCA method generated credible results for the considered investment alternative “direct bridge replacement in 2018”, correct valuation of “deferred bridge replacement in 2033” is performed using MCA since this alternative is subject to uncertainty and includes multiple investment options. Although the case study demonstrates that flexibility creates value, the NPV outcome for the deferred investment alternative determined with MCA is slightly negative relative to base case LCCA results that neglect uncertainty and flexibility. This can be explained in terms of the negative impact that comes with uncertainty overrules the positive effect of including multiple investment options in the MCA. Therefore, comments in literature about the underestimation of investment alternatives if valued using traditional NPV because it fails to capture the value of flexibility should be treated carefully. Furthermore valuation process in this study focused on including multiple uncertainties, whereas current flexibility valuation practices generally include one uncertainty on which managers can act by exercising investment options. Expected NPV results for analysis that include a single dominant uncertainty and valuation taking along all uncertainties considered to be relevant show significant deviations.

It can be concluded that flexibility valuation may affect decisions about infrastructure investments in different ways. Although the value of flexibility is always equal or greater than zero, research presented in this report showed that flexibility valuation taking along all relevant uncertainties can have a negative effect on expected NPV. Whereas well known auteurs claim that investment alternatives with possibilities to adapt strategies will profit from flexibility valuation and may become preferred alternatives, it is also possible that initially preferred alternatives are downgraded due to negative impact of uncertainty development. Furthermore for valuation practices with the objective to determine expected NPV, it is important to keep in mind that the analyst will obtain best results if future conditions are simulated as realistic as possible. In case future scenarios are based on a single uncertainty it is likely that analysis will provide misleading NPV outcomes which counteracts better decision making in bridge life cycle management. In general flexibility valuation is considered to be very useful as it forces the analyst to determine risks sources and define investment options that can be used to control uncertainty impact.

Limitations & Recommendations

Credibility of case study results is limited due to simplifications in the model. For example, including decision moments once in 5 years seems to be unrealistic as bridge settlement can occur any moment and will be detected during yearly deformation measurements. Furthermore the assumed settlement mechanism for simulating bridge condition is a simplified representation of reality. Besides the fact that bridge downtime can be caused by failures of elements other than the foundation, the occurrence of settlement itself can have multiple reasons. In the model settlement due to insufficient geotechnical bearing capacity of the piles is not included as it is assumed that degradation of wood will not affect this pile characteristic. Unfortunately the assumption cannot be verified as little research has been conducted on this topic. Moreover, underlying assumptions for the model are partly based on newspaper articles and expert judgement. Therefore subjectivity plays a role and may affect analysis results. Finally the model works with a fixed discount rate which means investment cashflows are not corrected for non-diversifiable risk. Although this could affect the expected NPV results generated by the model, the relevance of compensating investors for risk related to investments in public infrastructure seems to be questionable.

Based on these limitations further research is recommended on hybrid valuation methods that can be used to value investments subject to both exogenous as well as endogenous uncertainties. Furthermore, the proposed model and underlying assumptions should be specified and updated from time to time as uncertainties develop and more information becomes available. Research can be expanded by broadening the scope to network level instead of analysis for a single object. Replacement decisions on bridges in the infrastructure network of Amsterdam are likely to affect the investment option values and therefore expected NPV of the considered bridge in the case study. Research on bridge replacement decisions at network level would be a logical next step to improve expected NPV results for infrastructure investment valuation practices. Finally, inter-dependencies between different uncertainties and incorporation of non-quantifiable costs/benefits could be interesting research topics.

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APPENDIX A: BRIDGE LIFE CYCLE UNCERTAINTIES

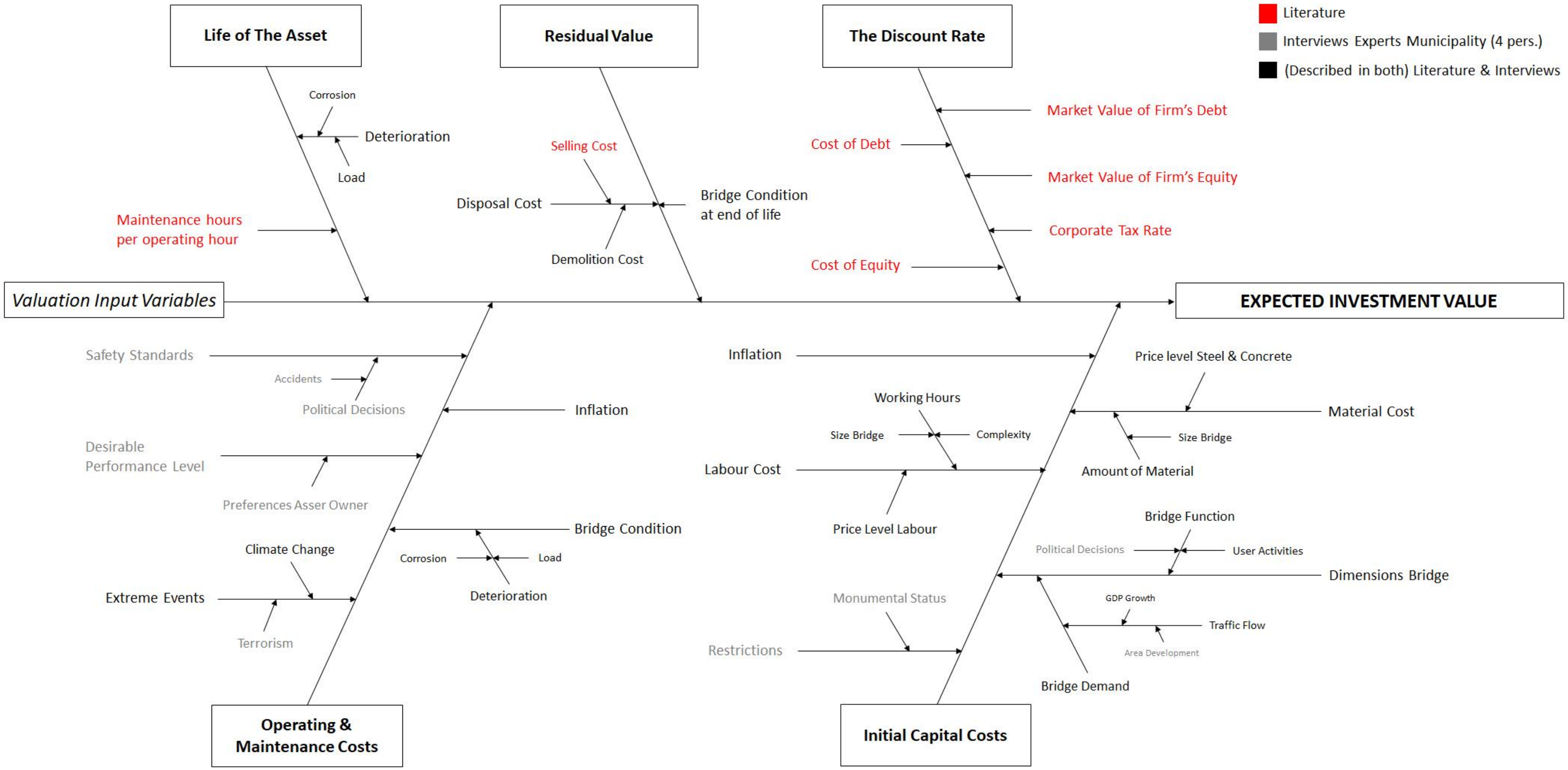


Figure 13, Overview bridge life cycle uncertainties (own figure, 2018)

Obtained from interviews and: (Power, Tandja M, Bastien, & Grégoire, 2015) (Fawcett et al., 2015) (Frangopol, Dong, & Sabatino, 2016) (Gervásio & Simões da Silva, 2012) (Centraal-Planbureau, 2013) (Dirksen & Ha, 2016) (van den Boomen, 2017) (Gökemeyer, 2016) (Bos & Zwaneveld, 2014) (Bos, Zwaneveld, & Van der Pol, 2016) (Kim, Ha, & Kim, 2017) (Ministerie-van-Infrastructuur-en-Milieu, 2015)

APPENDIX B: LITERATURE REVIEW

RO is een snelgroeiende valuatietheorie voor infrastructuurinvesteringen. De theorie werd voor het eerst toegepast in 1991 op een theoretische case voor Sydney airport. Sindsdien is de interesse in deze dynamische benadering sterk toegenomen en dat is terug te zien het aantal wetenschappelijke publicaties. De groei in de afgelopen eeuw komt de behoefte naar een nieuwe valuatiemethode tegemoet, aangezien met de traditionele MKBA-flexibiliteit in een project niet kan worden gewaardeerd (Martins, Marques, & Cruz, 2015). Voor deze literatuur review is met behulp van een opgesteld zoekplan een selectie gemaakt van relevante en recente wetenschappelijke artikelen op het gebied van ROA. Verderop is een overzicht weergegeven van de literatuur die is bestudeerd en waarvan de belangrijkste conclusies in de volgende sectie zullen worden besproken.

Als nadeel van de reële-optiebenadering wordt in de literatuur vaak genoemd dat deze weliswaar in theorie de mogelijkheid biedt tot het bepalen van de waarde van opties, maar dat dit in de praktijk erg complex is en tegenvalt. In het verbeteren van de toepasbaarheid ligt dan ook één van de grootste uitdagingen voor verder onderzoek (Acciaro, 2014; Bos & Zwaneveld, 2014; Bos et al., 2016; Clarke, 2014; Gijsen, 2016). Een ander punt van aandacht is het vergroten van urgentie bij asset managers om een dynamische benadering te gaan gebruiken in plaats van traditionele analysemethoden die een statisch karakter hebben. De afweging of flexibiliteit bij een project moet worden ingebouwd om onzekerheden in de toekomst op te vangen wordt tot op heden veelal op gevoel gemaakt en slechts kwalitatief onderbouwd. De meerwaarde die het kwantitatief waarderen van deze flexibiliteit oplevert is nog niet voldoende aangetoond, waardoor de toepassing van RO niet als een “proven concept” wordt beschouwd. Het intensief uitvoeren van casestudies waarbij de het gebruik en de waarde van deze valuatiemethode wordt aantoont wordt dan ook zeer aangeraden (M. A. Cardin, de Neufville, & Geltner, 2015; DiFrancesco & Tullos, 2014; Geltner & Neufville, 2012b). Een algemene observatie uit recente en relevante literatuur toont dus aan dat punten voor verder onderzoek een focus dienen te hebben op de thema’s urgentie en toepasbaarheid.Binnen deze twee hoofdthema’s worden een aantal speerpunten genoemd waar onderzoekers zich op kunnen richten. Zo zou het interessant kunnen zijn om te experimenteren met de waardering van flexibiliteit voor meer eenvoudige casussen met betrekking tot investeren in infrastructuur. Verder wordt RO in de meeste studies toegepast op casussen waarvoor MKBA’s al beschikbaar waren. Wanneer de analyse wordt uitgevoerd voor een nog te nemen projectbesluit kan dit voordelen hebben bij het vergelijken van de twee methodes (Bos & Zwaneveld, 2014; Bos et al., 2016).

Verdiepend onderzoek naar het karakteriseren en toepassen van onzekerheden wordt tevens genoemd. De keuze voor een discrete benadering met toekomstscenario’s en bijbehorende kansen of een continue benadering waarbij men met kansverdelingen werkt, kan tot zeer verschillende resultaten en aanbevelingen leiden. Onderzoek kan zich bijvoorbeeld gaan richten op scenario planning en de vertaling van onzekerheden in kansverdelingen (Bos & Zwaneveld, 2014; M. A. Cardin et al., 2015; Peters, 2016). Verder wordt er bij de toepassing van RO vaak een kleine selectie van onzekerheden meegenomen die invloed kunnen hebben op het infrastructuurproject. Dit is ook terug te zien in het literatuuroverzicht. In deze onderzoeken is telkens slechts één thema met betrekking tot onzekerheid meegenomen. Het reduceren van complexiteit en de beperking dat sommige valuatiemethodes slechts één onzekerheid per analyse kunnen includeren, worden hiervoor vaak als reden genoemd (Clarke, 2014; Kim, Park, Bang, & Kim, 2017). Ook de toepassing van verschillende valuatiemethoden is onderbelicht. Er zijn op dit moment vijf tools bekend waarmee de waarde van een optie kan worden bepaald: Black-Scholes Option Pricing Model BSOPM, Binomial Option Pricing Model (BOPM), Risk-Adjusted Decision Tree (RADT), Monte Carlo Simulation (MCS) en Hybrid Real Options (HRO) (Martins et al., 2015). In de meeste onderzoeksrapporten worden de verschillende reële optiemethoden slechts kwalitatief vergeleken. Een kwantitatieve vergelijking kan nieuwe inzichten verschaffen of gemaakte aannames in eerder onderzoek met betrekking tot de toepassing van deze methodes bevestigen (Bos & Zwaneveld, 2014; Gijsen, 2016).

Opties tot het inbouwen, identificeren en waarderen van flexibiliteit in een infrastructuurproject, worden in de literatuur ingedeeld in zeven categorieën. Dit zijn achtereenvolgens de opties tot uitstellen, faseren, schalen, stoppen, omschakelen, groeien en interactie (Martins et al., 2015). Alleen wanneer alle voor het project relevante opties voor flexibiliteit worden meegenomen in de analyse, wordt er optimaal gebruik gemaakt van RO. Uit het literatuuroverzicht kan geconcludeerd worden dat bij reeds uitgevoerd onderzoek dit niet het geval en er altijd een beperkt aantal opties wordt meegenomen in de analyse. Verschillende auteurs bespreken deze limitatie in hun onderzoek en raden aan om op dit vlak meer te experimenteren (Bos & Zwaneveld, 2014; M. A. Cardin et al., 2015; Gijsen, 2016; Haddad, Sandborn, & Pecht, 2012).

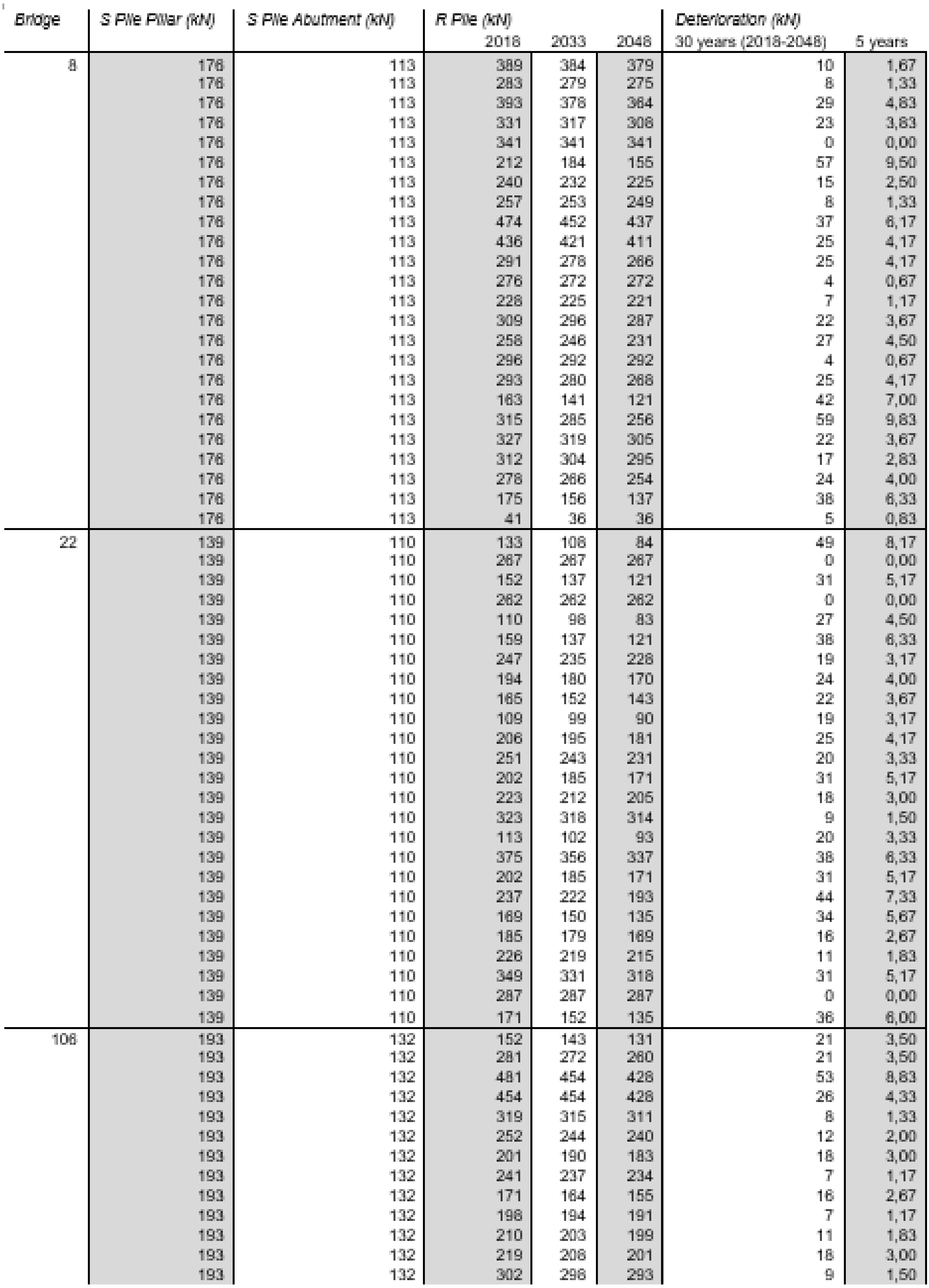
Tot slot is er in de literatuur met betrekking tot RO aandacht voor het zogenaamde “model learning”. Aangezien een ROA voor een groot deel gebaseerd wordt op aannames, zal de analyse moeten worden herzien naarmate veranderende omstandigheden zich voordoen en nieuwe inzichten met betrekking tot de toekomst zijn verkregen. Wanneer er bijvoorbeeld naar aanleiding van een ROA wordt gekozen voor de optie “uitstel van een project”, dan zal men moeten blijven monitoren hoe onzekerheden die relevant zijn voor dit project zich ontwikkelen. Ontwikkelen deze onzekerheden zich niet zoals is aangenomen in de ROA, dan zal er een nieuwe analyse moeten worden uitgevoerd. Er is dus behoefte aan een model die zelflerend is of een framework die het herzien van analyses eenvoudig maakt (Chan, Durango-Cohen, & Schofer, 2016; Gao & Driouchi, 2013; Haddad et al., 2012).

Er kan worden geconcludeerd dat in reeds uitgevoerde onderzoeken veelal versimpelde ROA’s zijn uitgevoerd. Slechts een beperkte selectie van onzekerheden die invloed kunnen hebben op de infrastructuurprojecten zijn meegenomen in de analyses. Daarnaast zijn niet alle mogelijke opties tot het inbouwen, identificeren en waarderen van flexibiliteit onderzocht. De voornaamste reden hiervoor is om complexiteit van de analyses te reduceren, zeker aangezien de onderzochte infrastructuurprojecten (vliegveld, waterafvoersysteem, waterkeringen, elektriciteitscentrales, etc.) al vrij complex zijn (Martins et al., 2015). Het grote nadeel hiervan is dat de RO-theorie hierdoor niet volledig wordt benut en de eventuele meerwaarde van de toepassing niet tot uiting komt. Het onderzoeken wat de invloed is op de uitkomsten van een ROA wanneer alle denkbare onzekerheden en opties met betrekking tot flexibiliteit worden meegenomen, is een gat in de literatuur waar dit onderzoek in zal duiken.

Year	Author	Object/Topic	Uncertainty Theme	Theory	Tool	Method	Note
2012	Booth, R.	Theoretical/general	-	RO, MCA	-	GTA	-
	Geltner, D. & R. D. Neufville	Urban planning	Population growth	RO	MC	GTA	-
	Gersonius, B., et al.	Flood management	Climate change	RO	BT	SCS	Option: expand; Compares RO and NPV
	Haddad, G., et al.	Wind Turbine	Maintenance cost	RO	MC, DT, HRO	SCS	Option: defer
	Pinon, O. J., et al.	Airport	Passenger demand	RO	BT	SCS	-
	Suttinon, P., et al.	Water supply system	Water demand	RO, GT	BT	SCS	Option: delay; Includes competition in open market
2013	Cardin, M. A., et al	Emergency service	Emergency demand	RO	-	S	Qualitative research; Design flexible projects
	Cardin, M. A., et al.	Theoretical/general	-	RO	-	E	Qualitative research; Design flexible projects
	Doan, P. & K. Menyah	BOT toll road	Traffic demand	RO	BT	SCS	Option: defer
	Espinoza, D. & J. W. F. Morris	Theoretical/general	-	RO, DCF	DNPV	GTA	Alternative RO
	Gao, Y. & T. Driouchi	Railway	Attitude planner	RO	MPM	SCS	Knightian uncertainty; immeasurable
	Koo, B.	Theoretical/general	-	RO	BT, EVM	GTA	-
	Pellegrino, R., et al.	PPP infrastructure	-	RO	-	GTA	-
	Zeng, L., et al.	Real estate	Housing demand	RO, GT	-	SCS	-
2014	Bos, F & P. Zwaneveld,	Water infrastructure	Multiple	RO, DCF	DT	MCS	Application in Dutch water infrastructure
	Campher, C. A. & P. J. Vlok	Mining	Return on stock	RO, DCF	BS, NPV	SCS	Option: defer
	Clarke, H.	Theoretical/general	-	RO	-	GTA	-
	Cunya, L. A. G., et al.	Flood management	Water discharge	RO	BT	SCS	-
	DiFrancesco, K. N. & D. D.Tullos	Flood management	Climate change	RO	-	GTA	Concepts of flexibility and adaptive capability
	Espinoza, R. D.	Infrastructure investment	Revenue	RO, DCF	DNPV	GTA	Alternative RO
	Jeerangsuwan, T., et al.	PPP toll road	Traffic demand	DCF	NPV	GTA	Demand estimation model
	Kim, B., et al.	Drainage infrastructure	Rainfall events	RO	BT	SCS	Option: expand, phase
	Marques, J., et al.	Water supply system	Water demand	RO	DT	SCS	Option: expand
	Martins, J., et al.	PPP airport	Passenger demand	RO	MC	SCS	Option: expand, phase
	Park, T., et al.	Drainage infrastructure	Climate change	RO	BT	SCS	Option: defer
	Tahon, M., et al.	Telecom infrastructure	User uptake	RO	BS, MC, BT	MCS	Option: scope, switch, scale
2015	Carmichael, D. G.	Flood management	Climate change	CST	-	GTA	-
	Fawcett, W., et al.	Highway	Traffic demand	RO	SA, MC, CILECCTA	SCS	Option: defer; Real option software
	Gijsen, F.	Highway, Bridge	Traffic demand	RO	BT, DT	MCS	Option: expand, phase, defer
	Marques, J., et al.	Water supply system	Water demand	RO	DT	SCS	Option: expand; Environmental impact
	Marques, J., et al.	Water supply system	Water demand	RO	DT, MODM	SCS	Option: expand; Environmental impact; Conflicting objectives
	Martins, J., et al.	-	-	RO	BS, BT,DT, MC, HRO	LR	Literature review
	Power, G. J., et al.	Bridge	Detoration, price & rate	RO	MC, SA	SCS	Option: defer; Physical & financial uncertainties
	Pringles, R., et al.	Power plant/grid	-	RO	MC, BT, BS	GTA	-
2016	Bos, F et al.	Transportation infrastructure	Multiple	RO	DT	MCS	Application in Dutch infrastructure
	Chan, R., et al.	Flood management	Climate change	DL	MC	GTA	Alternative RO
	Du, B. Z., et al.	Civil aircraft R&D	Technology	RO	BT	SCS	-
	Esders, M., et al.	Office buildings	Operating cost	RO	BT, SA	MCS	Option: defer, phase
	Jeong, J., et al.	BOT highway	Traffic demand	RO	BT, MC	SCS	Option: defer, phase
	Lyons, G. & C. Davidson	Transportation infrastructure	Car travel	RO	-	GTA	Scenario planning
	Manocha, N. & V. Babovic	Flood management	Climate change	RO,DAPP	BS	SCS	Dynamic learning; Compares RO and NPV
	Peters, L.	Parking Garage	Parking demand	RO	MCS, SA	SCS	Impact probability distridutions: uniform, beta, PERT
	Pizzutilo, F. & E. Venezia	Transportation infrastructure	-	RO	-	GTA	-
2017	Hawas, F. & A. Cifuentes	Transportation infrastructure	-	GCA	MCS	GTA	Alternative RO; Minimum revenue guarantees
	Kim, K., et al.	Flood management	Climate change	RO	BT	SCS	Option: abandon, expand, contract, continue
	Kim, K., et al.	Hydropower plant	Climate change	RO	BT	SCS	Option: abandon, continue

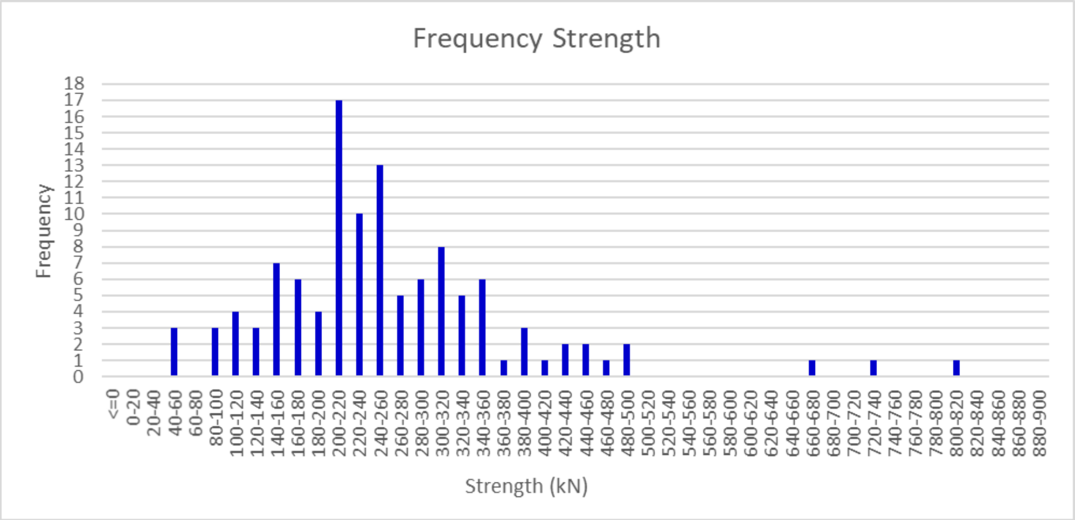
RO	Real Options
MCA	Multi Criteria Analysis
GT	Game Theory
DCF	Discounted Cash Flow
CST	Control System Theory
DAPP	Dynamic Adaptive Policy Pathway
DL	Dynamic Learning
GCA	Gaussian Copula Approach
MC	Monte Carlo
BT	Binomial Tree
DT	Decision Tree
BS	Black Scholes
HRO	Hybrid Real Option
DNPV	Decoupled Net Present Value
MPM	Multiple Priors Model
EVM	Earned Value Method
NPV	Net Present Value
MODM	Multi Objective Decision Model
SA	Sensitivity Analysis
S	Survey
E	Experiment
LR	Literature Research
GTA	Grounded Theory Approach
MCS	Multiple Case Study
SCS	Single Case Study

APPENDIX C: PILE STRENGHT & DETERIORATION



Bridge	S Pile Pillar (kN)	S Pile Abutment (kN)	R Pile (kN)			Deterioration (kN)	
			2018	2033	2048	30 years (2018-2048)	5 years
8	176	113	389	384	379	10	1,67
	176	113	283	279	275	8	1,33
	176	113	393	378	364	29	4,83
	176	113	331	317	308	23	3,83
	176	113	341	341	341	0	0,00
	176	113	212	184	155	57	9,50
	176	113	240	232	225	15	2,50
	176	113	257	253	249	8	1,33
	176	113	474	452	437	37	6,17
	176	113	436	421	411	25	4,17
	176	113	291	278	266	25	4,17
	176	113	276	272	272	4	0,67
	176	113	228	225	221	7	1,17
	176	113	309	296	287	22	3,67
	176	113	258	246	231	27	4,50
	176	113	296	292	292	4	0,67
	176	113	293	280	268	25	4,17
	176	113	163	141	121	42	7,00
	176	113	315	285	256	59	9,83
	176	113	327	319	305	22	3,67
	176	113	312	304	295	17	2,83
	176	113	278	266	254	24	4,00
	176	113	175	156	137	38	6,33
	176	113	41	36	36	5	0,83
22	139	110	133	108	84	49	8,17
	139	110	267	267	267	0	0,00
	139	110	152	137	121	31	5,17
	139	110	262	262	262	0	0,00
	139	110	110	98	83	27	4,50
	139	110	159	137	121	38	6,33
	139	110	247	235	228	19	3,17
	139	110	194	180	170	24	4,00
	139	110	165	152	143	22	3,67
	139	110	109	99	90	19	3,17
	139	110	206	195	181	25	4,17
	139	110	251	243	231	20	3,33
	139	110	202	185	171	31	5,17
	139	110	223	212	205	18	3,00
	139	110	323	318	314	9	1,50
	139	110	113	102	93	20	3,33
	139	110	375	356	337	38	6,33
	139	110	202	185	171	31	5,17
	139	110	237	222	193	44	7,33
	139	110	169	150	135	34	5,67
	139	110	185	179	169	16	2,67
	139	110	226	219	215	11	1,83
	139	110	349	331	318	31	5,17
	139	110	287	287	287	0	0,00
	139	110	171	152	135	36	6,00
106	193	132	152	143	131	21	3,50
	193	132	281	272	260	21	3,50
	193	132	481	454	428	53	8,83
	193	132	454	454	428	26	4,33
	193	132	319	315	311	8	1,33
	193	132	252	244	240	12	2,00
	193	132	201	190	183	18	3,00
	193	132	241	237	234	7	1,17
	193	132	171	164	155	16	2,67
	193	132	198	194	191	7	1,17
	193	132	210	203	199	11	1,83
	193	132	219	208	201	18	3,00
	193	132	302	298	293	9	1,50

	193	132	152	143	131	21	3,50
	193	132	255	247	239	16	2,67
	193	132	220	206	195	25	4,17
	193	132	228	225	221	7	1,17
63	130	126	87	74	63	24	4,00
	130	126	137	102	94	43	7,17
	130	126	244	233	222	22	3,67
	130	126	52	48	48	4	0,67
	130	126	202	185	171	31	5,17
	130	126	255	247	243	12	2,00
	130	126	345	331	322	23	3,83
	130	126	82	65	50	32	5,33
	130	126	355	346	341	14	2,33
	130	126	444	444	444	0	0,00
	130	126	322	304	287	35	5,83
117	145	-	155	140	126	29	4,83
	145	-	250	246	246	4	0,67
	145	-	219	219	219	0	0,00
	145	-	108	89	71	37	6,17
	145	-	234	234	226	8	1,33
	145	-	145	131	117	28	4,67
	145	-	309	309	309	0	0,00
	145	-	240	236	236	4	0,67
	145	-	240	236	236	4	0,67
	145	-	247	247	247	0	0,00
	145	-	209	198	188	21	3,50
	145	-	81	70	70	11	1,83
	145	-	219	219	219	0	0,00
	145	-	228	225	221	7	1,17
167	184	109	259	259	259	0	0,00
	184	109	309	309	309	0	0,00
	184	109	60	51	41	19	3,17
	184	109	159	150	138	21	3,50
	184	109	414	414	414	0	0,00
	184	109	394	389	389	5	0,83
	184	109	316	312	312	4	0,67
	184	109	440	430	420	20	3,33
	184	109	121	116	116	5	0,83
	184	109	491	480	469	22	3,67
	184	109	269	249	230	39	6,50
	184	109	349	349	349	0	0,00
	184	109	219	219	219	0	0,00
	184	109	203	196	189	14	2,33
	184	109	219	219	219	0	0,00
	184	109	344	339	335	9	1,50
	184	109	219	219	219	0	0,00
	184	109	219	219	219	0	0,00



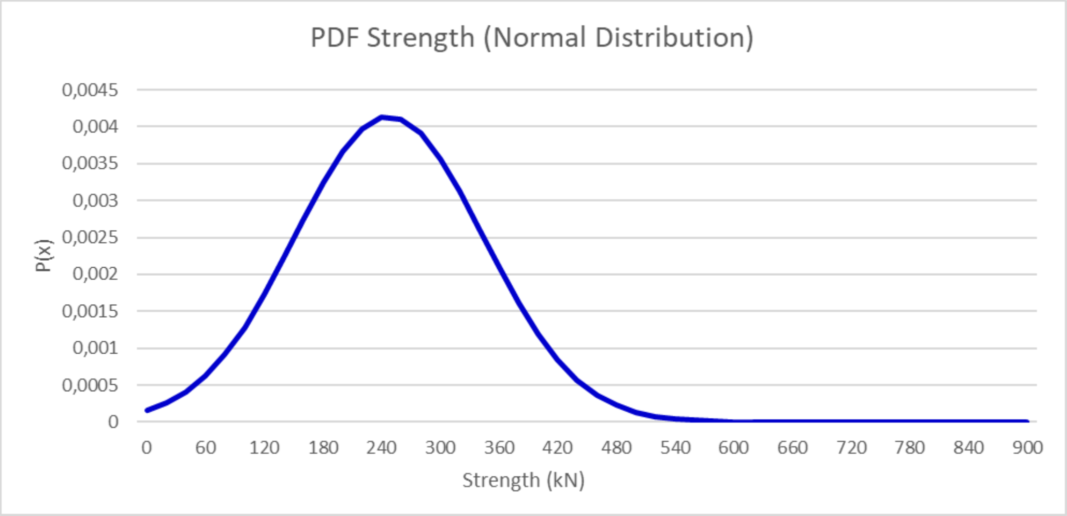


Figure 14, Probability distribution initial pile strength (own figure, 2018)

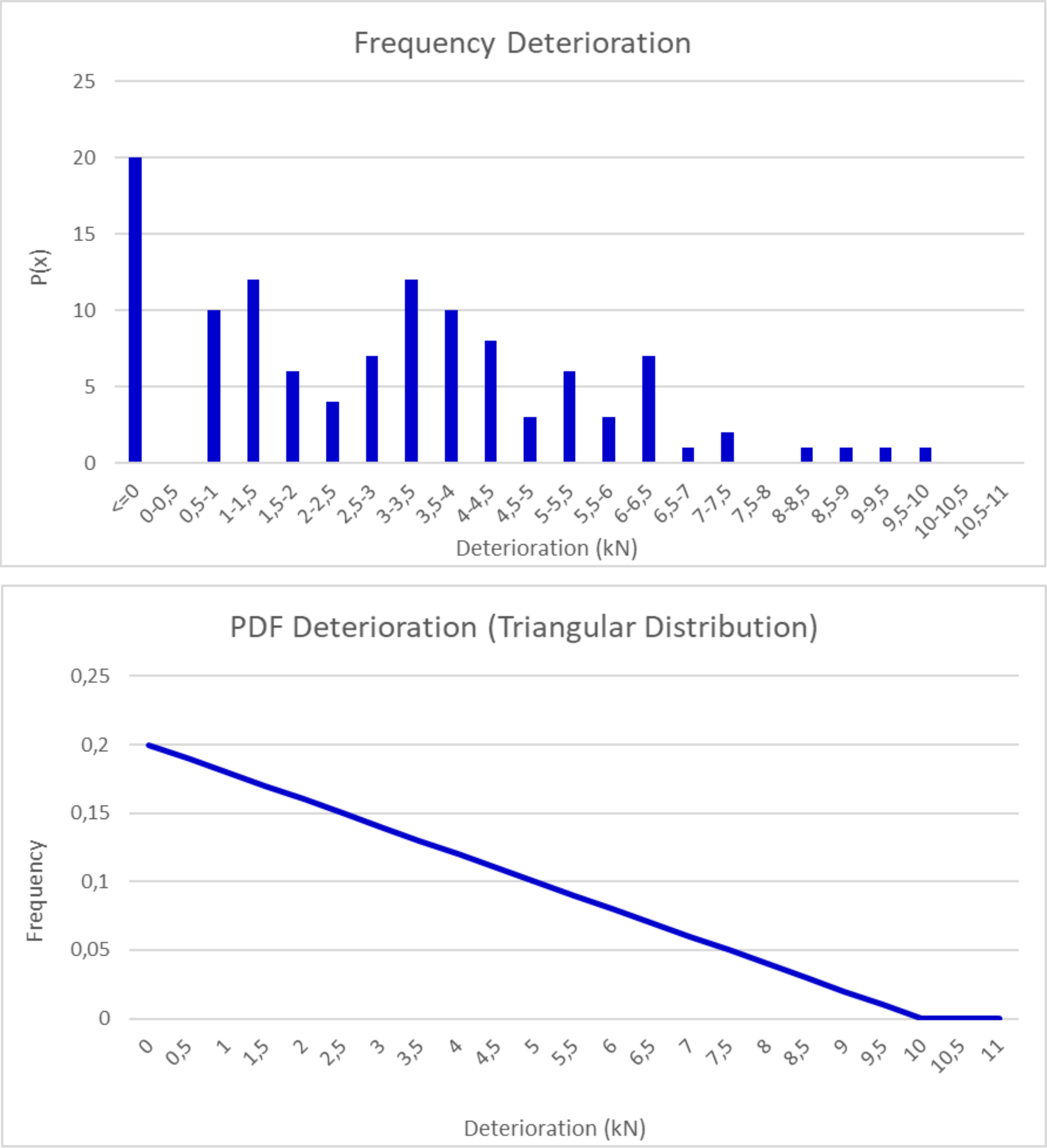


Figure 15, Probability distribution pile strengths deterioration (own figure 2018)

Data obtained from Dirksen et al. (2016)

APPENDIX D: BRIDGE USER DEMAND

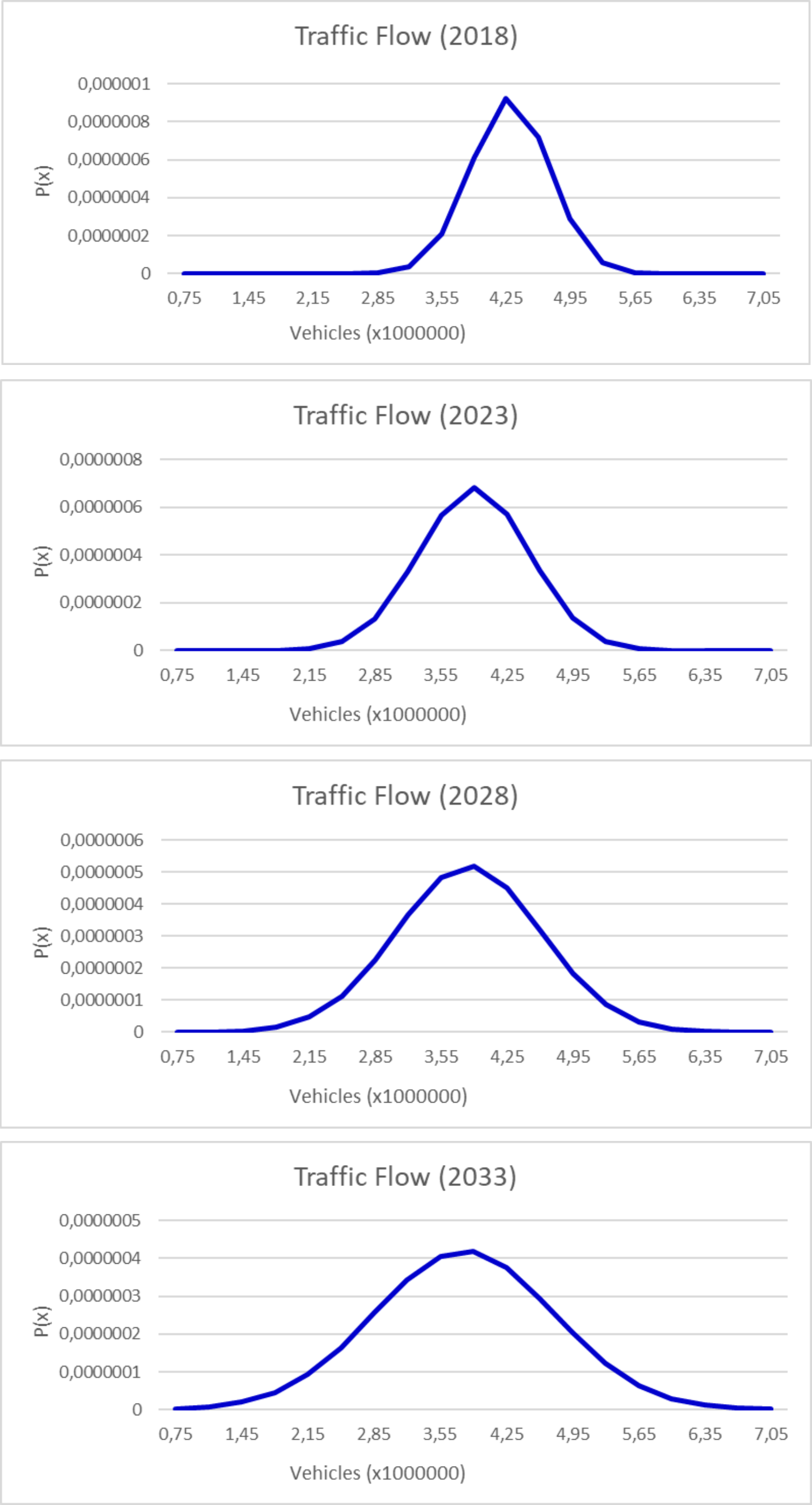


Figure 16, Probability distributions bridge user demand (own figure, 2018)

Data obtained from verkeersprognoses.amsterdam.nl (2015)

APPENDIX E: GBM STEEL PRICE

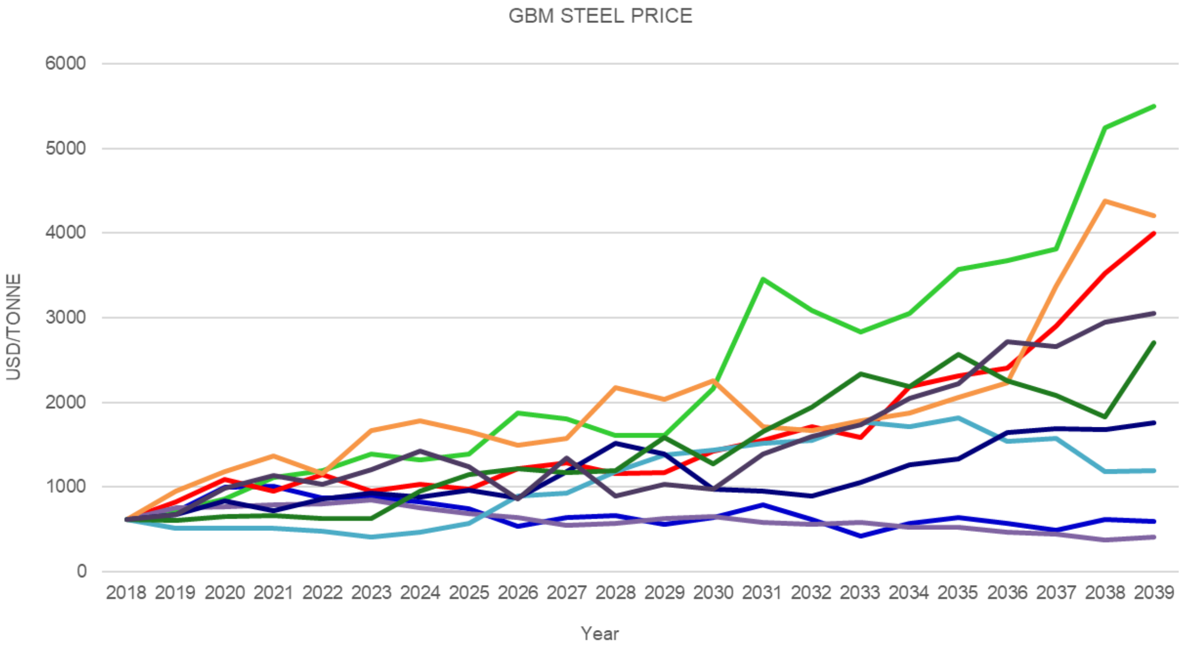


Figure 17, GBM example: a selection of simulation runs for the price of steel (own figure, 2018)

Data obtained from CROW Indexen Risicoregelingen GWW (CROW)