Life-cycle costing and risk management:

the influence of uncertainties on Dutch transportation infrastructure projects

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Decisions, decisions, decisions.... we are all confronted by them on a daily basis and some of them can be regarded as irrelevant, minor, big, very important or risky given their (unknown) consequences clouded by uncertainty. Still, we learn to cope with this fact and take them every day based on analytical thinking or gut feelings. The decision to put my professional career on hold in order to obtain a masters degree in this prestigious university did not come with ease and has proven to be one of many challenging tasks so far... and many more still to come.

This report contains the results of a study I conducted to finalize my master thesis in Construction Management and Engineering at TU Delft; one that could not have been possible without my thesis committee, their guidance and advice during these past months. Thanks to Professor Jan Vrijling, Pieter van Gelder and Ellen van Bueren for their continuous feedback and support to making this possible.

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Executive Summary

Investment in public infrastructure is a means to increase income, employment, productivity and other social effects that can be influenced by the project's appraisal. The extent of the impacts by its construction and implementation is very difficult to fully quantify it, but it has several components that make up different layers of project assessments, such as social, environmental, economic, financial and technical.

There are many criteria that are taken into consideration for appraisal of certain infrastructure projects, one of these being economic indicators. Regardless of this being the most important aspect or not, figures that reflect **benefits and costs** are usually of main concern. This can be explained by the fact that the size of the investment is quite high in comparison to the benefits, some of which are not easy to quantify. There are many tools that serve to engineers, economists and decision-makers to be able to try and forecast these as best possible, one of this tools is known as Life Cycle Costing (LCC).

LCC is a concept that can be of use to many types of industries in order to increase effectiveness of procurement. In general, it helps visualize all costs associated with an asset during its lifetime and improve future transparency of activities around the asset for possible asset management strategies.

When looking at costs and the extensive history of cost overruns in the construction industry, one can try to think about modern tools to try to make more accurate forecasts by incorporating adequate risks and uncertainties that could lead to cost increases but help solving the aforementioned problem. However, the amount of uncertainty regarding long-term incurring costs that go beyond a 20, 30, or 50-year timeframe is immense, and trying to 'accurately' predict these is filled with potential errors.

Current practices in cost estimations are shifting from a deterministic approach to a probabilistic one in order to account for some uncertainties that can unfold during the project's execution and exploitation phases. Also, within the cost estimation framework, LCC aims to increase long-term thinking about consequences of low investment options.

It should be noted that cost estimation is dependent on data that can be lacking (no statistically significance), unreliable or vague, making predictions, and therefore decisions, also unreliable. It is of best interest to gain insights on how long-term uncertainties and risks can affect adequate cost estimation, and more so the decision-making process.

Many limitations that are inherent to economic appraisal tools will be revealed and bring forward to evaluate LCC's applicability in a case study from a transportation infrastructure project in The Netherlands.

Two methods can be distinguished for visualizing life cycle costs: cost/year and present value of all costs related to a particular asset given a study period. While the former will

be reflected upon for its usefulness, the latter will be applied as the proposed costeffectiveness evaluation methodology, provided the following key points are met:

- Choosing amongst two or more **mutually exclusive** alternatives on the basis of lowest LCC (net present costs)
- All alternatives must **meet minimum performance requirements**, such as expected benefits
- All alternatives must be **evaluated using the same base or service date**, life **period**, **discount rate** and other assumptions (ceteris paribus)
- If the **impact is not measurable in monetary terms**, then it must be **applicable on equal terms** to all alternatives or accounted in some other way

Throughout the report, it will be noted that there are many tools for economic aspects of infrastructure appraisal, and that these are subject to various types of limitations, mainly on how they fail to be all-encompassing/accountable. Nonetheless, the benefits from an LCC analysis can best be served by comparing amongst competing project alternatives that serve the same purpose while focusing mainly in the following 3 output parameters:

- Investment costs
- Maintenance costs
- NPV of evaluated alternatives

It is unlikely that budget allocations will stem from an LCCA, or that incorporation of most significant risks and uncertainties will yield a full-scope risk management program for construction and/or implementation phases. However, much of its input can yield to useful insights around cost drivers and decisions being made around these. Also, by including adequate risks and uncertainties in the analysis, it establishes a framework that sets the base for grounds of comparison between alternatives which can lead to reasonable choices being made on a more scientific background base.

LCCA results can subsequently serve for design optimisation and can also yield some useful insights for asset management programs, although future events are subject to practical realities at their time of occurrence. Asset management strategies can be based on initial LCCA results, even though these are on a constant dynamic process and these cannot rely solely on an economic appraisal tool such as LCC. However, it can serve as a complementary tool to making more informed decisions based on analytical and collective thinking, experience and common sense.

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1. Chapter 1. Introduction

1.1. Background

Cost estimation in construction projects is based on several factors, such as the analysis of project scope, schedule, location factors, lifecycle approaches and risks.

"Life-cycle costs (LCC) are the sum of the total direct, indirect, recurring, nonrecurring, and other costs incurred or estimated to be incurred in the design, development, production, operation, maintenance, support and final disposition of a system over its anticipated useful life span." (U.S. Department of Energy, 2011)

Hence, life-cycle cost analysis (LCCA) is a decision-making tool for any client regarding the assessment of the total cost of ownership. It is particularly useful when choosing amongst alternatives that fulfil the same performance requirements; all things being equal, the alternative with the lower cost (maximizing savings) is chosen.

According to Fuller (2010), there are numerous costs associated with acquiring, operating, maintaining, and disposing of a building or building system. Building-related costs usually fall into the following categories:

- Initial Costs-Purchase, Acquisition, Construction Costs
- Energy or Fuel Costs
- Operation, Maintenance, and Repair Costs
- Disposal Costs or Residual Value (depreciation)
- Replacement Costs
- Non-Monetary Costs

All these costs become apparent thru a project's lifecycle and, according to literature, their forecasts have remained constantly and remarkably inaccurate for decades due to many factors (Bent Flyvbjerg, 2006), most of these based on several types of uncertainties. However, cost uncertainties is the main theme of this thesis and explanations for such inaccuracies can be provided as (Hinson, 2009):

- Errors in budgeting/estimating a project, such as omissions, miscalculations, vague drawings, scope and plans
- Costs required beyond the scope of work
- Tools and equipment costs exceeding budget allocation
- Accidents during construction
- Accounting errors

Figure 1 below illustrates the most typical cost drivers in construction projects; it is critical to keep in mind that even though information may become available helping further define these costs, these rarely remain static over a period of time after a decision has been made or even more so after implementation.



Figure 1. Key Determinants of Costs (European Commission, 2012)

Notice that these can affect original cost estimate during construction but also after it. This fact has led to the application of common practice in construction industry to add a contingency factor to the total cost of the project. Consequently, there is room for improving existing assessment models in project management.

Projects face several types of risks that may affect (usually negatively) a project's scope, cost and time promises. Being able to use resources during planning stage to minimize financial, economic and commercial uncertainties is an enormous challenge in the construction industry. There are several models, processes, schemes and tools available in order to deal with uncertainty. However, it is still difficult to implement models, involving components, structures and parameters that are assumed to be accurate because of lack of strictly enforced post-project evaluation practices, ambiguous data surrounding budget use and non-transparent figures, amongst others.

1.2.Problem statement

According to the EU (European Union) programme funding, time and cost overruns have obvious implications in the number of projects to be funded in a given period. Research has exposed a range of problems in both pre-construction and implementation stages, leading to overruns (European Commission, 2012), which are summarized in the following figure.



Figure 2. Cost Changing Factors (European Commission, 2012)

With all these variables it is not surprising that there are such problems in making accurate budget forecasts. Furthermore, the causes for cost overruns in the Netherlands are unknown and literature lacks any insights on cost increases varying with project phases (Cantarelli, 2011), such as maintenance activities.

As Flyvbjerg (2004) has established, there are several reasons for optimism bias in transportation projects, which have been categorized in: economic, psychological, political and technical.

For the past 10 years, lifecycle costing has been gaining more importance when it comes to serve as a tool for decision-making by clients. However, LCC is based on the prediction of the service life of an infrastructure asset, and it is difficult to anticipate or forecast the costs and uncertainties surrounding its lifespan (Rahman & Vanier, 2004). It seems that LCC would help in making more informed estimates by taking into account many other costs (future), yet tackling all of the above mentioned reasons seems farfetched for any kind of economic appraisal tool.

As it has been stated before, LCC serves as a tool visualizing long-term costs, but predicting future costs is fraught with potential errors, owing to the uncertainty in future costs, interest rates, future events and even hidden costs (social, environmental, user delays, etc). These last types of costs are difficult to quantify and capture in an LCC and thus, by leaving subjective environmental terms aside but focusing mainly in costs. Yet, Perrin & Jhaveri (2003) have shown that user delay costs due to unavailability

can be substantial and exceed actual (re) construction costs during large maintenance activities.

However, according to Boussabaine and Kirkham (2004), LCC has not developed to the extent envisaged as many design decisions are based solely on initial capital costs and not future operational and maintenance costs. If the latter exceed the former substantially, these may pose a larger threat in risk management and decision-making strategies. It will thus be reflected if such activities do actually exceed initial costs based on the service life of transportation infrastructure projects.

Many engineering firms are aware of these costs and thus incorporate long-term costs into their analyses; the challenge relies on incorporating uncertainties to these. The department of Cost and Risk Management at Royal Haskoning DHV has a process for developing a LCC analysis (LCCA) which is approached in two ways: deterministic and probabilistic.

With the deterministic method (traditional way), the analyst assigns input variables which are fixed and based on historical data and judgement. The probabilistic approach involves a Monte Carlo simulation that includes normal uncertainties and recorded special events that will yield an average investment cost and the future lifecycle costs. However, the latter is where the most uncertainty is found and thus, subject to study in order to produce more robust cost and risk estimations.

1.3. Research objective

Investment costs, even though difficult to forecast, are somewhat easier to calculate and measure given their shorter time span and relatively low uncertainty. A big problem still lies in making accurate predictions about maintenance and operating costs in a 100 year lifespan: there is too much uncertainty involved in trying to predict a system's behaviour and the effects of its surroundings in such an extended period. "The idea behind incorporating long-term costs into the overall decision making process will become more widely accepted when guarantees can be made about the accuracy of the forecasts." (Boussabaine & Kirkham, 2004) However, it is very difficult to implement measurement systems to provide such effective forecasts, particularly when such long periods are considered and data information systems are not strongly enforced, controlled or updated.

Furthermore, it is also worth mentioning at this point that, given the nature of maintenance activities when compared to new developments, imply less unique features and have more repetitive, standardized tasks; which could lead to more accurate cost estimations and fewer risks involved.

With the above premise, it is considered of high importance by RH DHV to improve its LCCA modelling in order to be able to provide a more solid background for decision-making to its clients. Therefore, the following objective is stated:

Improve an existing LCC model by taking into account the most critical uncertainties and risks in order to generate risk-awareness in decision-making.

1.4. Research questions

In relation to the objective of this research, the following questions are then formulated around the LCC model:

RQ1. Can LCC provide to be a useful tool for effective decision-making?

RQ2. In which ways can the cost drivers have an effect on the decision-making process?

RQ3. What are the major sources of uncertainty in long-term incurring costs in a project's lifecycle?

RQ4. Which aspects are most critical for a quantitative risk analysis during implementation phase over the lifecycle of a transportation infrastructure asset?

1.5.Report outline

This report begins with an introduction on cost estimation and some problems regarding typical cost overruns; a new shift from deterministic to probabilistic cost estimations in LCCA and their influence in decision-making.

Chapter 2 describes the research approach that was taken from its initial steps to the conclusions and further recommendations.

Chapter 3 provides the theoretical framework and relevant topics of research; going from a broad perspective to a more problem specific type of approach regarding infrastructure assessment and planning.

In Chapter 4 a risk-based model is proposed based on the findings of chapter 3 and a second literature research to provide more depth on these findings.

Chapter 5 is the application of the improved model to a specific case study in which the results are compared to other project alternatives.

Chapter 6 provides a discussion of the findings of such application based on quantitative and qualitative analysis of results. The assumptions around these, along with their implications are also reflected upon for adequate application of such model.

Chapter 7 provides answers to the research questions, leading to some conclusions and further recommendations.

2. Chapter 2. Research Methodology.

The following figure shows a step-by-step breakdown of the report outline to illustrate the research approach.



Figure 3. Research Outline

Step 1. Theoretical Framework

As it is generally suggested for research material, it is critical to conduct an extensive literature study to investigate the current knowledge of the concepts, applications, benefits and limitations regarding LCC.

Thus, the main topics of the literature study are focused on:

- Macro and micro-economic assessment of infrastructure projects
- LCC methodology and Probabilistic Cost Analysis
- Risk Management Principles
- Maintenance Theory
- Decision Making

It was advised by the author's thesis committee to investigate broader aspects of economic appraisal tools regarding infrastructure projects to gain a more rich and insightful understanding of the spectrum of these and the influence of LCC.

In order to answer some of the research questions not only relying on general theory and practices worldwide (books, articles, etc.), some interviews were conducted to provide a more insightful view from industry professionals in The Netherlands

LCC's applicability to different industries have demonstrated some of the many benefits and limitations that this appraisal tool might have. There is an increased need to identify what exactly needs to be included in the calculations to determine what exactly the cost drivers are, and their respective effect on the lifecycle of a project and their impact and implications on it.

As the concept of LCC can be often quite wide and go to many dimensions of depth, there needs to be a problem formulated as to see where the qualitative research will differ from the quantitative one. In principle, the qualitative research, based on an extensive literature review and interviews with professionals within the industry, will help observe, report and explain the problem statement and the outcome is then validated with the application of the theoretical framework to a real case in which quantitative research will determine the extent of some phenomena in the form of numbers. At the same time this phase will conduct a secondary data analysis also in the form of interviews with professionals who worked on this project. Thus, further refining the problem analysis on a more detailed level.

Step 2. Reflection and Analysis

Once the literature study is conducted as mentioned before, ranging from broader economic aspects to a narrower, problem-specific context, an improved model will be developed for the accomplishment of the intended goal of this research. This is done by tackling some of the deficiencies that current practices pose and have been identified during Step 1.

Step 3. Case Study

Within a deductive and exploratory research, the application of the model to a Case Study fits best as research strategy. This step also focuses more on the quantitative part of the problem analysis by looking at figures.

The choice of one single case study is due to time constraints for conducting this research and data limitations, due to both its sensitivity and availability. The case, however, can be found to be representative of transportation infrastructure projects in The Netherlands as it is not something unprecedented or particularly special in any use of technologies or other features.

Data collection methods.

There are two ways of data collection techniques for this research:

- 1. Qualitative data collection, from both literature articles/documents and interviews for developing and applying the model.
- 2. Quantitative data collection, also from documents, data bases and interviews for data input towards implementation of the model and analysis of results.

A secondary literature study was conducted, it focuses on dealing with the most relevant and critical aspects regarding LCC and subsequently improving the benefits of its applicability in decision-making.

Step 4. Evaluation.

The evaluation of the aforementioned model will define the problem analysis on a more detailed level and provide some insights of the limitations and applications of LCCA. These will be reflected upon on Chapter 6.

Based on this evaluation, some conclusions and recommendations will be provided for the proper implementation of the model in order to have a more robust decision-making process based on risk and uncertainty awareness.

3. Chapter 3. Literature Study

This section of the report will provide the theoretical framework, beginning with an overview of how infrastructure assessment and planning encompasses a wide range of appraisal aspects. This will provide general context as to where exactly the concept of lifecycle costing fits the picture and how it can influence the decision-making process.

There are several aspects that govern the use and influence of LCC, and so, these are also subject to research in order to evaluate how each of these has an impact on LCCA and vice-versa.

3.1. Economic Impacts of Infrastructure.

Amongst many benefits, infrastructure planning aims to maximize value towards society for an investment decision. In order for this to be achieved, a proper set of criteria should be addressed to be able to measure all impacts such as socio-economic, environmental, organizational, etc.

Infrastructure investment is one of the principal means for the public to promote the increase of income, employment and productivity in a given region, especially in times of crisis. It could be also argued that investment in transportation infrastructure is the highest contributor to productivity growth and thus, economic competitiveness.

There are several methods or approaches in place to plan and implement infrastructure projects, such as:

- Increased attention to match demand (generating value) vs supply (required investment)
- Pricing of infrastructure to improve effective facility use and increased cost recovery
- Asset management leading to an increased private effectiveness and maximization of value regarding the asset
- Sustainability, either financial, environmental, etc.

According to Verhaeghe (2011), the scope of an infrastructure project cumulates from technical up to financial, economic and social components with each aspect affecting the next associated one. The social scope requires the project to be technically efficient, financially feasible, (economically) efficient in resource use, and equitable in order to reach a maximum contribution to welfare with a minimum of input resources. Figure 4 below provides and overall view of the general context and incorporates some new concepts that will be incorporated throughout the following paragraphs.

The social context is concerned mainly with the distribution of welfare towards different groups of people in different places within a certain society. In the economic context, the main focus is the analysis of the contribution of the system to overall welfare and its environmental impact, plus the justification of the government's involvement, for example in case subsidy is needed. The financial aspect concerns especially the exploitation of the new system in relation to pricing and private aspects of the system.

With regards to these last two aspects, many advanced tools have been implemented in order to analyze economic and financial feasibility, such as Cost-Benefit Analysis (CBA), Profitability Index, Net Present Value (NPV), Internal Rate of Return (IRR), Life-Cycle Costing (LCC), etc. The use of each depends on the context being used, for example LCC focuses only in financial aspects.



Figure 4. Overall components of project assessment

Many of the aforementioned economic indicator tools, if not all, fail to address environmental and social (some more than others) impacts regarding infrastructure assessment, so, from a sustainable perspective, all these pose limitations to decisionmakers.

As societies strive to develop in a sustainable way, it remains a challenge to incorporate and balance all the aforementioned components when planning and assessing infrastructure projects. In construction industry, the concept of Life Cycle Analysis was introduced to tackle one of these issues: assess the full range of environmental effects brought upon the implementation of a project.

However, it fails to incorporate sustainability concepts such as two of its three main pillars: economic and social performances. Neither internal nor external economic aspects are included in decisions developed by the scope of LCA.

According to Norris (2006), this has limited the influence and relevance of life-cycle assessment by leaving aside an important relationship and trade-offs between the

economic life and the technical life of an asset. It is important to remark that sustainability as a principle can be easy to define but rather problematic to quantify, making LCA's applicability all the more difficult. Not only new scientific insights, research and ideas are not sufficient, but it needs more levels of sophistication, acceptance and new models should not neglect the needs and reality of decision making (Hunkeler & Rebitzer, 2005).

LCA seems to be generally accepted and somewhat standardized in some business practices; however, much room is left for improvement and formalization of the economic and social methodologies.

The development of the methodological basis for social assessments, however, is in its infancy, far behind LCA and LCC, and probably much more difficult to implement given its difficult quantification. Also, care should be taken not to develop this in isolation of the environmental context.

But putting aside the subjective term of sustainability and focusing more on the economic context, which can be measured easier by incorporating monetary terms, it is important that LCA takes economic consequences of alternative choices into account. Hunkeler and Rebitzer (2005) propose to do this by incorporating the use of LCC into life cycle analysis as this would eventually provide a bridge between environmental and economic aspects. LCC has emerged as a concept and a tool for the economic dimension of sustainability and is on a fast track to being established as an evaluation method of the economic implications associated with an infrastructure's life cycle. Particularly, if applied in parallel with LCA, utilizing common data and models that could provide more synergy and thus, a better application of it towards decision making (Rebitzer, Rydberg, & Norris, 2004).

However, it is argued that LCC only takes into account the technical lifetime of an asset and fails to incorporate the economic lifetime, which is expected to be shorter, and thus, its governing factor. Reasons behind this shorter life can rely on obsolescence due to new technological developments leading to the asset still being physically operable but at a rate that is economically unfeasible given unforeseen changes in relative costs. Also, the economic lifetime cannot be over-simplified by assuming that everything can be expressed in a one-dimensional unit such as monetary figures. Moreover, and in contradiction with decision theory, it cannot handle decision-making under genuine uncertainty as it assumes that a decision is rational and based on access to complete information regarding alternatives and outcomes.

As capital costs generate value for different stakeholders during a project's life-cycle (which can be introduced incurring in new costs), it is important to distinguish that these cash flows do not reflect the total value of capital expenditure choices as the fail to account for intangible non-monetary benefits, reduction of future costs and financial returns (Plenty, Chen, & McGeorge, 1999).

Focusing on infrastructure projects, an economic analysis is a critical component of a comprehensive program evaluation methodology that allows agencies to identify, quantify and value economic benefits and costs of projects or programs over a given timeframe. It can provide valuable information on the different phases of the decision making process, such as assisting engineers in the development of more cost-effective designs, plan the best return of investment, understand complex projects and their impact in the environmental assessment process and documenting the decision process (Federal Highway Administration, 2011). However, the analysis cannot serve as substitute for the environmental assessment process; just like LCC can serve as a useful complementary tool for an economic analysis, but should not be treated as an all-encompassing substitute.

3.2. Economic vs. Technical lifetime.

Some interviews with professionals has shed light on some of the limitations that LCCA poses regarding financial implications born from focusing on only costs rather than on broader aspects, such as value generated towards society through infrastructure development.

According to Vrijling (2011), there are three main considerations that should be taken into account when switching from a pure costs analysis to overall economic aspects of investment decisions.

First, maintenance theory, which currently governs LCC calculations, fails to provide a distinction between technical lifetime and economic lifetime. Therefore, much effort is placed in optimizing cost of inspection and repair versus the cost of failure (risk). Enough information should be provided in order to be able to assess if these costs differ a great deal from each other, but this all depends on the agency costs for their maintenance strategies, whether they are preventive or corrective (see Maintenance Theory).

Second, and subsequently stemming from risk of failure, an analysis of the actual maintenance costs of existing infrastructure versus new costs of new infrastructure (replacement) should be considered, however, the latter is omitted in theory of maintenance. This also holds true for any other approach towards investment appraisal as a new analysis is required when evaluating the new replacement. These types of short-comings are found common in tools that focus only in costs.

Cost types such as wages, materials, energy, maintenance strategies and risk should be compared amongst the existing and the proposed new infrastructure. Also, depreciation and interest rates of the current asset are to be analyzed and compared against new savings offered by the option of replacing; if the latter are larger than the former, economic theory would corroborate choosing this last option, maintenance theory does not. This proves to be a difficult task if applied to a unique infrastructure project, since it involves drawing up a new design with new technical specifications, and other tasks that require a substantial use of resources (read time and money). In other words, this requires a new CBA to see if benefits can be increased with maintained or reduced costs, i.e. more savings. The main criteria to decide between renew vs replace is by comparing 'integral' costs of new against 'variable' costs of existing asset. But also, for practical purposes, if the level of effort put into replacing is too costly, then waiting for the proper occasion is recommended, e.g. when large scale maintenance is carried out or when adjacent piping is replaced, etc. (F. van Ekkendonk, personal communication, August 20th, 2012)

Whenever the option of renovating vs. building a new system in order to make a cost effective decision, two important things must be analyzed in contrast:

- system functions, is there a new purpose for the system? and,
- level of performance, what would be the cost to have this system working for a specified purpose?

Other aspects should also be taken into consideration, such as number of failures getting disturbingly high and users have many complaints. Furthermore, there are environmental implications that should also be taken into account, such as the effects of demolishing and replacing the existing structure. It is assumed that the system (or the asset) will eventually be demolished at some point in time, and, as far as monetary effects are concerned, these can be accounted for in a deferred way with the use of discounting techniques. These, however, cannot be applied to the environmental effects as they generally yield very low values to future damages, playing against the environment and future generations (Philibert, 2003).

There is no set standard method for analyzing the option of replacing, but rather a combination of considerations, tools and policy within the organization and asset management practices. In infrastructure projects, the analysis should be carried out by a maintenance expert along an experienced team; yet the decision will be analyzed within different layers of the organization depending on related costs, impacts, and level of effort required to do a proper analysis of its worthiness.

If the decision for a new investment (replace) is taken, then a new consideration should be added: calculating benefits of the new asset.

Third, revenues of new infrastructure should be incorporated into the analyses; it will later be explained what revenues actually represent in transportation projects. This comes also as a limitation of LCC since it fails to incorporate benefits from mutually exclusive alternatives which could enhance future financial performance regardless of costs being minimized: *lower costs do not imply higher revenues*. LCCA cannot be used to evaluate a project where benefits amongst possible alternatives are not identical, or where an agency's decision to undertake a project depends on revenues generated (Clemons, 2011). If benefits vary amongst design alternatives, for example increases traffic capacity, then these cannot be compared solely on the basis of cost, but should incorporate a Cost-Benefit Analysis.

However, one could argue that limiting to forecasting costs and not revenues or benefits involves less uncertainty in the overall predictions. Forecasting costs and benefits is just as risky, as not only cost overruns seem to be a problem in construction projects, but also benefit shortfalls. As forecasters and project planners intend to be accurate when estimating these future cash flows, these are mostly based on assumptions of current trends, such as rise of oil prices, wages and land, flat interest and depreciation rates and lower energy or material costs. This leads to generation of data and models that are assumed to be accurate by the continuation of a trend. Yet, trends can quickly stop, slow down, intensify or reverse, creating actual events that diverge immensely from the forecasted path (Taleb, 2006).

Sources of benefits from transportation infrastructure projects come in the form of improvements in travel times, vehicle operating costs and safety. These, just like costs, can be quantified in monetary values based on travellers' wages, actual costs, and amount of travellers willing to pay for benefits. Furthermore, improvements in travel time can contribute indirectly in positive regional accessibility, land values, and economic development of the region, which are even more difficult to quantify as they usually cannot be directly proportionately to the direct benefits, which also involve future uncertainty. It is therefore important to take into consideration the addition of benefits to the economic appraisal criteria whenever a new investment is being considered, whether in the form of renewal or replacement. Since LCC does not consider benefits in the analysis, it is wise to include how benefits are being reduced/lost by limited asset availability; hereon after, these will be referred to as **user delay costs**. (See section 4.2)

Many techniques are in place for decision makers in order to deal with uncertainties regarding the future and the implications that the assumption of trends bring about leading to cost overruns, benefit shortfalls and underestimation of risks in infrastructure projects. To mention some: the Delphi method, Scenario Analysis, Reference Class Forecasting, etc.

Regardless of the method being used, the reliability and availability of the data, and the level of effort performed into the analysis of investment appraisals, there is always room for intentional and/or unintentional error in forecasting costs or revenues. It is up to the governance structure to better deal with these problems by rewarding more accurate estimates and punishing inaccurate ones.

3.2.1. Financing.

For proper assessment of project finance deals, it is essential to compose an investment plan which includes all costs required to complete a project, including operational/benefit losses during the start-up years, which are usually overlooked, or are accounted for, but in an overly optimistic way in order to emphasize on the benefits and have the project pass the business case test (European Commission, 2012). This brings about a question on the level of confidence that is expected from a cost estimations but not so much from benefits, given that these are more difficult to quantify.

It is argued that if projects costs would show the *real* figures in the initial development phases, not too many would get the appraisal from decision-makers, since, when it comes to numbers, most are concerned in getting projects funded and built, rather than getting the forecasts right from the beginning (B. Flyvbjerg, 2006).

As there is an inherent risk regarding financing in infrastructure projects, it is critical that partners and financers get involved to provide sufficient loans, without being fully dependent on future years internally generated cash. Partners provide equity and lenders provide loans. Depending on the size of the project (cost wise), the ratio of equity/loans is determined by the amount of risks involved. The higher the risks, the higher the rate: partners 40/lenders 50 and lower risks 20/80, respectively. Experience, operational and financial muscle of partners is crucial to mitigate risks. Infrastructure loans to the public sector usually have lower financing risks as the central or city government finances are backing up the project.

According to the European Commission (2012), in these transactions, it is important that the estimated finance costs during the start-up phase are taken into account and that at least 10% of capital expenditure is incorporated in the investment plan under a clearly specified contingency cost category.

In strategic planning, it is important for managers and policy-makers to have greatest possible flexibility for decision-making, currently and in the future. If future decisions are heavily influenced by several financial burdens, resulting from earlier imprudence or lack of attention during the development process, this flexibility will be less than optimum and may lead to project failure. It is also important to notice that once a decision has been made there should be some monitoring in order to evaluate and subsequently steer and control the effect of an investment decision thru the project's lifecycle, particularly the impacts that scope changes (which are common) can have during construction and in post implementation phases (Plenty et al., 1999).

Therefore, relying on LCCA outputs for any type of decision, whether budget allocation or selection of pavement material should take into consideration the limitations and reliability of estimates.

Furthermore, it was found that there are several other limitations regarding LCC in general, not only applied to the construction industry in which it has failed to overcome (Barringer & Weber, 1996):

Additional LCC limitations					
• It is not an exact science; answers are not either wrong or right, but reasonable or unreasonable.	 LCC outputs are only estimates, even when deterministic, and will never be more accurate than its inputs and/or intervals used. 				
 LCC models operate with limited cost databases and cost/effort of acquiring data is both difficult and expensive to obtain. 	 Cost models should be calibrated and carefully analyzed to be more accurate and thus, highly useful. 				
 Requires high volume of data to be accurate, and this data can even be unreliable. 	 LCC models developed by owner (agency) and by the supplier (contractor) have credibility gaps by the usage of different values and perceptions of risks. 				
 LCC results are not the best budgeting tools. They are useful only as a comparison/trade-off tools of capital expenditures. 	 The omission of some relevant data, due to vagueness of design/scope can lead to non- desired choice of alternatives. 				

Table 1. LCC Limitations

Also, it is important to mention that this appraisal tool fails to consider the evolution of the continuously evolving asset management concept and the extensive list of implications that these carry upon property ownership, this proves to be another limitation of LCCA, but then again, as do some other investment assessment tools. Also, these are limited to tangible and monetary benefits only and do not reflect the total value of capital expenditure choices.

3.3. LCC Benefits and Implications.

Having pointed out all the aforementioned limitations, whether applicable only to LCC or any other assessment tools, it is worth mentioning that these can be complimentary to each other and are not all-purpose type of tools and, as previously mentioned, have much room for improvement. Within the context of economic evaluation, and putting aside subjective environmental and social aspects, LCC provides to be a useful tool when it comes to evaluating amongst alternatives in a cost-effective manner.

In fact, according to Langdon (2007b) it is seen as the most reliable method for determining cost effectiveness of Public-Private Partnerships connecting it to the concept of Value for Money. Criteria for cost effectiveness is subjective and dependant on the decision maker doing the investment; however, regarding LCC, the one with the lowest NPV should be selected. It is important to mention though, that the lowest LCC alternative will not always be selected by default, this all depends on the client and its policy issues, perceived risk, funding availability, etc.

Regardless of its pitfalls, LCC-oriented tools may still be useful in practice if the decision makers are aware of the tool's inherent limitations. Plus, their participation in the LCC calculation process may contribute to learning effects, which in turn could increase their knowledge concerning economic dimensions. Still, the availability and reliability of the data used for the input of the LCC calculations must be verified and validated by a joint platform of the parties involved and affected by the ultimate decision.

Major construction clients have been calling for a better approach and integration of LCC analysis into their procurement activities in order to get their best value for money and maximize profit. Langdon (2007a) then argues that LCC typically yields the following benefits:

- Transparency of future operational costs
- Evaluation of alternatives, either for entire systems or sub-systems
- Ability to plan for future expenditure
- Improved awareness of total costs
- Ability to manipulate and optimise future costs

It has been established by now that anything regarding future activities is highly subjective, dependent on many external and internal factors, parties coming in and out of the process, along with the difficulty in monitoring, evaluating and steering decisions along the lifecycle process.

Yet, most of the Departments of Transportation in the United States have benefited from this useful tool by increasing communication between agency and industry representatives along the supply chain, leading to improved efficiency and roadway performance while at the same time helped transportation officials make informed decisions that can be presented and defended to the public, given its increased scrutiny (Clemons, 2011).

Only 6 States have failed to use LCCA and rip off the benefits of this tool in road infrastructure projects. Yet, there is much room for improvement as not all of them account for detailed costs and only in recent years they have been shifting away from deterministic approaches and into probabilistic ones to better incorporate uncertainties (Smith & Walls, 1998).

Public Sector Owners/Users	Commercial Investors/Developers		
 Demonstrate value for money procurement Minimize long term running costs Preserve asset value Predictability of future costs Ability to plan for future spend, e.g. sinking funds 	 Attract prospective tenants Preserve long term asset value Underpin funding mechanisms Calculate service charge levels 		

 Assess performance trade-offs against cost 			
Private Sector Users	PPP Contractors		
 Minimize operating costs Facilitate budgeting and forward planning Minimize disruption to business function Preserve asset value Satisfy leasehold requirements 	 Minimize operating costs Facilitate budgeting and forward planning Minimize disruption to business function Ability to plan for future spending Assess performance trade-offs against cost Satisfy contractual requirements 		

Table 2. Denenits of LCC (Languon, 2007b)	Table 2.	Benefits	of LCC	(Langdon,	2007b)
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Table 2 provides an overall view of the benefits of lifecycle costing as applicable to different entities. This also shows how it can be used in different ways affecting overall components of project assessment (Figure 4). For example, contractors would benefit on a technical and financial level mainly, as it is better to have profit by optimizing design, unless there is an incentive award by the sponsor to do so.

In a broader point of view, LCC can be used for the following purposes:

- An absolute analysis, when used to support the process of planning, budgeting and contracting for investment in infrastructure assets.
- As a comparative analysis, when used to undertake robust financial option appraisals (i.e. design approaches, alternative technologies, etc.)

One of the main objectives of LCC in DBFM type of contracts is to use and test tenders with an economically optimised structural solution. Tenders consist of initial design cost + initial building cost and maintenance costs. This aims to tackle the lack of transparency, an undesirable bargaining position and a tender process with increasingly stiff competition between contactors. Before the incorporation of LCC into PPP, contractors were not enticed to be inventive or innovative in realising cheaper or time and money consuming solutions. The political trends to decrease civil service and transfer of responsibility to the private sector have been important stimulus for this end. Not only it provides for a better opportunities for contractors to distinguish themselves, but also for them to gain from design optimisation strategies in maintenance programs, regardless of these being substantial against investment costs.

Still, it is noticeable to remark that construction industry has failed to embrace LCC mainly due to the following factors:

- Lack of universal methods and standard formats for calculating whole life costs.
- The difficulty in integration of operating and maintenance strategies at the design phase; with the latter depending usually on budget availability.

• The scale of the data collection exercise, data inconsistency options like direct estimation from known costs, historical data from typical applications (that perhaps did not have the expected outcome), models based on expected performance, used now but difficult to predict, best guesses of future trends in technology and professional skill judgement which can be subjective, as previously mentioned.

There are studies that reveal some problems of the application of LCC in construction projects, which have been categorized in: data, knowledge, procedure, management and cost. (Assaf, Al-Hammad, Jannadi, & Abu Saad, 2002)

These will be briefly described,

- Data, probably the most influential category. The input data will determine the output and its effects: "garbage in, garbage out". Whatever data is available from past projects might be from projects that didn't have a successful or expected outcome. Or it may be from an outdated data base which could not be reliable since there is no set standard method for collecting, recording and updating it. Literature reflects that there is a vast shortage of availability regarding maintenance and operation data.
- **Procedures.** The decision is said to be uncertain if it has several possible outcomes. Assumptions taken in LCCA are heavily influenced by the level of uncertainty which leads to an unreliable decision being made. In order to have integrity of the forecasting process, information should be expressed in terms of what could happen, what should happen and what did happen. This also proves to be a common pitfall as very little, if any, agencies have post-project risk assessment to record and evaluate their initial forecasts.
- Knowledge. Sometimes there is an unknown relationship between initial costs and future costs that leads to an inadequate decision being made as clients are unaware of the technique being used for LCCA.
- Management. Time and/or budget pressures on behalf of the client leading to unclear benefits of LCC and inadequate planning and control of management tasks at different stages of the LCCA.
- **Costs.** Conducting a LCCA can be very costly and time consuming; ripping the benefits of this is up to the client and is sometimes based on the level of effort and availability of collecting data. This should reflect the complexity and budget availability of the project.

This chapter placed LCC in a clearer context surrounded by social, environmental, political, economic, financial and technical aspects of infrastructure assessment. It also provided some explanations regarding its uses, applications, limitations, pitfalls, advantages and disadvantages when it comes to be used as an appraisal tool for decision makers. The following chapters will illustrate its methodology by placing important attention to the determination of uncertainties regarding future costs.

3.4. LCC Methodology.

As previously mentioned, LCC deals with all costs associated with a project's lifecycle, so the question is, which costs are to be incorporated in the calculations? The first part of this chapter will explain the LCC methodology and the determination of the most relevant and influential aspects affecting the analysis.

At this point it would be worth to establish that there are models in which LCC can be analyzed. These are:

- 1. Life cycle costs (expressed in €/year) over the lifecycle
- 2. Present value of the LCC (expressed in €)

This last approach will be taken for the analysis of the case in chapter 5. Some implications and conflicts (as well as useful insights) do arise from choosing one over the other and these will be revealed throughout the analysis.

After a project has been subject to feasibility studies in which the system is described and the main functions established to meet certain criteria, the economic criteria will be evaluated by CBA and LCC. Also, it is relevant to distinguish that the analysis should be provided by a system description: whether it is a preliminary analysis for strategic decision, detailed analysis for an entire asset or for component options. This will have an effect on the inputs such as: costs to be included, period of analysis, project and asset requirements, method of economic evaluation, risk and sensitivity analysis and sometimes the extent of environmental sustainability input. In general, the procedural steps for the latter can be summarized as follows:

- 1. Establish the analysis, whether absolute or comparative, and its period. Here, the system is identified, described and the design alternatives to be compared are analyzed. Remember that competing alternatives are assumed to have the same benefits and thus, excluded from calculations and forecasts. The analysis period should be long enough to reflect longterm cost differences with design strategies and include at least one major rehabilitation program.
- 2. Determine activity timing and performance periods. This has a big effect on both agency and user costs, as rehabilitation activities can constitute a substantial part of the LCCA (depending on the analysis period). These are usually based on past practices, theory, company's policies and budget availability, notice that there is already some uncertainty being incorporated at this stage.
- 3. Estimate agency costs. These are associated with quantities and costs directly paid by the company sponsoring the project, which include, but are not limited to: preliminary engineering, contract administration, acquisition, initial construction or rehabilitation, use, maintenance and

operating costs plus a salvage or residual value (usually taken to be a negative cost).

4. Estimate user costs. These are not borne by the agency, so they are not considered as out-of-pocket costs and literature has shown that they are more difficult to determine, but should enhance the validity of results. In transportation infrastructure projects they can be determined by calculating vehicle operating costs (VOC), travel time/user delay costs and crash costs. These rely on statistical data based on drivers' salary, time delays and by current and future roadway operating characteristics which, by now, literature and professional's opinions have shown to be very challenging to forecast. See Section 4.2 for more details.

Factors that affect the LCCA:

• Price adjustments (indexing)

Used to limit contractors' exposure to price fluctuations and shift the risk from the supplier to the employer, maybe does not apply to DBFM contracts.

Material quantity specification

Affecting mostly short-term costs. However, material quality may pose a large impact in long-term costs.

• Rehabilitation schedules (See Section 3.6 for more details on Maintenenace Theory)

Technology changes over time, so does accepted level of performance of the system.

• Discount rates /inflation rates Wrongly assumed inflation rates have a large impact on future expenditures and available funding. Adjusting these could be important. (See item 7 below)

5. Perform qualitative and quantitative analyses. There are several ways of modelling a LCC computation. A deterministic approach includes no variance in the cost inputs, which assumes no uncertainty in the forecasts. As research has shown, this assumption is too difficult, if not impossible, to be hold true. Therefore, in order to account for uncertainty, a probabilistic approach would prove to be more realistic explaining why more agencies nowadays, are shifting from the former to the latter type of approach (Clemons, 2011). The application of this stochastic approach, however, still remains a challenge and will be discussed on the next chapter.

- 6. Develop expenditure stream diagrams. These are graphical representations that aid visualizing cost expenditures along the life cycle of a project for each alternative. With the assumption that benefits are the same for each of these, the only concerns are differential cost values and the negative cost associated with the salvage value, if any.
- 7. Compute net present value. Using the discount rate (interest rate), the future costs will be converted to present value (See Appendix A for formulas applied for these calculations). It is important to distinguish real vs. nominal discount rates which include inflation rate as this can have a significant influence on the result. Good practice in LCCA calls for using real euros, which have a constant purchasing power over time and real discount rates (Smith & Walls, 1998). However, inflation of materials can have a big impact when choosing amongst alternatives and thus, the difference of the general inflation rate and the commodities inflation rate to the year of the activity should be escalated and then discounted back using real discount rates. Also, risk-free or risk-adjusted can be of influence, these two will be discussed in Chapter 4.
- 8. Analyse results. A thorough sensitivity analysis should be carried in order to determine the influence of different input assumptions, projections and estimates of the LCCA. These could include discount rate, user costs, agency costs, and risk exposure in order for the analyst to provide recommendations based on the output.
- 9. Re-evaluate design strategy. This should be an iterative process requiring verification and validation in order for the analysis to be comprehensive while evaluating all alternatives and as more information becomes available thru preliminary design or subsequent phases.

Having had this brief overview, both experienced professionals and literature show that the biggest challenge in LCCA lies in forecasting long term costs while incorporating risks and uncertainties in these forecasts. This process will be described in the next section.

3.5. Risk Management Principles.

There are several definitions of the concept of risk, for simplicity purposes and its application to LCCA, it will be defined as the probability times the consequence of an event, either positive or negative, and measured in a cost dimension.

"Although careful risk assessment typically results in an increase in initial cost estimate, it usually leads to a reduction in contingency" (European Commission, 2012). Literature shows that, if implemented correctly, risk management measures are worthwhile because they can lead to a more certain final project cost. Often it is not clear what is actually contained within a project's contingency budget, however, careful risk management yields a contingency allowance for larger projects that should cover three main types of contingency:

- Special risks contingency an allowance to cover the risks arising from higher land acquisition costs, changes in external factors such as the availability of funds, statutory requirements and force majeure. It can also cover the risk of a project sponsor changing his mind about the project specification, a fairly common occurrence.
- **Design contingency** an allowance for use during the technical design process to provide for the risks of changes due to design development or in estimating data.
- **Construction contingency** an allowance for use during the construction process to provide for the risk of changes due to site conditions or as a result of changed construction methods or poor performance by contractors or sub-contractors.

These three can be the most detrimental if not treated with enough importance; still, post-implementation contingency has been gaining importance as it can also prove to be a big source of risk if not considered in the previous phases.

Figure 5 below illustrates some of the main components stemming from life-cycle costing analysis and how the incorporation of risk management principles and its practice can generate different outcomes in the decision-making process.

The decisions should be based solely on cost drivers identified during the LCCA. For example the adequate discount rate, a (sub) system component, a major risk during construction or exploitation, etc. However, the main decision to undertake the project or not can be derived from the analysis as it can yield costs that are too high in relation to benefits, once again bringing up the importance of their inclusion for project appraisals.

This can establish some solid grounds for an asset management program in which most critical risks and uncertainties have been identified and their consequences assessed, to the extent of what information is available depending on project phasing.

It is important to maximize investment efforts by evaluating whole life alternatives under uncertainty; this can be achieved by incorporating risk management techniques. However, this fails to provide a robust approach since it is based on mysterious statistical data that the analyst is subjectively imputing and the end user may or may not have.



Figure 5. Components of LCCA

It is therefore suggested that a clear understanding is established from the beginning and made available to all stakeholders involved. The following steps are suggested,

- 1. System description
 - where is the project located?
 - what does the project comprise?
 - what are the project promises?
 - is the project dependent on any other projects?
 - who is undertaking the project and over what time span?
 - Costs
 - Benefits
- 2. Risk identification, a qualitative analysis in order to assess, qualify and categorize risks in order to estimate their effects. This process, ideally, provides an opportunity for all stakeholders and contracting parties to work together and manage project risk for their collective benefit.

- 3. Risk analysis, a quantitative approach in order to determine impacts and probabilities; this can be either deterministic or probabilistic analysis based on:
 - Size of project
 - Available data and resources
 - Computational aids and skills

Some concepts of probability theory should be incorporated at this stage.

Touran (1993) has shown that the expression amongst cost components modelled as random variables in a probabilistic cost estimating model can be arduous and often impossible to carry out given the lack of familiarity of the estimator and probabilistic concepts. Therefore, all variables are regarded as independent in most cases. What governs the reliability of the output is the reliability of the data input. If very little is known about this data, the uncertainties are highly subjective and the risks even greater. The analysis will yield a result that seems to be reasonable within a specific range and with a certain level of confidence, but this will **only be proven with the actual costs incurred after the project's completion**, when it is already too late and post-project (cost and risk) evaluations are often ignored.

When assigning probability distributions to cost parameters to create stochastic assumptions of LCCA inputs, it is critical that errors be minimized by assigning correct values and selecting an adequate distribution.

It is suggested that if there is relevant data available, it could provide a specific distribution based on one of the following approaches: a trace driven simulation, an empirical distribution or a theoretical distribution function (Boussabaine & Kirkham, 2004). However, in the case of construction processes, simulations relying on these data have not yet emerged from the research to practice due to the lack of reliable data or confidence in the selection of the right probability density function (PDF). With this premise, the following continuous PDF's are commonly found in literature:

- Triangular Distribution
- Normal Distribution
- Lognormal Distribution
- Beta Distribution
- Gamma Distribution
- Pareto Distribution
- Uniform Distribution
- Weibull Distribution
- Exponential Distribution
The following table illustrates a summarized overview of the most used probability distributions.

Distribution Type	Application	Limitations
Triangular	Easy to define	Parameters
	parameters if no	estimation is time
	historical data is	consuming
	available. Generally	
	used by experts	
	using LTU values	
Normal	Could be used for	Symmetrical and
	cost estimation if it	open-ended
	can be truncated	
Lognormal	Skewed and	Might give higher
	bounded at 0, could	estimates on high
	be used for cost	confidence level
	estimating	
Uniform	The simplest form,	No knowledge about
	not too much data	the concentration of
	required	values
Beta	Might give bimodal	Might give higher
	distributions which	estimates on high
	are not suitable for	confidence level
	cost estimation	
Gamma	Skewed and	Might give higher
	bounded at 0, could	estimates on high
	be used for cost	confidence level
	estimation	

Table 3. Summary of Probability Distributions (Evrenosoglu, 2010)

Notice that the triangular distribution, according to this source, is said to be time consuming, yet it is **the most common for modelling expert's opinions**.

For all these, two major problems are posed:

- Identifying the underlying statistical distributions for cost items
- Recognizing existing correlations

A histogram of the data must be constructed in order to determine the distribution type, and then perform a goodness of fit to be able to evaluate the assumption. There are three methods that can be employed for this approach: Kolmogorov, Chi-square and Anderson-Darling.

Furthermore, an important output of either a Monte Carlo or Latin hypercube simulation is a sensitivity analysis. In LCCA, this is carried out to determine the economic impact resulting from alternative values of uncertain variables that affect the economics of a certain project's lifecycle phase.

4. Risk responses, the analyst should provide the most effective manner of handling the risk concerned, based on the output of the analysis.

Theory and practice usually refer to four types of action regarding responses to risks: take, treat, transfer and terminate. All these based on several factors that are project-specific, such as data accessibility, complexity, level of effort, budget availability, etc.

Just like uncertainties, these responses can also change from phase to phase as risks firing can have severe consequences on the LCC of an asset. Therefore, it should also be an iterative process as shown:



Figure 6. Systematic project risk management process

Where possible, the analyst should make recommendations to try and optimise risk responses while aware that best possible responses may incur on higher costs. Responses must be clearly defined and allocated so that it is possible to track their effectiveness; this is still a major pitfall in construction industry, as post-evaluation risk management plans are not strongly enforced by most agencies. Still, given that sometimes it is impossible to assess effectiveness, the focus should rely mostly on how risks are identified and managed.

- 5. Risk management plan. Although it is impossible to foresee all risks associated with costs and even if these are foreseen, predicting their impact also proves to be difficult, it is important for the project manager to be prepared if these risks were to occur. Keeping always in mind the dynamics of costs and uncertainties, important choices should be made by the sponsor regarding: who takes the risk (usually the party who is better able to deal with it), forms of contract, clauses, penalties, etc. Risk management is a matter for all layers within an organisation and, moreover, amongst all parties involved (Gemeentewerken Rotterdam et al., 1992). Other than supporting optimal decisions, it should generate awareness within the team and relevant stakeholders, creating support and involvement. However, modern decision theory implies the following about the decision-maker (CUR-publicatie 190, 1997):
 - Has complete information about the decision situation

- Knows all the alternatives
- Knows the existing situation
- Knows which advantages and disadvantages each alternative provides, in the form of random variables
- Strives to maximise that advantage

Given that literature regarding LCCA and uncertainties thus far has shown that these implications are not possible, the concept of bounded rationality should be mentioned. It states that, in decision-making, *rationality of individuals is limited by the information they have, the cognitive limitations of their minds and the time allocated to take a decision*. This concept should provide a framework for the analyst, as it has been shown so far, it is impossible to analyse all alternatives (some of which might be unknown), incorporate uncertainties based on data (which might be incorrect), and is subject to a time frame in which a specific decision has to be agreed upon by several parties.

6. Risk monitoring and feedback. As mentioned earlier, risks might be changing constantly thru a project's lifecycle; therefore, it is important that these are reviewed and updated on a timely basis. This is often difficult and rarely implemented in practice as resources tend to be scarce for this purpose, or not enough importance is placed in having post-implementation risk evaluations. Be that as it may, some organizations within the supply chain place more importance than others when it comes to recording data for future benchmarking and evaluating both costs and risks. Yet, this still remains a challenge, as there is little available data on actual costs, as opposed to material prices, limited reliable information on maintenance and operational strategies, and a lack of structured procedure to measure effectiveness. This, however, remains beyond the scope of this research.

Because individuals' perceptions of risk vary, decisions incorporating risk management concepts in LCC will depend largely on the decision maker's tolerance for risk.

3.6.Maintenance theory.

Maintenance strategies are largely governed by the type of asset being subject to these and its complexity due to its sub-components. It is argued that maintenance theory gives the benefit of cost optimisation strategies using theoretical tools of reliability and deterioration models. This does not come without a limitation given its restricted theoretical applicability and, as mentioned before, the fact that economic factors remain aside. However, practice differs much from theory, as agencies do rely on most things being theoretical at the moment of decision making, but when the time comes for that first planned maintenance, it is highly dependent on many other factors, such as economic, political, organizational, etc. Main reasons for maintenance include:

- 1. keeping the structure and the technical installations in a state that they continue to function properly;
- 2. the prescribed lifespan is not deleteriously affected;
- 3. the appearance remains unchanged (not including normal wear and tear, contamination and discolouration between maintenance sessions);
- 4. structure and technical equipment provide no increased danger to the surroundings;
- 5. maintenance takes public interest into account;
- 6. maintenance must be carried out in such a way that it is cost effective and the periods of unavailability are minimised;
- 7. where necessary maintenance will be modified so that it is always carried out as efficiently as possible, whereby account is taken of the statutory provisions regarding safe working.

"A chain is only as strong as its weakest link"; meaning that a single-component failure can lead to a complete system failure, thus, maintenance is also governed by the probability of failure. Generally speaking, there are two types of maintenance: corrective and preventive, the former excludes inspections as it assumes failure has already taken place, provided the consequence of failure is acceptable and does not carry large impacts, these should be predetermined by the asset owner.

Different sorts of analyses and simulations can offer insights to failure probability based on assumptions and stochastic data. For example, even though a Monte Carlo outcome is stochastic with a mean and standard, the coefficient of variation decreases with more iterations and is conversely proportional to the probability of failure. The results, theoretical as they may be, provide for a robust analysis that yields data surrounding failure probability and the many implications or decisions that this might carry.

Slijkhuis (1996) showed that economic optimisation of a structure can be driven by determining the probability of failure. This can be done by incorporating uncertainties such as data that leads to failure, in this case by the overtopping of a dike, construction costs and failure costs, which are difficult to quantify. Roughly speaking, these costs are the initial costs, the costs of modifying the dike in order to avoid failure, and the damage costs (discounted). It was also shown that the **incorporation of statistical uncertainty leads to all these costs increasing**, and even though the probability of failure is aimed to be reduced, the costs for doing so were **quite high**. Furthermore, the only failure mode was taken to be a flood event, but there are several mechanisms that can lead to system failure.

In transportation infrastructure projects this is not easy to do as it could range from several potholes in a certain area to a bridge collapsing. These failure modes, as mentioned earlier, should be established by what is and what is not acceptable by the

owner regarding the asset (governed by safety) and is subject to a level of risk aversion, and many other issues.

Indeed, there is a growing need for optimisation strategies and deterioration predictions; these can be in the form of statistical models in which time is taken into account, such as Markov, Gaussian and/or Poisson processes. These models offer a theoretical framework that ideally would provide for an analytical decision making process. Regardless of the model provided, there is still a challenging aspect regarding maintenance optimization. The time to reach a deficient condition is uncertain and varies from asset to asset depending on many factors, such as material quality, geographical location (effect of wind, rain and temperature), workmanship, traffic density and many others. A Markov process has the property of the future state of the process being independent of the past given the present state. Using Markov processes for maintenance optimisation in bridge infrastructure in the Netherlands, Kallen argues that the validity of this assumption is highly questionable by the experts given that in the context of Maximum Likelihood estimation, there is no 'true' model (Kallen, 2007). Furthermore, given the fact that the primary uncertainty in the optimization of maintenance activities is the deterioration rate of structures, it is not possible to acquire complete information and provide a true model that predicts lifetime of structures.

With these in mind, it can be concluded that determining the probability of failure is also very difficult to predict since it is highly dependent on the asset being analysed and by what exactly is the accepted level of performance before leading to failure.

However, some agencies prefer to avoid failure, but it depends on several aspects, such as budget and time availability for inspections, predictability of deterioration subject to time, location, usage and loadings (CUR-publicatie 190, 1997). Most agencies rely on inspecting and repairing techniques, but nowadays, with the increase use of technology such as BIM, asset management for post-implementation phases will be easier given data accessibility for certain components that would lead to cost-effective solutions. However, both data availability and use of BIM in transportation infrastructure projects still pose big challenges and much room for development. It is gaining popularity worldwide and it is speculated that by 2016, all publicly funded projects in the United States should be BIM compliant (2012) and try to rip off one of its most valuable tools: increased communication across the entire project team. In the Netherlands, there is a standard called NEN 2767, which provides a method to assess the condition of a building and the system components in an objective and unambiguous way. Its applicability is intended for all types of buildings and structures, but is still not widespread nationwide.

Several aspects are found to have a big effect on lifecycle costing when it comes to maintenance activities.

First, it is important to determine how user delays are affecting the LCCA within the maintenance activities. Some literature suggests that these have the potential of

exceeding actual construction costs. Thus, any initial savings that occur from selection of a specific material or sub-system with a lower life expectancy has to be evaluated against subsequent replacement **and** user delays, as these may rapidly exceed the former.

Then, the incorporation of maintenance strategies into the design phase can prove to be beneficial to reducing long-term costs. Research has shown that the following factors can have an impact on post-implementation phases:

- insufficient involvement in engineering
- inadequate supervision during construction
- no attention to long-term maintenance strategy
- a lot of money needed for repairs afterwards (at emergency rates)

"If it isn't broken, don't fix it". In public projects, this expression is found to be a common public approach towards asset preservation, all have to understand the cost-effectiveness and the return on investment from such intervention, instead of when the deficiencies are evident.

In general, the application of LCCA to maintenance and/or operational stages is not found to be widespread. Whether it is due to the fact that it does not account for a large percentage of costs in projects' lifecycles, or the fact that agencies do not rely heavily on these forecasts when it comes to decision making, professionals, practice and theories have supporting and contradicting viewpoints. However, one of the most significant drivers behind the desire to develop methodologies for these, is the Public-Private Partnership contract in order to distribute risks more adequately to the private sector. Yet, the concept (or strategy) is just starting to grow in importance as normal practices thus far have been limited by the tedious, hard and neglected benefits of data collection by the agencies, their rather practical, informal and budget dependent practices, and the time lag between efforts and benefits from the implementation of models, processes and strategies regarding maintenance of infrastructure.

3.7. Decision Making and Asset Management.

Being able to align agency programs and projects to predetermined goals and policies is difficult for some reasons. First, as mentioned before, analytical tools, models and software do provide aid towards informed decision-making, but are subject to technical constraints related to data inputs, assumptions, and theoretical understanding on behalf of all decision makers. Second, practical realities are on a constant dynamic process in relation to institutional considerations, social objectives and political goals. And last, planning, programming and assessment in general, may rely on antiquated data systems, unstructured management systems and limited communication channels, particularly amongst the horizontal lines.

The MIRT process developed by RWS (Figure 7) defines a framework with clear rules, decision points, related documents and products required at each stage.



Figure 7. MIRT Process (Bakker, Schavemaker, & ten Cate, 2010)

The phases described are representative for Design and Build type of contracts, these are found to be the mostly used by RWS, along with Financing, Maintaining and Operating.

- Bidding is considered as a parallel step before construction
- **Exploitation/Implementation** precedes Maintenance phase and also runs in parallel to these
- Disposal/Removal occurs at the end of the asset's life cycle

Promising alternatives for project appraisals are evaluated based on a CBA and then the most realistic alternative is priced in detail. This is then submited to the House of Commons for approval. If it is approved by a governmental decision, it will then go to a more detailed analysis in the planning phase before being called out for tendering.

The influence of LCC during this decision-making process will be discussed further in the next chapter.



Figure 8. Level of Assets

Figure 8 illustrates the influence of lifecycle as the basis towards corporate management thru the different levels of asset management, which reinforces the challenges and opportunities reflected upon thus far.

Many transportation agencies are currently relying on a standard known as the PAS 55 which provides a guideline for correct asset management practices and covers many of the aspects discussed until now. Mainly the procedures for the implementation of asset management plans regarding the influence of LCC activities should (British Standards Institution, 2008):

- be sufficient to ensure that operations and activities are carried out under specified conditions,
- be consistent with the asset management policy, strategy and objectives,
- ensure that costs, risks and asset system performance are controlled across the asset life cycle phases.

Risk management practices have been gaining importance as an integral part of asset management programs. Organizations should ensure that results and recommendations of risk assessments and the effects of risk control measures are given thoughtful considerations. Moreover, while conducting a LCCA, it is possible to identify, even on a broad basis, risks and uncertainties that will unfold during the asset's lifecycle. It can provide valuable information that saves time (and money) during the MIRT process.

As far as risk management practices are concerned, it should provide input to:

- the asset management strategy,
- the asset management objectives,
- the identification of adequate resources including staffing levels,
- the identification of training and competency needs,
- the determination of controls for assets' life cycle activities,
- the organization's overall risk management framework.

It is clear that an LCCA will not yield a full risk management program for a given asset, but it can provide for a good qualitative (mainly) and quantitative contribution towards it. The biggest challenge remains in monitoring it, and updating it constantly if it were to benefit and have an impact on asset management throughout the entire lifecycle. This differs much from standard practices as it requires efficient use and cost effective implementation of plans.

Literature and some interviews with industry professionals at DHV, agree that decision makers are faced with practical realities that interfere with objective and analytically based decisions. Also, resource allocation and project selection is highly dependent on budget availability, institutional considerations, social objectives and political goals (U.S. Department of Transportation, 1999).

Committing available funds to long term periods is very difficult given that the short budget cycle and the uncertain future of funding levels. These create pressure to selecting alternatives that may have, or lead to, conflicts of interest between costeffective vs. politically practical solutions.

Different solutions to meeting the business need could result in significantly different cost profiles and contract forms and durations; appraisal of alternatives should be flexible to compare different kinds of approaches, and at the same time reflect a significant difference/impact of choosing one alternative over another. If differences are minimal, then it should not be worth the effort spending too much time and costs in taking a decision. Engagement with the integrated project team at the earliest possible stages allows the parties to work together to identify risks/problems and resolve them. One of the most important aspects when considering LCC is how it will affect the core business operations that will take place in, on or around it. There has to be a clear understanding of what the business operations are, how they are intended to be, and how the decisions will shape these.

In many organizations, there will be more potential tasks to carry out than resources, time or budgets will allow for. The continuous optimization and prioritization of tasks and plans are a way of life for such organizations.

There are numerous tools and methodologies associated with asset management as it has been shown so far, and one of these is LCC. It is essential for organizations along the supply chain of a project's lifecycle to recognize that good asset management with the incorporation of all of the above concepts, practices and implications, cannot be achieved thru the use of one-and-only exclusive tool, or let alone, by these tools alone, since they are not all encompassing, controlling and problem-solving. These are tools that professionals can use, complementary to each other, to make more informed and analytical decision making, supported by experience, collective thinking and common sense.

It can be agreed that better decisions can come from access to more complete information, thus accounting for uncertainty and risks in a project's lifecycle will improve decision making within the context of bounded rationality. Still, there is not a "single best" technique or tool for handling these when evaluating infrastructure appraisal. This is highly dependent on the circumstances around the asset in question and the organization making a decision.

4. Chapter 4. Risk Based LCC Model.

Taking long-term economical implications is most critical during the initial and conceptual phases, as LCC's influence is then reduced with subsequent project phasing (see Figure 9). This figure is taken in accordance to each phase established by the MIRT process shown in Figure 7.

Therefore, it is highly important to take into account as many details as possible regarding different LCC components in order to be able to assess with more confidence appraisal of infrastructure projects.



Figure 9. LCC influence in project phasing

It is worth noticing that exploitation precedes M&R phase, but it is not explicitly mentioned in the MIRT process as it runs parallel to phase 6. The same goes for removal/disposal.

The problem arises due to the fact that the largest influence takes place where LCC estimates are rougher because many variables (such as materials and design details) are yet to be determined. However, the level of accuracy should be such that if provides distinction in two parameters (Bakker et al., 2010):

- estimates should be able to differentiate amongst alternatives, and
- estimates should be sufficiently reliable to be used for budgeting.

Also, the boundary conditions for investment and exploitation cost should fit within budget constraints for each of these: some alternatives with the lowest LCC might not meet any of these requirements. If there is enough budget for investment costs, but not enough for exploitations, the risk incurred on the new infrastructure is that it might not meet the expected level of performance intended during design, hence the importance of looking at long-term costs.

As each of these project phases evolves, the level of details incurred in the LCC should be more robust (and probably higher in NPV), however, three relevant decision parameters should be constantly revised for the evaluated alternatives:

- 1. construction costs (within construction budget)
- 2. expected annual exploitation costs (within maintenance budget)
- 3. net present value over the life cycle (to determine the most economical favorable option)

Phases 1, 2 and 3 show in Figure 9 depict the importance of better LCCAs in each decision being made along the MIRT process. As it is normal that the design and scope of project become clearer at each gate review, the incorporation of more relevant data would be further enhanced and increase robustness of results.

As it has been shown in the previous chapter, good LCC practices call for including the following input variables into the calculations. These might change depending on the level of accuracy demanded by the organisation, the size of the investment, time constraints, etc.

LCC Component	Input Variable	Source
	Construction Costs	Estimate
	Maintenance	Assumption
Investment and Future	Operation	Estimate
Costs	Risks (during construction and exploitation)	Estimate
	Renew or Replace	Estimate
	Residual	Assumption
	See Time Period of	Projection
Timing of Costs	Analysis	
	Frequency of Maint.	Assumption
	Current Traffic	Estimate
	Future Traffic	Projection
User Costs	Value of Time	Assumption
(lost benefits)	Type of Vehicle	Estimate
	Work Zone Area	Assumption
	Work Zone Duration	Assumption

Table 4. LCC Input Variables

Note: user costs are not costs incurred on the agency, but expenses on society

1. Investment Costs.

These are associated by all costs incurred by the agency over the life of the project. These typically include preliminary engineering, planning, design, purchase, contract administration, construction supervision and construction costs.

2. Maintenance Costs.

Routine and preventive type annual maintenance costs have only a marginal effect on NPV in comparison to initial construction and rehabilitation costs. Furthermore, they are very hard to obtain and differentials amongst competing alternatives are rather small, particularly when discounted over a 50 or more year analysis period.

On the other hand, corrective maintenance weighs more heavily on the analysis as it involves replacement of the system or a sub-system(s), depending on the impact that these have on the overall asset. Maintenance costs are drivers in agency costs and user costs, the latter will be discussed further below.

3. Operational Costs.

Also carried upon by the agency, at least in infrastructure projects. In a tunnel it includes lights, energy pump stations, ventilation, safety systems, and other technical installations.

4. Replacement Costs (risk of failure during exploitation).

Stemming from maintenance costs, but in this case it would be considered as one individual cost as it has larger effects than routine maintenance, see Equation 1.

5. Risk Costs / Insurance.

According to the LCC framework developed by RWS DVS (2011), there should be a substantiated (and wherever possible quantified) risk profile, which includes the calculated variance and bandwidth. These are done in detail for short-term costs (investment) but not so for long-term costs.

6. Residual value (salvage or disposal).

This represents the value of the investment alternative at the end of the analysis period. It should be based on the remaining life of an alternative at the end of the analysis period as a prorated share of the last rehabilitation cost. Disposal costs are associated with the costs of removing the object, some of which may not be easily quantifiable, i.e. environmental. As far as public infrastructure projects in the Netherlands are concerned, there are no salvage values like in other industries, so these will be disregarded (as is also suggested by the LCC methodology by RWS).

LCCA, in general (see literature study), does not include risk and uncertainties during implementation as determining these is still somewhat vague and subjective, depending on the availability of historical data on certain cost items. Furthermore, user costs due to unavailability are not always included, but as mentioned before, incorporating these would validate results and should be incorporated in the decision making process.

As LCCs methodologies can vary from organization to organization and industry to industry, it is important to mention that the current methodology as per RWS standards calls for a Net Present Value calculation (see Appendix A for relevant formulas), yielding a \in (euro) unit, and not a \notin /year. However, the two give insightful results. The first result shows which is the most cost-effective alternative (lowest NPV), however, when developing cash streams, the \notin /year approach is taken, in order to show clearly what the future costs look like and thus, serve as a basis for budget allocation.

This model proposes the incorporation of the aforementioned user delay costs for a different bearer (not the agency) and incurred risks to selected alternatives by including the probability of failure. This would be calculated as an expected monetary amount. Since predicting its timing is impossible, this cost item should be based on the annual equivalent failure probability (see Equation 5) dependant on the parameters to be considered as failure drivers. The assumption behind this equation is that failure rate is constant over the lifetime.

Equation 1 shows the proposed formula for calculating the NPV at time zero. Each item is described in the equations to follow.

$$LCC (\epsilon) = C_{INV} + C_{RES} + \sum [PV (C_{O\&M}) + PV (C_{RISK})]$$
 Equation 1

where,

 C_{INV} = investment costs C_{RES} = present value of residual/disposal costs $PV(C_{O&M})$ = present value of operation and maintenance costs $PV(C_{RISK})$ = present value of the cost of failure

All these costs should be of **probabilistic nature** in order to account for uncertainties around these figures. The importance of this approach was mentioned during the introduction of this report in order to make more accurate or reasonable forecasts that account for some uncertainties. It is possible that some stakeholders seize upon these in order to contest validity of results. A **deterministic approach** can generate endless debate over which alternative truly reflects the lowest life cycle costs. Nonetheless, a deterministic will be determined and then evaluated in chapter 5 against a probabilistic one.

The latter will be carried only in price and quantity figures for all cost items included in the LCC. These variables, such as the uncertainties in investment cost items and risks,

have triangular probability distribution functions as they are the most common for modelling expert opinion or there is lack of data to do otherwise. Other types of sensitivity analyses will be conducted for other sources of uncertainty.

However, a deterministic approach will be also conducted in order to measure how these figures differ, and furthermore, how these could impact the decision-making process.

In other cases, such as data for the maintenance cost item inputs, relies on historical data obtained from normal distribution curves. These, however, do not seem to be as accurate as one would like them to be, as interviews and research (see literature study, maintenance theory chapter) has shown that data gathering in the field is not well structured, and furthermore, not provided or openly shared by contractors performing these maintenance activities.

The investment costs can be summarized as:

$$C_{INV} = C_{DES} + C_{CSV} + C_{CON} + C_{IND} + C_{RISKS}$$
Equation 2

where,	C_{DES}	= cost of design/engineering
	C _{CSV}	= supervision cost of design and construction
	C _{CON}	= construction costs
	C _{IND}	= other indirect costs
	C _{RISKS}	= cost of risks during construction

The long term costs associated with operational and maintenance activities can be described with the following formula:

$$C_{O\&M} = C_{MAI} + C_{REH} + C_{ROU} + C_{RISKS}$$
 Equation 3

where,	C_{MAI}	= maintenance costs
	C _{REH}	= cost of rehabilitation
	C _{ROU}	= routine inspection/safety costs
	C _{RISKS}	= cost of risks during exploitation and maintenance

Then, the risk can be calculated as follows:

$$Risk = C_{FAIL} = P_f * [C_{REC} + C_{UD}]$$

where,	P_f	= probability of failure	
	C_{REC}	= reconstruction costs	
	C_{UD}	= user delay costs	
and		$P_{FAIL*AN} = 1 - (1 - P_{FAIL*LC})^{1/L}$	Equation 5
where,	P _{FAIL*AN}	= equivalent failure probability	
	P _{FAIL*LC}	= failure probability of life cycle	
	L	= life cycle period	

After having described all these parameters, it is important to mention and include in the analyses what has been identified to be the largest sources of uncertainty and critical inputs into the LCCA.

4.1. Time period of analysis

In LCC, it is important to define the constraints of the alternative to be evaluated, these can be physical, functional, safety-related, budgetary, etc. Also, when setting the time period, making sure that all alternatives are subject to the same one, more about this restriction will be explained in the discussion section.

This is dependent on factors such as technical and economic lifetime, and other obsolescence factors such as functional, legislative, political, etc.

In theory, an LCC calculation can be derived into an endless stream of cash flows but for practical purposes, current practices call for a 100 year time frame based on the expected technical lifetime (Rijkswaterstaat DVS, 2011). If uncertainty were to be reduced, it would make sense to reduce the time period of analysis. This would also create awareness to decision-makers as to what could be considered the leading factors towards the end of an infrastructure's lifecycle, other than its technical lifetime.

During the literature study and a deeper analysis of this main driver, it has been concluded that the economic lifetime is usually shorter than the technical one, and furthermore, the real economic lifetime can be shorter than the expected one.

Within this context, the general principles for selecting the analysis period are:

- Timeframe should be set equal for all alternatives.
- Timeframe should be long enough to capture majority of the benefits, but not so long as to exceed capabilities to develop good traffic information. RWS uses a traffic forecasting model called Nieuw Regionaal Model (NRM) in which predictions can be made about traffic-use based on the aforementioned WLO scenarios (ranging from positive to negative) to account for uncertainties,

demographic shifts and others. These predictions are subject to 10-year time periods of analysis.

• Timeframe should be consistent with that used for other analyses being considered as input for the project's appraisal, such as traffic forecasts and lifecycle costing models.

Benefits in infrastructure projects are dependent on traffic and demographic information, which is very unclear exceeding a 20-year timeframe due to demand ('revenue') uncertainties. Also, due to the effect of time value of money, most of the benefits from these type of projects are said to come within the first 10 years of implementation (E. van Zwet, personal communication, June 12th, 2012). Furthermore, and also because of this concept, after 50 years of maintaining the asset, the costs incurred are very little (see Figure 10) and provide no critical/valuable information to decision-makers.

4.1.1. NPV approach

Project-related costs occurring at **different points in time** must be discounted to their **present value** as of the base date before they can be combined into an LCC estimate for that project. The choice of discount rate used for the analysis should be based on the investor's time-value of money. In private sector, this differs much from public, as the investor's (contractors) discount rate is usually determined by the investor's minimum acceptable rate of return for investments of equivalent risk and duration. Throughout the course of this project, it will be shown what type of rates should be chosen, and how these may affect project alternatives, parties and decisions.

The advantage of using this approach is that it can account not only for annually recurring amounts, but also for **activities that occur in the future**¹ and could pose a significant influence on the NPV and thus, the choice of alternative. Still, using a lengthy period of analysis, such as a technical lifetime of 100 years is filled with uncertainty and irrelevant cost figures.

To better illustrate this, an example of taking the first approach of LCCA (with the use of NPV) is provided below. This is only done to illustrate how the difference from using the first approach can be put into contrast with the second one (see Figure 11). This example also aims to show the effect and little influence that future cash flows have on the total cost after a certain period of time.

It is important to note that for the proposed methodology and application of it to the case study, future costs are estimated in **constant dollars** and with the use of **real discount rates** (**excluding** inflation). This leads to the implication that inflation is equal to all alternatives.

¹ See equation 10 on Appendix B



Figure 10. Cash Flow vs Time

Having seen this figure, one can deduct that it is highly debatable that a 100-year analysis will provide for accurate information to decision-makers since it leads to more room for uncertainty and it is highly likely to exceed other factors that could lead to the asset rendering obsolete.

4.1.2. Cost/year approach

This approach takes into account the effect of interest and depreciation (and therefore salvage value too). The conflict between choosing one approach over the other will be briefly discussed in the following paragraphs, and will be further evaluated for the specific case in chapter 5.

It was mentioned that the time value of money plays an important role on long-term costs. According to the literature study and some professionals, the influence that the discount rate has also been mentioned to be highly volatile.

Simply put, the higher the discount rate, the lower the NPV (see Appendix A for relevant formulas). When a CBA is conducted, the alternative with the highest NPV (Net Present Benefits - Net Present Costs) is generally chosen amongst the others. In this case, a higher discount rate is intended to take into account some risk factors, meaning, if the project involves more uncertainty (i.e. inflation) or other risks, adding 3% to a nominal discount rate, will take into account for these events, thus reducing the NPV. In economic theory this is known as risk-adjusted discount rate. This cannot hold true for NPV regarding LCC, if the discount rate were to be increased in order to account for

risks, the NPV of the costs would be reduced. This means that the riskier alternative would be chosen on the basis of lowest NPV.

It is also important to mention that depreciation has effect on the annual expenses incurred on the agency. It can be calculated with the following equation and assumptions.

$$C_{DEP} = \frac{C_{INV} - C_{RES}}{N}$$
 Equation 6

where, C_{DEP} = cost of depreciation

C _{INV}	= investment costs	
C_{RES}	= residual costs	
Ν	= lifetime	

Assuming:

- Straight line depreciation over its lifetime
- Residual cost = 0 at the end of technical lifetime (100 years)
- Economic lifetime = 30 years



Figure 11. Annual expenses vs time

For this example, a discount rate of 5,5% was used and the removal cost is equal to \in 86,000,000. The PV for this cost is calculated to be around 5% of the investment, yielding the following table (to two decimal points so that no value equals zero):

Cost type	Cost/year to investment	Relative to total
Interest	5,50%	46,60%
Construction		
risks and		
uncertainties	0,41%	3,47%
Depreciation	1,18%	10,01%
Maintenance	3,41%	28,91%
Maint risk and		
uncertainties	0,03%	0,34%
Risk of failure	0,02%	0,23%
Removal Cost	0,18%	10,43%
Total	11%	100%

Table 5. Cost components vs investment²

Notice that the largest contributor to the total cost is interest, making it worth to put much attention to this item. Also, maintenance and depreciation constitute the next highest percentages to the total asset costs. Large maintenance figures can be attributed to cost items in assets such as tunnels and bridges, the same cannot be said about normal roads that do not have many technical installations or (sub) components that account for expensive cost items.

The same conditions can be applied to depreciation: depreciation rates can be different from one asset to another. A tunnel will depreciate less than a bridge since it is underground and has less external deterioration factors. A bridge close to the coast can be said to have higher deterioration rates than one located inland, etc.

Therefore, it is important to analyze which interest rates will be used, which deterioration rates should be applied, and which maintenance cost items are the largest cost contributors.

As one can see, there is a **significant contradiction** when one looks at cost/year items instead of using the NPV approach. As mentioned before: a large interest rate will yield a lower NPV (see Figure 12), whereas looking at costs/year, it seems a major disadvantage to have a large interest resulting in larger annual expenses.

This can lead to the following deductions regarding interest rate fluctuations:

• The risk falls mainly on the contractor, whose borrowing interest rates are likely to be higher than those of the client (state)

² Description of risk of failure see section 4.3

• The client's capacity to distribute its risks over its highly diversified portfolio seems to be less harmful and can compensate for this fact by trade-off (loose here, earn there

As far as the interest rate goes, it could be said that most **public infrastructure projects** can be considered **risky due to their high investments** and relatively low (in comparison) benefits, as some of these cannot be quantified monetarily.

Theoretically, there is a **risk-free** discount rate in which a Monte Carlo simulation of the cash flow streams will lead to a distribution (S-curve) representing the risk (see Appendix J).

With the **risk-adjusted** discount rate, the Monte Carlo simulation will yield the mean of the NPV. Which one should be used is not up to the LCC analyst to decide, but should be mentioned explicitly to the decision-makers, and the same one should be applied to all alternatives. Either option, however, would avoid double-counting the risk component.

One of the advantages of using a Monte Carlo analysis is to describe the sensitivity of a number of chosen uncertainties on the project's NPV. This does not replace the risk premium. It is commonly said that the spread of the S-curve should say about how the uncertainties have been modelled and captured, this obviously depends on the inputs, so being honest and objective regarding uncertainties should reflect the level of accuracy. This assessment can only be done and verified with post-project evaluations.



Figure 12. NPV sensitivity to discount rate

The above figure illustrates what was previously mentioned, this is also put into contrast by comparing different timeframe options. Notice that above 5,5%, these tend to have no significant difference. However, when comparing within the same time period of

analysis this can pose a problem, as a difference from 2,5% to 8% has an impact of 30% on the NPV. RWS recommends using 2,5% for LCC and 5,5% for SCBA. This is set by the Ministry of Finance as it is derived from the long term average discount rate on state bonds.

According to an LCC expert in the Netherlands, the discount rate of a contractor (in the order of 8-10%) is much higher than the discount rate adhered to by the public sector, thus, given these significant differences, the optimal LCC-solution for the contractor may not be optimal for Rijkswaterstaat. Furthermore, a contractor may optimize its design over the DBFM contract period only (30 years). These come about as yet some other disadvantages of LCC (M. ten Cate, personal communication, 6th August, 2012) and further standardization of its methodology is definitely required to tackle these defficiencies.

Nonetheless, if a sensitivity analysis like the one described above does not change the ranking of alternatives, then it should not pose a major threat (to the final decision), if it does, more considerations should be given to the choice of rate. It should also be clear that the NPV approach is being used for evaluation of the most cost-effective alternatives.

4.2. User costs due to unavailability

As benefits from transportation infrastructure projects come mainly from gain in travel time by users of the asset, it would be wise to also include what type of costs are incurred on these by construction and implementation of the project at hand. Furthermore, including these in the calculations could help tackle one of the LCC deficiencies: exclusion of benefits.

The literature study and interviews with some professionals in transportation infrastructure from both the Netherlands and abroad, have brought upon a new type of cost defined as the user costs, which are the **delay**, **vehicle operating** and **crash** costs incurred by the users of the facility. Few transportation agencies conduct extensive LCCAs, and even fewer include these costs in their analyses. Reasons behind it are because these are not considered as costs to the agency, but expenses on the users (opportunity costs); yet, these have an effect in construction, maintenance and replacement costs.

Crash costs are not likely to vary much amongst alternatives between periods of construction, maintenance and rehabilitation operations and are highly debatable and difficult to estimate, due to setting a cost to accidents (value of life) and thus, they will be left out of this research.

User costs can become a significant factor as vehicle operating costs affected by work zones. These are heavily influenced by current and future roadway operating characteristics. They are directly related to the current and future traffic demand, facility capacity and the timing, duration and frequency of work zone-induced capacity restrictions or detours.

For example, in pavement design, the choice of pavement will have an impact in travel time during normal traffic flow, thus affecting user costs. Furthermore, these are not expected to be affected substantially during construction periods amongst competing alternatives, however, during maintenance and rehabilitation services, they will have an effect that could have a substantial difference amongst alternatives.

When user costs diminish agency costs for any of the alternatives, the importance of looking at long term costs is more appreciated as it may indicate that none of the alternatives to be analyzed are viable. Some reasons to include user costs are:

- designer needs to evaluate design strategies to minimize impacts on future maintenance of traffic, such as increased capacity.
- enhancing structural design of the main lanes, either concrete or asphalt, in order to minimize frequency of subsequent rehabilitation activities.
- reducing construction periods, if these have a large impact on user costs.
- revising maintenance of traffic plans proposed by the contractors, restricting their work hours, areas and determine lane-occupancy fees.

Notice that these alternatives or actions may have an impact on agency costs (higher), but should try to minimize the overall long-term costs, making them transparent, and aware of their existence to decision-makers.

As user benefits are calculated by:

$$TTG = (VoT_o * \Delta ATT + \frac{1}{2} * (VoT_1 - VoT_o) * \Delta ATT) * ADT$$
 Equation 7

where,	TTG	= travel time gain
	VoTo	= value of time of current users (euro/hr)
	VoT ₁	= value of time of new users (euro/hr)
	ΔATT	= change in average travel time (hr)
	ADT	= average daily traffic (cars/day)

The fact that a new road will tend to attract *new users* has lead to the addition of the second segment of Equation 7 in order to account for this impact; this is in accordance to SCBA standards.

Therefore, in a given circumstance where maintenance activities involve large traffic disruptions and nuisance produced to users, the same reasoning could be applied: some users might decide not to use the road anymore, but take other alternative routes or means of transportation. Therefore the following equation is proposed:

$$UDC = (VoT_o * \Delta ATT + \frac{1}{2} * (VoT_1 - VoT_o) * \Delta ATT) * ADT$$
 Equation 8

where,	UDC	= user delay costs
	ΔATT	= change in average travel time (hr)
	VoT	= value of time of users (euro/hr)
	ADT	= average daily traffic (cars/day)

It is very likely that at the early stages of the LCC not much will be known about maintenance strategies and traffic control plans. Furthermore, given that no substantial relationship between (re) construction costs and user delay costs was found in Dutch practices, the premature stages will yield very rough figures. It is desirable that these can be improved with time if these practices are encouraged.

Once the maintenance activities are determined, the next equation could be applied in order to further improve the estimates:

$$\Delta ATT = \left(\frac{L}{V_M} - \frac{L}{V_N}\right) * n * upv$$
 Equation 9

L	= length of working zone (km)
V_M	= velocity due to maintenance (km/hr)
V_N	= velocity on normal conditions (km/hr)
n	= number of working days
upv	= user per vehicle type

This last multiplier factor is to take into account the number of users in each vehicle. This is also based on types of users and different scenarios, the forecasting model provides figures up until 2040 (See Appendix D).

The following table illustrates the rates at which the value of time has been calculated for users and its respective projections depending on the type of vehicle or purpose, and based on different WLO scenarios: Regional Communities (RC), Strong Europe (SE), Transatlantic Market (TM) and Global Economy (GE). See Appendix B for full description of rates and scenarios.

Regional	Communities (RC)				
	VoT commuting	VoT business	VoT other persons	VoT all motives	
Year	(Euro per hour)	(Euro per hour)	(Euro per hour)	(Euro per hour)	
2010	8,84	30,63	6,11	9,88	
2020	9,58	33,17	6,61	10,7	
2040	11,7	40,51	8,08	13,07	

Regional Communities (RC)

Table 6. Value of time rates (Regional Communities scenario)

The change in average travel time is dependent on the work zone set by the agency executing maintenance activities, i.e. # of lanes closed, length, working hours, type of users, urban or rural area, etc.

It is worth mentioning that maintenance activities are highly dependent on the asset in question, furthermore, the impact that these have on users are also dependent on these. For example, in a bridge, it can have an effect on the users on the actual bridge, but also on users under the bridge, as some safety measures might call for traffic interruptions for those users.

Given the fact that there are four types of user rates and four different scenarios, one can come up with 16 different results for user delay costs. However, it would be best to choose one scenario (in general Strong Economy) and apply the respective rates to each type of user and include all these in the calculations as it would be likely to come closer to a worst-case scenario for cost inclusion in the LCCA.

According to RWS personnel, user delay costs are not part of the LCC because these are not out-of-pocket costs for RWS. Instead, these are boundary conditions for the design and planning of maintenance, leaving their LCC relevance aside to some extent. These could be a separate criterion in the bidding process as an EMAT (Economic Most Attractive Tender): a contractor with less vehicle loss hours can receive a 'virtual bonus'. He also mentioned the importance of these in performance contracts where a contractor will try to have better performances with significant fewer impacts on traffic. They serve as good indicators to establishing penalties set by minimum availability of the road, but have very little attention in the decision-making process during preliminary design and construction. Because of this, the road built might end up being too small for the desired maintenance (J. Schavenmaker, RWS, personal communication, July 26, 2012), posing a major risk and thus, highlighting the importance of such inclusion. This shows some contradicting viewpoints regardless of the limitations of data availability and the fact that the calculations will be more timeconsuming and perhaps more costly, but they should increase the amount of information for adequate decision-making, particularly since the largest benefit from these types of infrastructure projects come from time gain, the opposite effect should be carefully considered.

Furthermore, it is strongly recommended by other agencies (E. Ross, FHWA, personal communication, June 24, 2012) that when making a decision, these costs should be

compared to agency costs in order to analyze if they are dwarfing the latter for the selected alternatives. These, again, depend on the type of transportation infrastructure project being analyzed and the level of detail to be incorporated into the LCC calculation for the adequate decision-making stage/point.

Further options would include revising maintenance of traffic plans, reducing construction period, restricting contractor's working hours or imposing lane rental fees and subsequent planning of routes. It is very important to analyze each alternative carefully to see if user delay costs should really be taken into consideration, for example in highly urbanized areas, major freight movement and their micro and/or macro-economic impact. Some agencies might decide to look into further details once a certain threshold has been reached regarding these costs.

A major limitation of LCC has been established to be overlooking at benefits, so it is proposed that calculation of user delay costs be included, thus taking into consideration **minimization of lost benefits.** This could be part of the overall economic appraisal criteria, but should not be part of budget allocation practices.

4.3.Cost of failure (Risk during exploitation)

This chapter regards structural (sub) system failure for different failure modes. It was noted in Section 3.6 that modern tools regarding maintenance address the optimal intervals for either preventive or corrective maintenance. The cost of maintaining vs the cost of failure is analyzed in this chapter in order to assess if these costs are high in comparison to the latter. It was also mentioned that it is not common practice in infrastructure projects to allow for system failure due to risks leading to extreme consequences, such as fatalities. Only user delay costs are to be included in these calculations and not accidents or death, as noted in the previous section.

Recent research has shown that replacement costs and user delay costs associated with system failure are rarely included in LCCA (Perrin, 2003), only three transportation agencies (out of 50) in the United States do so. Tracking different modes of failure and its associated costs would help agencies and decision-makers better understand the risks that these imply.

When costs of failure are included, resources required can be engineered or estimated in order to avoid the use of antique rules of thumb about the establishment of maintenance budgets. For example if the cost arising from failure is low, the corrective maintenance would best fit to the budget allocation. On the other hand, if the cost is high, then one would choose for preventive maintenance in order to avoid these. Again, as with user delay costs, a certain threshold should be established in order to assess what constitutes high or low costs in regards to investment costs.



The following figure illustrates time sensitivity with respect to failure probabilities:

Figure 13. Equivalent P(f) vs Time

Notice that above a failure probability of 1*10⁻¹, there is a 'significant' difference between several periods of analysis. It is important to see which data is available for different failure modes and their respective failure probabilities. However, it is safe to assume that for a maximum failure probability of 1*10⁻¹, which is relatively high, there is not a large influence between time-period of analysis.

Nonetheless, a value assigned to a failure probability does not provide much insight. It is important to see the risk (P_f *cost) associated with it. Not only that, but also the bearer of this risk AND their respective relationship (percentage) to investment costs, as this is one of the advantages of LCC: comparing long-term vs. short-term costs.

There are several ways of determining the reliability of an element. If we are to focus on what could constitute the highest contributors to costs we could use methods such as a Fault Tree Analysis (FTA) or Probabilistic Method (Statistical or Bayesian). These, however, depend on data availability as the input for different variables requires being statistically meaningful. In case of a Bayesian Probabilistic Method, a triangular distribution is used based on expert opinions using LTU values on different variables. In other cases, such Level II and Level III (Monte Carlo), there is a need of using mean values and their respective standard deviations. By determining the Limit State Function (LSF), the probability of failure can then be derived using a Level II analysis.



Figure 14. Failure Space as function of variables (CUR-publicatie 190, 1997)

This type of analysis, in which the variables are considered to be fully independent, as it is recommended that correlations between these best be avoided, will typically yield the following outputs:

- Probability of failure
- Contributions of stochastic variables to the total result (critical parameters)
- Design point boundaries

The first two will provide good insights into project risks and values towards determining what the priorities for further analysis of a project could be. This type of analysis is quick with the use of software (such as VAP) and can be used for many purposes. In this particular segment, for determining failure probabilities given a limit state function for different project alternatives.

For example, structural reliability is generally defined as the capability to satisfy some design objectives, assuming that structural failure has the largest consequence (probability*cost), the limit state function would be derived from this basis. The reliability analysis is adopted to determine the representative failure probability, provided there is sufficient historical data in order to be statistically meaningful. Decisions can then be made based on the estimation of the reliability level produced by comparing alternatives. Meaning, both failure probability and reliability index have to be closely analyzed amongst alternatives.

Once the probability of failure has been calculated, the equivalent failure probability can be determined using Equation 5. Obviously, the lifecycle period has to be the same for all alternatives. Then, an estimation of (re)construction costs and impact on user delay costs to calculate the total risk.

It is important to mention that the amount of data regarding failure can provide enough information to determine probability density functions and other type of qualitative analysis that would lead to better and improved forecasts before project execution. But not only forecasting is of relevance, but also monitoring and evaluating, such as good risk management principles suggest, although there is much room left for improvement in this spectrum.

There is an increasing need for failure databases, although gathering these cost time and money. The level of detail and importance in decision-making process will determine the effort put into developing these, with a more adequate gathering, documenting and most importantly, to disclose them to relevant parties.

As with user delay costs, given the early stage of the project phasing, not many details are available to ensure accurate data regarding failure probability and, for that matter, its effects. Nonetheless, including them as a rough estimate (as is the case of other cost items), and subsequently updating them as design details become clearer, increasing validity of results.

Also, it is worth to distinguish that what benefits a person, might harm the other. For example, in case of bridge closure, traffic flow for car users will be brought to a halt, but it would be increased for ships under the bridge, or vice versa. If this is seen on a wider macro-economic context, it could be seen as benefit for the oil business, but have an increase cost in logistics and so on. To keep things simpler and on a micro-economic level focusing only on costs, these implications shall be disregarded.

4.4. Risk in maintenance

Research was also done to identify what type of special events, translated to risks, often occur during maintenance of such projects. Even though there is not much recorded, most professionals agree that the timing and frequency of these activities are uncertain, but do not pose a major risk. As it was mentioned, technology developments can have an effect on productivity regarding these activities. Labor costs may rise, energy costs may be lower, and other factors might affect future costs, so it has become a rule of thumb to add a 10% contingency factor for accounting for these risks.

The scope of the execution is clear and the ground has already been laid to carry on without many surprises. Permits, licenses, environmental assessments, etc, pose fewer limitations. There are less safety factors at risk, usually less manpower and equipment being used when compared to new constructions. If maintenance activities seem to be meaningless after 50 years time, risks regarding these pose even a lesser impact on the LCC calculations.

The main risk regarding maintenance activities is that these are not included or thoroughly thought-off during design. If a road is built too narrow only because of cost drivers, subsequent maintenance activities might prove to be more expensive than expected and incur on higher costs than that of investment. It was mentioned that adequate inspections can provide for a more detailed description of deterioration rates and factors. In a tunnel, for example, where inspections take place where very limited vision, this should be taken into account. Being able to access critical areas where deterioration or repairs are needed is very essential. These could lead to increased time (and cost) for inspection, unsafe conditions and additional materials or equipment for such.

It is very common that the asset will still be utilized while maintenance is carried on, so minimizing traffic flow is usually necessary, working at night or in different phasing with very well detailed traffic control plans (higher costs). This is highly dependent on the location and type of project in question, but very common to all transportation infrastructure projects.

When maintenance activities are being executed, some external factors may come into play, such as weather conditions, overloaded trucks, supervision, etc. However, these pose not a major risk regarding these types of works. Also, these factors or errors, whether they are systematic or human, also occur during normal construction. However, clients usually have a guarantee certificate in which any deficiencies deviating from technical specifications are to be repaired on the contractor's behalf; these can range from 5 to 10 years, depending on the contract. Design flaws are sometimes corrected during execution, and execution flaws are sometimes corrected during maintenance/repairs, these are normal to all types of projects and are not considered a major problem, but should always be accounted for, cost wise, in some way. These are usually covered by a special contingency factor (% of maintenance works).

Risks unfolding during maintenance activities, probably result in higher costs incurring in both the agency and the contractor. However, depending on the type of contract, the contractor might be held fully accountable as it is more capable to take the risk. In a DBFM contract, the contractor has to price each risk and decide on how to mitigate it, but can only spread the risk within the contract. RWS, on the other hand, is able to spread the risks over its whole network and can cover for some risks with godsends from other parts of the network, balancing off these unexpected costs and minimizing the effects of such.

New constructions certainly have more risks than future interventions on these same constructions. When talking about maintenance activities, these are somewhat standardized and repetitive. Their constructive methodologies do not involve a high amount of innovation or inclusion of new technologies to the degree of posing a major threat, until now. . .

It is uncertain how further developments can have an impact on future maintenance activities, but as experiences and history has demonstrated, it could lead to cheaper or more productive solutions. For example, the development of pre fabricated elements that lead to cheaper and faster constructions taking place nowadays due to its standardization and other advantages (controlled workspace, safer, accessible, etc). There is a learning curve for these types of innovations, but new technologies aim to making these shorter. Thus, it would be safe to assume that as labor and material costs may increase, energy and learning curves for implementation of new constructive/maintenance methodologies can be reduced, thus balancing off these uncertainties.

Nonetheless, as a factor of safety, and taking into account that scenarios may unfold into pessimistic ones, there should be a special events contingency allocated in case some risks do occur.

Changes during post-implementation phases can have an impact on the project's outcome, particularly in costs if these occur within the first few years. Scope changes during construction or immediately succeeding it due to unexpected functional or stakeholder requirements should be carefully dealt with by making these as transparent as possible and explicitly mentioning the impacts that these may involve. These can be in terms of costs or benefits, but are **difficult to capture them in LCCs** by trying to quantify only their cost implications.

Furthermore, these implications are difficult to recognize and trying to address their solutions is likely to lead to wicked problems. This issue will be further elaborated during the discussion section of this report.

5. Chapter 5. Case Study, Via 15 Tunnel.

5.1.Introduction.

For the application of the theories and concepts of this model, a real project was selected as a case study, this is the Via 15 Tunnel. This case could be said to be representative of the different sorts of transportation infrastructure in the Netherlands as having been discussed in the literature research and for the inclusion of the proposed model discussed during the previous chapter.

5.2. Project Description.

The project takes place in the region of Arnhem - Nijmegen in The Netherlands (see Figure 16).



Figure 15. Overall Map

For some time now, there have been daily traffic jams on the A50, A12, A325 and N325 (Pleij Route). And the traffic problems in the future are forecasted to be even greater, despite previously planned measures (such as the widening of sections of the A50 and A12, upgrading of the N18 and construction of a second bridge at Nijmegen). It is anticipated that by the year 2025 the entire transportation network around Arnhem will be overloaded. The accessibility of the region and the reliability of the national & regional road network are therefore under pressure. The traffic problems have a negative effect on the international attractiveness of the Randstad and the port of

Rotterdam. The region of Arnhem - Nijmegen itself can no longer spatially and economically develop. The overload occurred in the region also problems with the quality of life (cut-through traffic, air pollution)

Part of some alternatives is a prolongation of the A15 from junction pads to the A12 with a connection thru the Pannerdensch canal.

The LCC analysis was performed (but excluded from the scope of this research), on the following three alternatives:

- 1. Alt 1: a fully immersed tunnel, as previously described
- 2. Alt 2:a bridge
- 3. Alt 3: a semi-underground tunnel

Underlying assumption is that **benefits for each and every alternative have been already established to be substantially the same**.

5.2.1. Specifications and Assumptions.

The following are some of the technical specifications and assumptions of alternative 1, the tunnel. The length is 1737m and there is a 250m connection between the tunnel tubes (See Appendix C for project description and Appendix D for detailed drawings).

Figure 17 (not to scale) below illustrates the location of the project, focusing mainly on the tunnel sector.

To the extent envisaged by what is the expected output and usefulness of LCC regarding:

- Investment costs,
- Maintenance costs,
- and NPV of alternatives.

Table 8 shows these along with other the incorporation of the proposed items from the previous chapter. Notice that user costs **do not contribute to any of these three items**, but are included in the table to be able to compare how these vary amongst alternatives. Also, **no interest rates** are applied either investment or maintenance costs.



Figure 16. Project Location (satellite view)



Figure 17. Project Location (Pannerdensch canal)

The investment costs are broken down as such:

- Construction Costs
- Property costs
- Engineering Costs
- Other additional costs
- Skewness (due to uncertainties) and Risk Reservation

In general, the maintenance costs of the tunnel are divided into:

- Asphalt
- Tunnel technical installations
- Concrete works (for more details on assumptions on these, see Appendix C)
- Other additional costs
- Skewness and Risk Reservation

For carrying out the LCC-analysis, the following starting / assumptions are made for the investment costs:

- Construction costs will take place from 2014 to 2016
- Property costs are held from 2012 to 2015
- Engineering Costs from 2012 to 2016
- Other additional costs will take place from 2014 to 2016

Quantities and unit costs are derived from estimates, cost data (BON), and expert opinions regarding uncertainty in cost variables.

The following assumptions were made regarding the following items.

General.

- Discount rate is 2,5% based on suggested LCC methodology
- 30 year lifecycle based on:
 - estimated economic lifetime
 - DBFM contract
 - one large maintenance activity occurring at year 30 (replacement of TTI)
 - construction completion (2017)
- Net Present Value starting on January 1st, 2012
- VAT of 19%

Depreciation.

- Straight line depreciation over its lifetime
- Residual cost = 0 at the end of technical lifetime (100 years)
- Economic lifetime = 30 years

User delay costs.

As previously mentioned, these should not be considered as costs on the agency, but rather expenses to society. Including them in the LCCA should only serve as base of comparison between minimization of lost benefits amongst mutually exclusive alternatives.

- Scenario applied was *Strong Economy* (highest values and common practice) for a conservative estimate
- Value-of-Time per person (€) beyond 2040 are increasing by a annual factor of 0,5% for vehicles (all types) and 2% for freight.
- Estimation of number of persons per vehicle beyond 2040 based on a trend line.
- Average daily traffic based on figures from similar tunnels in the Netherlands (www.cijferboekje.nl).
- As there are no details, at this stage, on maintenance activities and traffic control plans, a broad assumption based on a percentage and historical data from international sources. Refer to User Costs in Section 3.4, LCC Methodology.

Risk (Failure) during exploitation.

- Failure mode established to be large fire caused by accident.³
- 6 day closure for reconstruction activities affecting user delay costs
- (re) construction costs estimated from original investment costs, as no information could be obtained from impact of such event.

		Alternative 1
Frequency	Failure Prob	1,00E-01
Frequency	Equivalent Failure Prob	3,51E-03
Cost	Reconstruction Cost	120,00
Cost	User Delay Cost	80,00
Dick (E/vr)	Agency	0,42
RISK (€/yi)	Users	0,28
Risk (€/yr)		0,70
Total Agency C	cost (€)	12,62
Investment Costs (€)		326,13
Total Cost / Investment		3,87%

Table 7. Risk during exploitation

³ Probability of failure obtained from RWS, Infrastructure Department (RWS Dienst Infrastructuur, 2012)

5.3.Results⁴

The results for Alternative 1 (tunnel) are presented in Table 8. See Appendix F for detailed spreadsheet of results. The analysis of all three alternatives can be seen in Table 16 on page 69. For this first part of the analysis, only the tunnel is being considered, even though it is not the most cost-effective option. Nonetheless, the application of the model could be done to all alternatives for good grounds of comparison.

LCCA	Alt 1	Notes	
	(€M)		
Investment	326,13		
Risk	41,10		
Reservation +			
Skewness			
User Cost	0,00	Not Applicable: New	
		construction	1
		assumed to have no	
		impact on users	
VAT	69,77		
Σ Investment	437,00		
M&R	482,02		
Agency	371,72		
Users	110,30		
Risk	39,77		
Reservation +			
Skewness			
Risk (Failure)	12,62	largest risk of each	
		alternative	
VAT	80,58		
ΣM&R	504,69		
Σ All Costs	941,70	μ	2
(LCC)			
Variation	17%	σ/μ	
Coefficient			
NPV (as of 1 st	483,80	Date and discount	
January 2012)	/	rate (2,5%)	

Table 8. Results LCCA for Tunnel

3

⁴ Real figures (prices and some quantities) have been modified due to data sensitivity as these are future projects undergoing feasibility studies. These have been modified proportionally.
These are the 3 key parameters that deserve the most attention to the extent covered by decision-making based on LCCA. Simply looking at a figure does not say much, so there should be thresholds (budgets) for construction (1) and maintenance (2), while choosing for the most cost-effective alternative (3).

5.3.1. Deterministic Results

To put these results into contrast, a deterministic value has also been obtained.

The following table shows the results of a deterministic cost estimate without taking into account uncertainties on both: quantity and price in all cost items.

LCCA	Alt 1
	(€M)
Investment Costs	\$ 326,1
Risks Construction	\$ 28,7
VAT (19%)	\$ 67,4
Σ Investment	\$ 422,2
Maintenance Costs	\$ 371,7
Risks Maintenance	\$ 37,4
Cost of failure	\$ 12,6
Tax (19%)	\$ 80,1
ΣM&R	\$ 501,9
Project Most Likely	
Value (T)	\$ 924,1

Table 9. Deterministic Results

For more detailed qualitative analysis of risks during construction check Appendix K.

NPV of the alternative is still the same. However, the difference between the most likely value and the mean value is **almost negligible (1,87% extra)**, which indicates that uncertainties (skewness) in prices and quantities account for very little in the total cost estimation, yet these depend on the time period of analysis.

To summarize, reducing the life cycle analysis can increase level of confidence. It is also important to notice that the Monte Carlo analysis should be done with a fixed risk-free discount rate, as previously stated. This was the NPV remains unchanged.

1. The NPV approach

When looking at discounted cash flows for calculation of NPV (box 3), the residual value is subject to the time period of analysis. In this case, since the time frame has been reduced from 100 to 30, it is assumed that there is a residual value after the first large maintenance activity.

A side note on this assumption: in practice, public infrastructure projects owned by RWS have no re-sale value, unlike other types of private organizations or industries where the concept of salvage value has more importance.



Figure 18. Discounted cash flow for tunnel⁵

The following table shows a breakdown of the NPV calculations.

		NPV			
		@ 2,5%			
Investment	€	296.459.285			
Risk and	Γ				
Uncertainties					
Construction	€	37.432.952			
Maintenance	€	220.751.589			
Risks and					
Uncertainties					
Maintenance	€	24.523.944			
Risk	€	12.971.201			
Residual	€	(108.342.929)			
TOTAL NPV	€	483.796.042			

Table 10. NPV Tunnel

⁵ Residual value assuming straight line depreciation (see Equation 6)

By looking at all these figures, not much can be said, as LCC is a tool that best serves for evaluating alternatives. This will be done in Section 5.4, however, the remaining part of the analyses in this section will be done for this specific case.

2. The cost/year approach

It was previously mentioned that there are two approaches to LCC. When looking at costs/year one can clearly see which are the yearly expenses and the main cost contributors compared to the investment (see Table 11). For example, one can determine the cost of maintaining the asset by looking at these costs specifically. It is worth noticing that for this case, maintenance activities account for a large percentage, this is mainly **due to the technical installations**, which constitute a major cost driver and a large influence factor both in terms of cost and quantities in relation to the total costs.

Cost type	Cost/year to investment	Relative to total
Interest	2,50%	28,81%
Depreciation	1,00%	13,60%
Maintenance	3,37%	38,87%
Maint risk and		
uncertainties	0,36%	4,16%
Risk of failure	0,19%	2,20%
Removal Cost	0,79%	12,37%
Total	8%	100%

These figures can be seen as a percentages of the investment and a useful evaluation of how each of these contribute to the total fixed costs can be made:

Table 11. Fixed Costs for Tunnel

The figure below illustrates the annual expenses for the prescribed lifecycle:



Figure 19. Annual Expenses Tunnel

The size of the investment (including risks and uncertainties) is reflected in box 1 on the previous page.

From this approach, we can deduct that the largest cost contributors are Maintenance, Interest and Depreciation. This is due to the abovementioned TTIs and other expensive items in maintenance activities. This will be further elaborated during a level II and level III analysis.

The following section includes a sensitivity analysis on this specific case to show how changing certain parameters can affect certain outputs of the LCCA.

5.4. Sensitivity Analyses

A sensitivity analysis was conducted in order to assess for the impact of the following changes:

An individual analysis applied to the tunnel only, based on:

- Increased life cycle
- Increase in cost of maintenance activities
- Variation in frequency/timing of maintenance activities
- Level II analysis (VAP) to assess cost contributors in maintenance activities
- Level III analysis (Monte Carlo, @Risk) to estimate coefficient of variation and tornado graphs for a more detailed analysis of cost contibutors

Also, a comparative analysis of the best two alternatives based on:

- Increase in discount rate
- Increased life cycle
- User costs and discount rate

Increased lifecycle.

Obviously, with an increased time period of analysis, there are higher figures for long term costs, resulting in a higher NPV for a 100-year service life. See Table 12 for full comparison on different outputs.

Lifecycle	Long-term costs (€M)	NPV (€M)	Project µ (€M)	Variance
30 years	594.1	483,6	941,7	17%
50 years	787,4	595,8	1169,6	18%
100 years	1083,4	647,5	1464,3	22%

Table 12. Increased lifecycle results

The effect of increasing the lifecycle does not say much, obviously, long-term costs increase as expenses are assumed to be constant throughout the entire lifecycle. This is a very limiting assumption, given that there is much uncertainty as time goes by (variance also tends to increase).

However, regarding NPVs, notice that there is not much change once the 50-year time frame has been surpassed. A graphic representation of this can be seen in Figure 10. Also, after the 50th year, the present value of all maintenance activities constitutes around 17% of the net present value of the project⁶. Furthermore, replacement of the tunnel at the end of its technical lifetime represents around 1,4% of the total present value.

Increase in cost of maintenance activities.

Each and every activity was increased by the following percentages to see the impact on the NPV. Reasons behind this might be increase in labour costs, rise in oil prices having an impact on asphalt or others. Given that each activity was raised by the following percentages, this would be considered a worst-case scenario, as it is not expected that all activities should have such negative effects.

		% increase in Maint Activities				
	Base	5% 10% 20% 30%				
NPV	€ 483.796.042	€ 490.859.464	€ 497.729.368	€ 500.825.663	€ 513.888.156	
% change in NPV		1,46%	2,88%	3,52%	6,22%	

Table	13.	NPV	Sensitivity t	o Maintenance
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⁶ Calculated from adding all maintenance costs from year 51 to 105 and dividing by NPV @2,5% (€M 647,5)

As one can see, the impact of such changes has very little influence on the NPV, and as long as these are treated as constant to all alternatives, they pose no major threats when deciding amongst projects.

Variation in timing of activities.

Another major uncertainty prescribed by experts was mentioned to be the timing of these activities as there could be some deviations from the initial forecasts as deterioration factors (chemical or physical) can lead to earlier interventions, OR new technologies can lead to later ones (less wear and tear from better tires). Also, during construction, some external factors such as environmental effects can affect quality, leading to a level of performance that was not predicted and requires earlier interventions.

It is also recommended, given the time value of money, that major interventions such as corrective maintenance or replacements are postponed as much as possible.

	Frequency change of Maint Activities					
		much earlier (-4 later (+2				
	Base	earlier (-2 years)	years)	years)		
NPV	€ 483.796.042 € 483.844.421 € 483.941.181		€ 483.646.065			
% change in NPV		0,0010%	0,0030%	-0,0310%		

Table 14. NPV Sensitivity to frequency of Maintenance

The same can be said about these potential risks, the effect on the NPV is so little that they virtually can be disregarded.

Statistical Probabilistic Estimation.

As mentioned before, the following coefficients provide a measure of how the output would be affected if the input were to be changed by one standard deviation. To put it simple, it provides to be a useful tool to assess the level of influence of cost items on the margin, and from a financial point of view, set priorities when dealing with uncertainties.

A level II analysis was performed **for maintenance activities only** by setting target goal (annual budget) for these while assess the sensitivity of cost contributors. See Appendix L for LSF and input parameters.

Maintenance Cost Items	Regression coefficients
Yearly TTI	0,875
replace TTI	0,439
Yearly Concrete Tunnel	0,202
Large maintenance concrete tunnel	0,015
Recover Damage (2%)	0,012
replace top layer all lanes (100 mm)	0,005
Control Smoothness Road	0,003

replace top layer all lanes (50mm)	0,003
replace top layer right lane of road (2 x 3,5	
m1)	0,002
sweep road (10 cent / m2')	0,001
	_

Table 15. Maintenance Cost Contributors (level II)⁷

Notice that the tunnel technical installations are the highest cost contributors. This reinforces the fact that maintenance can account for a large percentage in relation to the asset fixed costs.

Furthermore, a probabilistic estimation was done with a level III analysis and represented in a Tornado Graph (Figure 20), in which the estimate for each unit price and quantity has lowest and highest values estimated from a triangular distribution. This expert estimation serves as input for the Monte Carlo analysis (usually 10,000 simulations) using the @Risk software that yields a coefficient of variation and a tornado graph that shows the top 10 contributors to the overall LCC.

What can also be obtained from a level III analysis is an S-curve in which the probabilities of exceedance are plotted against incurred costs to represent the risk, this was done using a risk-free discount rate (see Appendix J).



These items should be the main focus of attention for evaluation of alternatives and furthermore, for design optimisation once an alternative has been chosen.

Figure 20. Tornado Graph (Tunnel)

⁷ Given that VAP software does not accept triangular distributions as input parameters, the assumption of a rectangular distribution was made, with $\mu = \frac{U+L}{2}$ and $\sigma = \frac{U-L}{\sqrt{12}}$

The aforementioned effects are taken into account in the probabilistic estimation method (level III) by incorporating uncertainties in both cost and quantity items. As with the previous method, the technical installations provide to be the most critical (both in terms of costs and quantities), followed by their replacement, etc.

It can then be concluded that the TTI's should be the main focus of attention as they contribute the most to the LCC and therefore explaining high costs in maintenance activities. Careful consideration of its selection and their probability of failure should be considered in order to estimate their economic cost and their impact on user costs due to unavailability.

5.5. Evaluation of Alternatives

The following table shows the LCC results for all alternatives being analyzed:

LCCA	Alt 1	Alt 2	Alt 3	Notes
	(€M)	(€M)	(€M)	
Investment	326,13	242,85	399,65	
Risk	41,10	31,39	71,94	
Reservation +				
Skewness				
User Cost	0,00	0,00	0,00	Not Applicable: New
				construction
				assumed to have no
				impact on users
VAT	69,77	52,10	89,60	
Σ Investment	437,00	326,34	561,19	
M&R	482,02	336,30	417,00	
Agency	371,72	238,30	292,00	
Users	110,30	98,00	125,00	
Risk	39,77	31,78	43,80	
Reservation +				
Skewness				
Risk (Failure)	12,62	1,00	4,30	largest risk of each
				alternative
VAT	80,58	51,51	64,62	
ΣM&R	504,69	322,59	404,71	
Σ All Costs	941,70	648,93	965,90	μ
(LCC)				
Variation	17%	18%	19%	σ/μ
Coefficient				
NPV (as of 1 st	483,80	248,73	680,00	Date and discount
January 2012)				rate (2,5%)

Table 16. Results LCCA for all alternatives

In this case, an evaluation of all alternatives shows that Alternative 2 (bridge) is the most cost-effective one. It is lower in both investment costs, and maintenance costs. Also, its NPV is lower than all the others. It could happen that maintenance costs of the chosen alternative are higher than the others, yet the NPV is still lower, given the timing of its maintenance activities. This could be affected by the choice of discount rate, and thus, a comparative sensitivity analysis should be undertaken, considering the two most attractive alternatives, as Alternative 3 should be ruled out given that it is more expensive in every aspect (criteria 1, 2 and 3).

Comparative Sensitivity Analysis.

For practical purposes, and for the purpose of this research, a primary sensitivity analysis was done on Alternative 1, as shown in the previous section. However, Alternative 2 (the bridge) proves to be the most cost-effective alternative in every aspect (lower investment, maintenance and NPV). Therefore, a more detailed sensitivity analysis should be done for the latter as it is most likely to be selected for design optimisation. The next phases of LCC should be applied to these as more details and design specifications become apparent.

Alt 1			Alt 2		
Cost type	Cost/year to investment	Relative to total	Cost type	Cost/year to investment	Relative to total
Interest	2,50%	25,96%	Interest	2,50%	47%
Depreciation	1,00%	22,14%	Depreciation	1,18%	10%
Maintenance	3,37%	35,03%	Maintenance	2,95%	29%
Maint risk and			Maint risk and		
uncertainties	0,36%	3,75%	uncertainties	0,39%	3,80%
Risk of failure	0,19%	1,98%	Risk of failure	0,02%	0,23%
Removal Cost	0,79%	11,15%	Removal Cost	0,16%	10,29%
Total	8%	100%	Total	7%	100%

Looking again at the cost/year approach to LCC in order to get insight on annual expense figures, one can see the following:

Table 17. Comparative Fixed Costs

The same interest rate accounts for much more regarding fixed costs of the bridge. Maintenance still accounts for a large percentage so it should still be regarded with attention as there are some cost items in maintenance activities which incur in large costs. However, the higher the interest rate, the less effect other costs will have on the total fixed costs.

Alt 1			Alt 2		
Cost type	Cost/year to investment	Relative to total	Cost type	Cost/year to investment	Relative to total
Interest	8,00%	52,87%	Interest	8,00%	59%
Depreciation	1,00%	14,09%	Depreciation	1,18%	8%
Maintenance	3,37%	22,29%	Maintenance	2,95%	22%
Maint risk and uncertainties	0,36%	2,39%	Maint risk and uncertainties	0,39%	2,92%
Risk of failure	0,19%	1,26%	Risk of failure	0,02%	0,18%
Removal Cost	0,79%	7,09%	Removal Cost	0,16%	7,89%
Total	14%	100%	Total	13%	100%

For example an interest rate of 8% constitutes more than 50% of the total fixed costs for both cases. Whereas the other costs now contribute less to the total percentage. For ground of comparison, now we can look at how the NPV is affected by these changes.

Increase in discount rate

	Discount Rate										
		2,50%		5,50%		8,00%		10%			
Total NPV Alt 1	€	483,80	€	409,56	€	357,14	€	322,03			
Total NPV Alt 2	€	338,39	€	302,46	€	271,42	€	248,72			
Cost Advantage Alt 2 vs. Alt 1	€	145,40	€	107,10	€	85,72	€	73,31			

Table 18. Sensitivity of NPV to Discount Rate

Table 18 shows that Alternative 2 is preferred over Alternative 1 **at any given discount rate**. This may happen to change at higher discount rates, in which one alternative is no longer preferred given a higher NPV at above certain rates, due to the amount and timing of some large maintenance activities, as mentioned before. It is important to take this into consideration as it was stated that contractors and agencies may use different discount rates.

This is shown graphically in the next page (Figure 21).



Figure 21. Sensitivity of NPV to discount rate

Increased lifecycle

The two alternatives are subject now to different periods of analysis to see how their NPVs are affected.

	Life cycle								
years		30		50		100			
Total NPV Alt 1	€	483,80	€	595,80	€	647,50			
Total NPV Alt 2	€	338,40	€	440,20	€	555,38			
Cost Advantage Alt 2 vs. Alt 1	€	145,40	€	155,60	€	92,12			

Table 19. Increased life cycle NPV

It is expected that the NPVs will increase, but Alternative 2 is still preferred over Alternative 1.



Figure 22. Increased life cycle NPV

The same can be concluded by looking at these on a cost/year basis and determining annually recurring costs, these are first converted to present values and then derived to annuity costs⁸:

	Life cycle		30		50		100
Alternative 1	NPV	€	483,80	€	595,80	€	647,50
	Annuity (€/yr)	€	23,11	€	21,01	€	17,68
Alternative 2	NPV	€	338,40	€	440,20	€	555,38
	Annuity (€/yr)	€	16,17	€	15,52	€	15,17
Cost Advantage Alt 2 vs. Alt 1		€	6,95	€	5,49	€	2,52

Table 20. Increased life cycle annuity

This is shown graphically below:

⁸ see Equations 12 and 13 in Appendix A



Figure 23. Increased life cycle annuity

It is noticeable that the longer the life cycle, the more costs are reduced. This is due to the uniform present worth increasing with time (see Appendix L).

Inclusion of user delay costs

Deciding whether to include or exclude user costs can significantly affect the LCCA decision outputs (not the costs on the agency). These can also be affected discounting techniques and could be considered as separate decision criteria, but should also be done in a comparative analysis. The alternative with the least reduction of benefits should also be closely evaluated, particularly if up to this point proves to be another alternative. The graph should clearly differentiate the bearer of such expenses:



Figure 24. Agency vs Users Expenses

A comparative analysis should be done between the costs that have been so far described incurring on the agency and user delay costs. This can be done also with the effects of discount rate.

The bottom of Table 21 includes an incremental B/C ratio in which it is proven that Alternative 2 should be chosen at any given discount rate. This is computed by dividing the difference of user delay costs (read minimized reduction of benefits) by the agency costs associated with maintenance activities.

Cost Component		Discount Rate										
		2,5%		5,5%		8,0%		10,0%				
Agency Cost Alt 1	€	2.890.194	€	2.881.583	€	2.875.877	€2	2.872.071				
Agency Cost Alt 2	€	2.728.605	€	2.702.275	€	2.673.319	€2	2.660.755				
Agency Cost Advantage												
(Alt 2 vs Alt 1)	€	161.589	€	179.308	€	202.558	€	211.315				
User Cost Alt 1	€	1.867.553	€	1.862.386	€	1.858.962	€ 2	1.856.679				
User Cost Alt 2	€	1.400.665	€	1.445.677	€	1.555.706	€ 2	1.612.289				
User Cost Advantage (Alt												
2 vs Alt 1)	€	466.888	€	416.709	€	303.256	€	244.389				
Incremental Benefit/Cost		2,89		2,32		1,50		1,16				

Table 21. Sensitivity to User Costs and Discount Rate

5.6. Analysis of Results.

First and foremost, it can be safely concluded that the decision for Alternative 2, the Bridge is the best option. By focusing on what is best envisaged from an LCCA:

- Investment costs,
- Maintenance costs,
- and NPV of alternatives

and different types of sensitivity analyses addressing the last bullet points, it has been clear that the choice of alternative 2 over alternative 1 is best in each and every aspect.

Throughout this chapter many types of analyses have been done, first on the tunnel only and then on a comparative basis, given the two most promising alternatives.

Looking at LCC on a cost/year basis will give insights on the first two bullet points. Comparing different components of LCC to fixed costs such as with table 9 can yield insightful results on the largest influencing factors. In the case of the tunnel, it was discovered that interest rates can affect results heavily. The same can be said about maintenance and thus, this item, for the tunnel, deserves particular attention. This was further reinforced with the level III analysis in which it was determined that the largest influencing items are the TTIs. It was mentioned that looking at figures that stand alone does not say much about anything. Therefore, it is important that a threshold is established (budget) for both investment and maintenance costs. If none of the alternatives meet these criteria, then not much more could be done. However, if all of these are within the specified target goal, then the following step is choosing for the most economic option. This can be done with the NPV approach. Given that each and every alternative has its respective maintenance characteristics (cost, timing, frequency, etc) and risks, this approach will yield the most favourable option based on the lowest net present costs.

Once the two best (if any) alternatives have been selected, different sensitivity analyses will further reinforce that the one with the lowest NPV is in fact the best alternative that meets the pre-established benefits. On the inclusion of minimized benefits due availability, it should also be noted that also the preferred alternative is better than the other in this criteria as well. If this is not the case, it is up to the organization to reevaluate the decision of the alternative considering how 'loss of benefits' compare to agency costs.

A primary shortcoming of these types of sensitivity analyses is that they give equal weight to any input value assumptions, regardless of the likelihood of occurring. In other words, extreme values (worst case scenarios) are given the same probability of occurring, which is not completely realistic, but for grounds of comparison, they can provide for some qualitative insights.

Nonetheless, after doing some comparative analyses, it can be concluded that, regardless of some uncertain parameters, if these are hold equal for all alternatives, Alternative 2, the bridge, is the most cost effective one regarding a life-cycle costing analysis.

The implications regarding this choice will be discussed in the next chapter.

6. Chapter 6. Discussion

Within the concept of bounded rationality, the information provided to decision-makers is certainly not ALL the information that could be provided. But certainly the more information provided, the better the decision can be said to be founded on a more solid scientific background, as long as it is relevant and, for the purpose of LCC, regards costs and lifetime, as its initials clearly describe it.

This information can be of qualitative and/or quantitative type, but should be considered as valuable input from a bottom-up point of view: starting from the engineers, to economists and then reaching decision-makers. This information should be conveyed in a manner that can be easily interpreted and thoroughly understood by all channels of communication given the cognitive limitations of humans along the planning phases of infrastructure projects.

It is also important to take into consideration how much time is allocated to this complex process. But not only time is important, but human resources, money, data, etc. All of these factors have proven to be interconnected with each other as time and budget limitations can threaten to restrict the type of resources that can be used to gather, process and monitor data. It comes as no surprise to state that unreliable data will yield unreliable results and therefore, unreliable decisions. The unreliability of data can be highly contested amongst different participants along the supply chain as it is a matter of perceptions and can lead to controversial discussions. However, its accessibility and availability will be briefly discussed in the following sections.

6.1. Comparing Alternatives (Ceteris Paribus)

The most important and critical underlying assumption of everything discussed so far is known as *"Ceteris Paribus"*. Meaning, all things being equal, at the moment the decision is made for the alternatives being evaluated, LCC can provide to be a useful tool. Indeed a strong and restrictive assumption given all the events that can unfold after a decision has been made. Particularly when not only costs should be looked at, but also benefits, environmental and social effects, deterioration factors, obsolescence drivers, political contexts, so on and so forth.

However, it was clearly stated that this appraisal tool is not all-encompassing or an allaccountable, problem-solving technique; in fact, it has been shown that the extent of its limitations is large.

When taking into consideration some factors that decision-makers should take into account, such as:

- Economic principles,
- Technical properties,
- Human behavior and
- Organizational Aspects,

it becomes clearer that LCC aims to address these by providing valuable insights into each, which would subsequently affect many decisions being made along the project phases. However, it does not attempt to solve each and every aspect surrounding these factors, especially when future uncertainties are taken into consideration and remembering that trends can change abruptly. Yet these are assumed to be applicable to the alternatives being evaluated (and not the ones that are unknown).

To the extent previously envisaged by what is the expected output and usefulness of LCC regarding:

- Investment costs,
- Maintenance costs,
- and NPV of alternatives,

one recognizes that the benefits of LCC can best be exploded by focusing on these while addressing the aforementioned factors.

Also, and regarding its methodology,

- on a cost/year basis
- on a NPV of all costs

it can be concluded that using either approach can yield useful results. As current methodology dictates within RWS and amongst several other agencies that make use of this tool, using the second approach will yield the most cost-effective options by using discounting techniques of future activities whose **frequency and time of occurrence are highly uncertain**. Still, the first approach can provide for useful information and good grounds of comparison for cost drivers to fixed asset costs.

Transportation agencies have recognized the importance of LCC as it was described during the literature study. As of April of 2012, RWS has decided to introduce LCC into the decision making process, identifying the need to make use of it in the following ways (Bakker et al., 2010):

- Contractor Selection Procedure, by means of choosing the best contractors based on their LCC approach, innovation on maintenance strategies, high quality of delivery resulting in less incurred risks and earlier maintenance interventions.
- Technical and Functional Requirements, stimulating the reduction of long term costs by implementing improved technical specifications such as material selection, construction methodologies, increased capacity and availability, etc.
- Standardization, leading to reduction of product costs and risk of flaws.
- Incentive towards contractors, particularly with DBFM contracts and EMAT (economic most attractive tender) award mechanisms, by means of optimization of long-term costs.

As it is still in its developing phases and has not yet been strictly enforced or, for that matter, well structured, it is still unclear if it serves the full spectrum of these purposes. It was noted during the literature study and some interviews that allowing for more contractor's freedom of knowledge input (read innovation), can be very risky; particularly when a project involves new technologies/methodologies and the parties involved do not have the required know-how.

It should also be noted that LCC's main purposes, for now, is focused on costs. Yet it was mentioned that it is not the optimal estimating tool due to many factors, and also it is not in everyone's interest to have more accurate and transparent estimates. As there are many stakeholders involved in infrastructure projects, some can benefit from budget slacks, others, create competitive advantage given financial freedom in budget allocation.

Following the MIRT process, it was established that LCC influence on cost optimization is reduced at every phase. However, at each of these, new information should be available in the form of data, design details, technical specification, etc. This can be translated to a 'more accurate' cost estimation and it can certainly have an impact on the decision-making process.

For the purpose of this research, and to analyze if the model contributes to the problem definition, it was decided to focus mainly on the most influential uncertainties, yet, the full scope of effects of further developing the proposed model and its successful implementation is dependent on the indicators that will be mentioned next.

6.2. Predicting Service Life

It has been established that trying to determine a project's lifecycle is just as hard as trying to predict the future. Reasons behind this are reliability of tools that provide for deterioration factors such as physical stress/load, chemical degradation, environmental effects (natural disasters), and other risks. When trying to determine the economic lifetime, factors such as human behaviour, legislation effects, politics, natural resources, etc. should be incorporated. These economic factors are changing faster than the former and thus, making prediction of economic lifetime even more difficult, perhaps explaining why the real economic lifetime is even shorter than the expected one. There are so many indicators that need to be taken into consideration, i.e. demand. Functional capacity, for example, is changing faster than technical requirements (economic growth is changing faster than rising sea levels).

Yet, it has been shown in the previous chapter that whether using a technical lifetime (50, 80 or 100 years) or an economic one, the purposes of LCC can still be fulfilled: compare alternatives on an 'all things are equal' basis and furthermore, choose one based on their respective outcomes.

In an effort to improve service life predictability of infrastructure assets, Koops (2012) emphasizes the importance of having a structured process starting from Systems Analysis to Functional Analysis and ending in Technical Performance Measurements, either

quantitative or qualitative. His conclusions further reinforce the fact that economic lifetime and the fast pace of safety standards changes are much more likely to supersede the prescribed technical lifetime.

It is important to monitor economic indicators that may point towards its desired lifetime. It is up to top management, in this case asset managers, to effectively monitor if the asset in question is performing as expected and based on different indicators, evaluate if large rehabilitation is preferred over complete renewal. Decision-makers need to be aware that the options exist, that these options can be **economically better**, **given increased benefits**, yet these are beyond the scope of LCC capabilities, given that at this stage, a new CBA should be able to assess the full range of impacts of this last option. Although in transportation infrastructure expanding a road, building a parallel bridge/tunnel, is generally the preferred alternative.

6.3. Discount Rate.

It was shown that the discount rate selected for an LCCA has a large effect on the final result. Using a low rate, future costs will be exaggerated and yield the impression that annual expenses are lower. And using a high one will do the opposite, emphasize on initial costs over future ones.

Not only that, but it was also shown that it constitutes the highest percentage of the total costs. With a range of 2,5% established by the government to a possible 10% used by a contractor, it reflects potential earnings on a project that could have been invested elsewhere and earn some return. Typically, contractors get commercial loans from banks at higher rates which can pose a major risk in their financial performance. It is normal that they would cover for this risk by modifying some figures and balancing large present investments and recurring ones in the future to adjust a desired NPV. This can pose a risk in the decision-making process by increasing credibility gaps by the usage of different values aversion to risk by different parties. Not to mention inadequate decisions by lack of knowledge between the relationship of initial and future costs. However, the risk of fluctuating rates can best be absorbed in a finance agreement depending on the form of contract.

Different discount rates can be used for different types of industries, markets, commodities, etc. Data on interest and inflation rates based on past and future trends can help establish a middle ground for deciding what type of rate should be applied for the analysis. As an LCC result will not provide definite-exact figures, but rather reasonable ones, the same approach should be used for the choice of rate. Performing sensitivity analyses on different rates (ranging from low to high) should reflect any change in the ranking of alternatives, if this does not occur, then it should not be a major cause of concern.

6.4. User Delay Costs.

Some equations were provided to account for user delay costs based on how benefits are estimated in transportation infrastructure projects. Given that the latter can be said to

be reliable in a 20 to 30-year time span, it does not prove to be insightful to try forecasting these costs associated with maintenance activities exceeding this time horizon either.

The aforementioned equations require input that may or may not be available during the LCCA along the MIRT process. During the initiation phase, if little is known about maintenance figures, then maintenance strategies are even more obscure at this stage.

What is known, though, is that based on the CBA, the number of hours saved per 24-hour period can be estimated. Therefore, equation 8 can be used at this stage to provide a rough estimate on these costs. More information is required on number of travellers per day, and the classification of these, i.e. business, freight, etc.

The subsequent phases can provide more information that can be used as valuable input to try improving the forecasts and thus, validity of results.

Once the design is complete and before calling for bids, the level of detail should be enough to decide on maintenance strategies as well, and thus, be able to use equation 9, where more details are required.

Remembering that sometimes user delay costs can or cannot reflect a large amount of investment costs and large rehabilitation activities, it is also important to see if the latter are being accounted for in lifecycle analysis. It would therefore be recommended that two separate analyses be conducted depending on the type of project and when a large maintenance is expected to occur. After a threshold has been established by the agency, if user delay costs are calculated to be very little when compared to agency costs, then they could be excluded, given that the bearer of this cost is not the agency itself. However, it has been argued that these can in fact be large and can yield interesting opportunities to improve design, develop maintenance strategies, and more important, to provide insights to maintenance contracts, possibly an indirect benefit of LCC.

There are some incentives towards contractors that can be derived from LCCAs during design and construction phase, such as bonus for added quality, scope optimization and long-term maintenance responsibility (in DBFM contracts). These are always based on a reward on the contract as such efforts do require time and money on behalf of the contractor. There could also be a reward based on minimisation of user delay costs reflected on their maintenance programs, which would subsequently lead to development of contracts in which penalties are also established due to an exceedance of an expected level of unavailability.

Therefore, it is highly recommended that these are included into the LCCA in the earlier stages of decision-making, as completely ignoring these can lead to future risks unfolding, as opposed to interesting opportunities.

6.5. Risks and sensitivity analyses.

The incorporation of project-specific risks, particularly during exploitation and during maintenance has still room for improvement; although it was shown that these pose no major threat to the cost calculation, and more so for the NPV of any given alternative. When developing risk registers, a qualitative analysis of long term risks might be useful, but the same could not be said about a quantitative one as its potential benefits (if any) can be seen as being reduced with time given its little weight on the overall LCC calculation.

A sensitivity analysis (Level II or Level III) can provide valuable information on the cost drivers that can lead to focus of attention. For example, in the case of the tunnel, the most critical item was the TTI, and thus, deserves more attention than let's say, cleaning the asphalt. The cost of failure (risk) for such cost item should be analyzed further with Equation 4 and Equation 5. Again, the costs associated with user delays or unavailability should also be incorporated into the analysis, as they can prove to be substantial.

As with user delay costs, the type of data required for a careful sensitivity analysis can be difficult to be acquired. Some parties can allege that data sharing in general is too confidential to be disclosed, could generate conflicts of interests, or even lead to loosing competitiveness in the market. All these seem reasonable causes, but if cost estimations are to be transparent and lead to more robust decisions being made, it seems unreasonable to expect better results based on solid scientific background.

One could argue that while arriving to these results, much valuable information has been acquired, whether in the form of qualitative or quantitative input, it contributes (to some extent) to the decision-making process. Identification of some risks, incorporation of uncertainties, forecasted lifecycle, discount rate sensitivity, user benefits and user delay costs, data base reliability, the need for standardization, so on and so forth, all have a say in decisions to be made. Furthermore, they bring to light some explanations on deficiencies currently being faced by the construction industry, specifically regarding data gathering in maintenance projects.

There is need of a more structured organization for transportation infrastructure projects in general. In order to guarantee client's satisfaction and talking only about costs, there should be a more robust and firm approach to verifying the validity of results based on data availability and reliability on behalf of transportation agencies, (sub) contractors, engineers, suppliers, etc. As far as LCC is concerned, it could prove to be easier than doing so for the measurement of total benefits given its simplest unit dimension.

6.6. Decision making.

Given that when too much uncertainty is involved, decision-makers do not make rational decision within the context of social, political and/or environmental issues. According to Gluch and Baumann (2003), there are some inherent limitations in neoclassical economic

theory that restricts the adequate use of LCC for transportation infrastructure appraisals:

- It cannot handle decision-making under genuine uncertainty since it assumes that the decision-maker is always rational and has access to complete information regarding competing alternatives and their outcomes.
- It ignores items that have no owner and/or indirect effects, either short or long term.
- It can over-simplify multi-dimensional environmental and social problems by assuming everything can be expressed in a one-dimensional unit, such as a monetary value.
- It uses discount rates that rely on principles based on today's knowledge that can lead to a relatively small weight on the LCCA, particularly on the environmental context.

These come about as limitations, aside from all the previously mentioned ones, to the decision-making process. However, within the context of bounded rationality, as it was discussed in Section 3.5 of this report, the more information provided to decision-makers should involve a more rational decision being made, as long as this information is relevant and contributes to the desired outcome.

LCC cannot aim to provide a full risk/asset management program, nor solve the problems of cost overruns in public infrastructure projects, nor other problems that are aimed to be solved for public good by their implementation. Trying to come up with solutions to all these issues is trying to solve wicked problems that have no right or wrong solutions, but rather reasonable or unreasonable ones, as it is impossible to determine all sets of solutions.

These types of wicked problems can be minimized by trying to identify what type of solution should be applied earlier. Therefore, by focusing mainly on costs and the probabilistic approach to try forecasting them, it could be stated that identifying these in the earlier stages of the decision-making process can provide to be one of many solutions to cost overruns. Furthermore, when comparing project alternatives, the more information regarding costs, risks and uncertainties, on an all-things-being-equal basis, can lead to a more robust decision being made on the hands of knowledgeable professional experts and politicians.

6.7. Validation.

After comparing the results of each alternative, with the incorporation of user delay costs, cost of failure (risk during exploitation), additional future risks and some extra sensitivity analyses involving comparative evaluations and Level II and III probabilistic estimations, it appears that the method yields reasonable results and increases risks/uncertainty awareness throughout its development in different decision-making phases.

A major requisite for this method, however, is that different data should be obtained and modified along these phases. To have an adequate Level II and Level III analyses one has to know the means and spreads of each individual cost item. Also, the probabilities of failure regarding the most sensitive cost items should be incorporated along with their associated (re) construction costs and user delay costs. These are determinant factors to evaluate if they should or should not be included in the analysis in order to be able to state that risk awareness is indeed being created and they contribute to a robust type of analysis.

Relying only in expert estimation can lead to subjective results and furthermore, subjective interpretations leading to non-robust decisions being made. Having an insight into these types of data cannot only be of quantitative aid to provide more accurate estimates, but also improve other processes such as material selection or maintenance contracts.

Furthermore, given that there might be some time/resource limitations at each phase along the decision-making process, it is up to decision-makers to establish the level of detail for such analysis provided the availability of the aforementioned data.

7. Chapter 7. Conclusions and Further Recommendations.

It was suggested to the author of this thesis by the members of the advisory committee to approach the subject of risks and influences of uncertainties in infrastructure projects from a general panorama into a specific level. Beginning with socio-political to environmental aspects; from a macro-economic point of view to micro-economic details, such as Cost Benefit Analysis (CBA), deeper into useful tools such as Life Cycle Costing (LCC).

Chapter 1 reflects the main goal of this thesis, that is to improve an existing LCC model by taking into account the most critical uncertainties and risks in order to generate risk-awareness in decision-making.

Based on the *problem statement* and the *proposed objective*, the following research questions were formulated:

RQ1. Can LCC provide to be a useful tool for effective decision-making?

RQ2. In which ways can the cost drivers have an effect on the decision-making process?

RQ3. What are the major sources of uncertainty in long-term incurring costs in a project's lifecycle?

RQ4. Which aspects are most critical for a quantitative risk analysis during implementation phase over the lifecycle of a transportation infrastructure asset?

7.1.Conclusions

The abovementioned questions will be answered to draw the conclusions of this report from the theoretical framework and the case study.

Can LCC provide to be a useful tool for effective decision-making?

In theory, LCC aims to address some of these statements:

"It is unwise to pay too much, but foolish to spend too little."

"Cheap solutions can lead to costly decisions."

"You get what you pay for."

by thinking about long-term costs that can be affected by (high or low) investment options.

In the construction industry, and particularly for transportation infrastructure projects, the concept of life-cycle costing **may not be as useful as in other industries**, in which long term costs represent a larger percentage when compared to the investment costs, yielding more useful results from an analysis.

Yet, if many assumptions hold true, even though this is unlikely, **LCC can be very useful to compare alternatives on an all-equal basis** and make the decision to build if, and

only if, there is budget to maintain it. It was said that looking into future costs might be subject to potential errors, and trying to forecast these with accuracy is next to impossible, but this reality applies also to any other type of forecasting tool or parameter, such as benefits.

LCC seems to provide useful answers on WHAT to spend on, than HOW MUCH to spend on. It is unlikely that an 'accurate' cost estimate will come out of an LCCA, or even a budget for construction and maintenance programs, or for that matter, a full risk management program. Even more so in future maintenance activities that are confronted heavily with practical realities at their time of occurrence. **Still, it establishes figures that are based on scientific principles and serve as grounds of comparison** for different alternatives and/or for design optimisation once an alternative has been chosen.

However, there is much difficulty integrating maintenance and repair strategies during design phases in a contract other than DBFM. Maintenance theory is driven by the probability of failure, and analyzing the economic implications of their occurrence is bound to data collection exercises, difficult predictions and several sources of uncertainty. Still, for this case, it was shown that the economic implications are extremely low, posing very little effect on a decision. Furthermore, it is not common practice to allow for failure in public transportation infrastructure.

Although LCC helps visualize future costs and their economic implications for a decision being made today, it **does not address the future option of renewing vs. replacing**. **Assumptions should be checked regularly** as times goes by in order to evaluate if costs of current asset are higher than costs of a potentially new one. This would imply the end of its economic lifecycle and at the time a decision is being made, this is impossible to forecast. This implies a proactive asset management program to keep the system alive in order to analyze initial assumptions such as variable costs, functions, lifetime, benefits, etc.

LCC is also restricted by **one major assumption: benefits of evaluated alternatives are substantially the same**. This might be true at the moment the decision is being made, but might prove otherwise in the future. Trying to overcome this obstacle can lead to the incorporation of user delay costs in order to visualize how benefits are being reduced by an asset's availability. This, as it has been stated before, should not be considered part of agency costs even if budgets are being allocated from an LCCA. However, these could be part of the overall appraisal package for infrastructure projects and being able to forecast these, could be an additional benefit from LCC.

Furthermore, by incorporating these, plus risks and uncertainties both in short-term and long-term costs, one could say that decisions regarding maintenance activities amongst competing alternatives can rely on the **choice to be based on more solid and complete scientific background**. This is highly subjective to data input, which may or may not be

reliable. However, a decision-maker should assume that **data is non-biased** to any alternative.

Knowing that it is impossible to accurately forecast a project to the last penny and trying to minimize cost overruns is a wicked problem, the incorporation of all relevant costs in an LCC will contribute to the reasonable vs. unreasonable estimation, rather than the right vs. wrong one. Choosing a bridge over a tunnel has been shown to be more cost-effective for this case; being able to say that the forecasts are accurate or not, lies well beyond LCC capabilities and organizational strategies for post-project evaluations.

Given the ever-changing pluralism of public and the complex intertwining of infrastructure projects and their impacts on society, the ideal solutions are confronted by the valuations of a large array of groups of individuals: a problem might be solved for one while another is created for the other.

Effective, better, intended, expected, accurate, useful... so many adjectives that can precede a positive end to a decision-making process. Yet the extent of the consequences of these decisions can never be said to be captured or even yet, desired. Therefore, LCC will not answer what is best for society regarding transportation projects. It is merely a means to deciding for the most cost-effective option amongst competing alternatives with one big underlying assumption, which is the most restrictive of all, "all things being equal": benefits, environmental and social impacts, service life, discount rate, etc. Something that might be true at the moment the decision is being made, but is very likely to change right after it.

In which ways can the cost drivers have an effect on the decision-making process?

For this specific case, it was shown that interest, maintenance and depreciation are the largest cost drivers.

Putting aside what type of rate should be chosen and how it could pose a risk to who, it was shown that regardless of the choice, an alternative is still ranked best than the other with different sensitivity analyses.

It is important to **evaluate how each alternative will behave** regarding its future cash flow streams based on different (but plausible) discount rates. Knowing that there is not one correct/true value to be chosen, and the fact that this value has to be held constant for all alternatives being evaluated, there is still the possibility that using different rates might lead to an incorrect decision, i.e. not the most cost-effective one.

It is safe to assume that for this case, and regardless of the choice of rate and alternative, any fluctuation of it should pose no major threat to the decision, but not so a bearer (agency, supplier, user). The risk being derived from this can best be absorbed by a finance agreement depending on the form of contract. Allocating contingency funds, balancing, trade-offs, overheads and other, are all tools available for different

organizations to mitigate this inherent risk, at least to some extent. Furthermore, any effect of its change will hold true for any alternative that was not chosen. There are some inherent risks that are project-specific, yet interest rates can be regarded to be risky for all alternatives, even the ones that are not known.

Depreciation is determined by the size of the investment, the residual value and the asset's lifetime. The first one is a forecast derived by an LCC, and the second two are assumptions that serve as input for it. Assuming straight line depreciation over the end of the technical lifetime of any alternative is very limiting, as practical realities may prove otherwise, particularly in applications where there are usually salvage values (a % of the investment). Still, in public transportation infrastructure, and for this specific case, it was shown that different life spans leading to different residual values does have an effect on the NPV of the alternative, but not so on the ranking of these.

Maintenance activities have also shown to be large cost drivers, a level III analysis reinforced the fact that, for this case, maintenance of TTIs are highly influencing factors and deserve particular attention during design. Maintenance optimisation during design phase can provide to be beneficial in this case as well as the adequate choice of (sub) system components.

Still, LCCA results are just **one of many factors that influence the ultimate selection** of a design strategy. The final decision may include a number of additional factors outside the LCCA process, such as local politics, availability of funding, industry capability to perform the required construction, contractor and agency experience, etc.

It has not been proven in this thesis that user delay costs can have a large effect in maintenance activities, but its importance and benefits in the LCCA have been thoroughly highlighted over the course of this report. Thus, their importance and influence in decision-making can be improved when maintenance and (re) construction cost due to failure can be associated with user delay costs due to unavailability and even establish a connection to loss of benefits (if any). **Maintenance contracts and budget allocations being derived from an LCCA** is a question that will be answered when there is more maturity in the process of incorporating the aforementioned costs leading to their acceptance by guarantees of their accurate forecasts. Asset management strategies or programs can be obtained from all of that has served as input for an LCCA. Nonetheless, this can be difficult to implement, monitor and evaluate, given that practical realities of future activities are on a more dynamic process in relation to institutional considerations, social objectives and political goals.

If maintenance activities account for very little of the total costs, optimising these during design would not provide to be fruitful, but these depends on the asset in question.

What are the major sources of uncertainty in long-term incurring costs in a project's lifecycle?

When focusing only in long-term costs, the major sources of uncertainty, which may or may not be eventually translated into risks, can be divided into categories that affect the asset in general, and ones that affect maintenance activities.

When considering factors that can have an effect on optimal selection given the results of a LCCA, two were repeated amongst professionals, the findings of the literature study and the case study: *Lifecycle* and *Discount Rate*.

Asset Lifetime.

The concept of lifecycle has been mentioned over and over throughout this document. It is the most determinant factor of all, as it regards the life of the asset in question. Many factors that can lead to the end of a service life have been identified, but mainly the economic and technical lifetimes have been addressed. Given elegant tools in maintenance theory, predicting a technical lifetime has been increasingly better, regardless of several external factors of deterioration coming into play. As far as economic lifetime is concerned, the same could not be said as the full range of micro and macro-economic aspects surrounding a project's implementation is extremely difficult (if not impossible) to fully quantify. **Monitoring this has to be done on an asset management level**, checking assumptions on a regular basis, making this an iterative process involving relevant stakeholders, much like risk management.

Nonetheless, if these economic scenarios are held to be transpiring equally for evaluated alternatives, the choice of the most cost-effective alternative can be said to be the reasonable one. It was previously stated that LCC will not yield one exact answer that can be said to be accurate to its last cent, even more with a newly probabilistic approach involving uncertainties regarding its cost items. What it does provide, is a reasonable answer with an adequate range of costs that can lead to a rational choice when comparing alternatives (ceteris paribus).

This same implication has to be hold for the application of the discount rate.

Discount rate.

It was proven during the report that a change in discount rate can have several implications in the results of the analysis: a higher discount rate will yield lower NPV (read net present costs) but a higher interest cost. The difference between risk-free and risk-adjusted discount rates in economic terms was emphasized and should be of particular importance regarding public infrastructure projects as these involve such high investments which can be very risky.

Using an 'unreasonable' discount rate can lead to projects being rejected, given their perception of being too costly/risky in the long run. The word unreasonable is used as opposed to 'right' or 'correct' since engineers are not as qualified as economists to

determine which number is correct; economists and even decision-makers might be in a more capable position of doing so, but sill, no one definite precise number will yield a definite precise answer.

These impacts though, may or may not prove to be of high consequences for ground of comparison, as it was shown for this case during a sensitivity analysis regarding discount rate modifications, that one alternative is always preferred over the other. The implications regarding the choice of rate were previously discussed.

Other sources of uncertainty that were found to be substantial regarding maintenance activities were:

User delay costs.

It was mentioned that the largest risk about maintenance activities is that they are not included during design; the same can be said about user delay costs. Not only can they lead to a better choice of alternative, but subsequently to design improvements.

However, this depends on two important things: level of detail of design at any given phase of the MIRT process, and data availability regarding effects of maintenance, such as: length of work zone, velocity changes, average daily traffic, types of users, etc.

During the decision-making process, the earlier they are included, the earlier its effects and benefits can be implemented. They can increase validity of results and provide for advantages during the tendering process as they could be part of the award criteria and aid in preparation of maintenance contracts.

Cost of failure (risk).

Even though it was shown for this case that the cost of failure (risk of large fire) during exploitation does not contribute much to the LCC, it can contribute qualitatively towards generating risk awareness for more specific decision-making processes, such as material selection for (sub) system components, but not necessarily project appraisal.

Maintenance theory addresses preventive and corrective efforts to keep the asset functioning to its expected level of performance. Inspect and repair is a norm in this theory. However, the cost of failure is usually neglected as the consequences of such failure can prove to be detrimental. It was also suggested in this model that this cost be added to account for a major risk leading to (re) construction and try to quantify its economic implications. There are many tools for determining failure modes, and risk experts on tunnels, bridges and roads can provide valuable information on failure probabilities regarding the top event in a fault tree mode.

Others.

Timing and frequency of maintenance activities, and risks associated with these do not pose any significant impact on the LCC calculation and thus, should not have any major influence in the decision-making process.

Which aspects are most critical for developing a risk analysis during the lifecycle of a transportation infrastructure asset in order to support effective decision-making?

It was shown that risks during construction are larger than during exploitation or maintenance. Given the repetitive and standardized characteristics of maintenance activities, these pose less risks and uncertainties than the former. This can be said to be true for project-specific risks and not so for external risks that are applicable to all alternatives, as far as it can be grasped on an LCCA.

There are many **other types of risks occurring during a project's lifecycle** that do not necessarily regard maintenance activities, such as some brought upon by new technologies, stakeholders, markets, financing, administrative, functional changes due to legislations, environmental or macro-economic changes, etc. These are almost impossible to predict and rely **beyond the scope of benefits of LCC** as trying to quantify all these uncertain effects would seem an impossible task, even more if this is to be done for each alternative during the initial phases, where there is even more uncertainty regarding the project in general.

These can certainly be considered as risks that have an effect on future costs, but would be better dealt with on an asset management level. These changes and their impacts can be assessed at their time of occurrence in a more transparent way than trying to predict and account for at the moment a decision is being made while only looking at the cost drivers of a project.

As it was stated, risks related to maintenance activities are far less of that a new construction given the repetitive and standardized character of the former. Regardless of these facts, a sensitivity analysis has shown that the impact of different uncertainties in maintenance activities such as their frequency, timing, and order of magnitude, **pose such a little change in the NPV** that they could practically be disregarded and the rule of thumb of adding 10% for risk reservation or a special events contingency factor should prove to be sufficient for each alternative.

When conducting a probabilistic estimation, a Level II or Level III analysis will yield the most critical cost contributors and therefore, yielding good insights into project risks and values towards determining what the priorities for further analysis of a project could be.

Given that minimizing risks and uncertainties involve time and costs, the question then could be, is it worth the effort?

A qualitative risk analysis regarding future costs might provide some important information and knowledge to the organization (client or contractor) for improved processes in decision-making and also regarding some sources of uncertainty. An extensive quantitative risk analysis can support this but is not always possible or even desirable since it does not provide to be worth the effort, particularly considering that these account for so little compared to short-term costs. If the effectiveness of risk management practices is questionable regarding construction phases, then for postimplementation it should be even more questionable as post-risk management evaluations occur mainly in large projects, and only to some extent. It seems only fair to assume that some uncontrollable risks are inherent to all types of projects, and decisionmaking based on scientific principles will always be confronted with eventful realities of the future.

7.2. Recommendations

This section will provide some recommendations and also suggestions for further research.

Based on an LCC level, the calculation of user delay costs vs. a long-term quantitative risk analysis can provide to be more useful in the long-run. As DBFM contracts are increasing in popularity and importance, it seems of more benefit and added value to provide clients with more information and insights regarding these, its effects and impacts both on technical and financing aspects. The same could be said about accounting for risk in design optimisation, even though it might not contribute much to the overall decision (low influence on NPV), it can provide useful information in subsequent phases: material selection and other specifications can arise from an LCCA. It seems it would contribute more towards the desirable objectives set by RWS that go beyond just providing cost insights.

The limitations on these are mainly resources on both ends, client and engineer. Furthermore, since LCC has not ONE true answer, there cannot be said to have what is called an optimal solution.

As LCC's rely on mostly on data, but very little is known about their validity, particularly concerning maintenance activities, it is very difficult to be able to say that a forecast is reliable until the moment the money has been spent. Many current maintenance practices are characterized by *observe & repair* traditions in which some data might be recorded, but not with enough detail to provide a robust analysis in the forecasts. This comes as a major limitation for the analysts in the sense that the results and recommendations can be either based on pessimistic or optimistic outcomes on a specific item. Data collection is indeed expensive, difficult and many times neglected. It requires strategy, legislation, rigorous processes and the use of several resources that could be used otherwise. The question is, is it worth all the effort or are decision-makers comfortable/confident with the decision made provided the information at hand? This is also suggested for further research.

Regarding user delay costs:

It was found that these are not considered in current LCC methodology by RWS since they are not incurred on the agency but are expenses on another bearer: the users. Given that the user is also the bearer of the benefits, it is also recommended that these are included in the analyses provided they will contribute to maintenance programs or contracts and even to asset management practices. Research has shown that the earlier they are included into the analysis, the better, as design optimisation (including material selection) can be achieved thru it. Obviously, this depends on data, resources and timing between each decision point.

Regarding cost of failure risks:

The previous statement holds true for the cost of failure (risk) of some critical parameters as a result sensitivity analysis thru probabilistic estimations. The most critical items should be carefully analyzed as they are the largest cost drivers. This could result in improved material selection and a better analysis of their economic implications when they do fail. Material selection should consider replacement costs and difficulty of (re) construction as well as traffic delay resulting in user delay costs due to unavailability. This would result in an improved process regarding engineering and economics.

It is recommended that a database be developed, in which detailed costs (emergency repair rates, labour force, working hours, etc.) are recorded immediately after repairs in order to avoid information loss. More important, the economic implications of these failure probabilities have to start being associated with user delay costs too, not only (re) construction costs. The process of documenting these should be standardized and encouraged, if not enforced, to contractors.

Only then, it can be concluded if these costs are indeed contributing to LCC's objectives and at the same time worth being considered in the selection criteria for alternatives.

There should be a national database for documenting failure and their respective costs, both reconstruction (normal or emergency rates) and user delay costs. This should be then made available for contractors and engineers to better understand

- 1. Service life of (sub) system components
- 2. Failure modes and rates
- 3. Impacts of replacment costs relative to scheduled maintenance (preventive or corrective)

7.2.1. For further research

Regarding choice of discount rate:

It has been shown that regardless of the choice of discount rate (for this case), the choice of alternative is still the right one, given that ranking of alternatives has remained unchanged for any 'reasonable' discount rate. This MIGHT NOT always be the case and therefore, it would be interesting how decision-making could be affected by it. Who carries more risk, and how is this mitigated.

Regarding user costs:

Other types of user costs were found to be vehicle operating costs and crash costs.

Vehicle operating costs can be affected by pavement material selection. When optimizing a design, this selection can have an impact on how fast a vehicle can transport on the road, more wear and tear on the tires, and other factors. These are the hardest type of user costs to quantify.

Also, crash costs are not as difficult to quantify but are more of a sensitive type, trying to assign a monetary value to a fatality can lead to many heated discussions. If it was only restricted to accidents that do not result in death, but on delays and cleanups, then it could be less sensitive, but sill subjective.

Regarding data for LCCA:

 Data regarding maintenance and investment costs should be carefully gathered and reported in order to be able to establish the most likely probability distributions. This would yield a more "accurate" probabilistic estimation. If maintenance budgets and programs come out of the results of an LCCA, it would be interesting to evaluate how these differ from the original estimates. Not much information could be gathered regarding cost overruns in maintenance projects.

It would also be important to see if there are any substantial risks in maintenance programs that are incurring in higher than 10% special-risks-contingency allocations.

2. It is of high importance to validate if these forecasts can be evaluated against actual results and try to establish reasons for discrepancies, which are likely to occur. Yet, this remains a major challenge in the construction industry as it still very difficult to account for every penny spent during short and long-term activities, not to mention that post-project evaluations are not strongly enforced within the industry.

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Glossary of terms and abbreviations

Abbreviation	Description	Definition (if not in report)
CBA	Cost Benefit Analysis	
DOT	Department of Transportation	
DBFM	Design Build Finance Maintain	Contractor is responsible for designing, building, financing, and managing an asset
EMAT	Economic Most Attractive Tender	
FHWA	Federal Highway Administration	
LCA	Life Cycle Analysis	
LCC	Life Cycle Costing	
LCCA	Life Cycle Costing Analysis	
LCM	Life Cycle Management	
LSF	Limit State Function	
MC	Monte Carlo simulation	
MIRT	Meerjaren Programma Infrastructuur Ruimte en Transport	From Dutch: Regulation of Long- term Program Infrastructure and Environment
NPV	Net Present Value	
NRM	National Regional Model	New Regional Model forecasting tool
RWS	Rijkswaterstaat	Directorate General of Public Works, Traffic and Water Management of The Netherlands
SCBA	Social Cost Benefit Analysis	
UDC	User Delay Costs	
VoT	Value of Time	Cost/hour assigned for different types of users in transportation infrastructure

Appendices

Appendix A. Formulas for Time Value of Money

Formulas governing the LCC calculations for discounting time value of money (U.S. General Service Administration, 2012):

Present Value	$PV = \frac{FV}{(1+d)^n}$	Equation 10
Real discount rate	$d = \frac{1+D}{1+i} - 1$	Equation 11
Uniform Present Worth	$UPW = \frac{(1+d)^n - 1}{d(1+d)^n}$	Equation 12
Annually recurring fixed	PV = TV * UPW	Equation 13
Annually recurring escalating	$UPW * = \frac{\left[\left(\frac{1+e}{1+d}\right)\right]^n - 1}{1 - \left(\frac{1+d}{1+e}\right)}$	Equation 14

Freelation water	E-i	
Escalation rates	$PV = \frac{1+i}{1+i}$	Equation 15

where,

- PV = present value
- FV = future value
- TV = today's value
- n = number of years
- d = real discount rate
- D = nominal discount rate
- e = escalation rate
- E = budgetary escalation
- i = inflation rate

Appendix B. Value of Time for Types of Users

These are figures from NRM Forecasting Software used by DHV.

People Tra	ansport travel time va	aluation growth over	time	
Mode of t	ransport: car			
WLO scen	arios: Regional Comm	unities (RC), Strong	Europe (SE), Transatla	ntic Market (TM),
Global Ecc	onomy (GE)			
Regional C	Communities (RC)			
	VoT commuting	VoT business	VoT other persons	VoT all motives
Year	(Euro per hour)	(Euro per hour)	(Euro per hour)	(Euro per hour)
2010	8,84	30,63	6,11	9,88
2020	9,58	33,17	6,61	10,7
2040	11,7	40,51	8,08	13,07
Strong Eur	ope (SE)			
	VoT commuting	VoT business	VoT other persons	VoT all motives
Year	(Euro per hour)	(Euro per hour)	(Euro per hour)	(Euro per hour)
2010	8,98	31,11	6,2	10,03
2020	10,03	34,72	6,92	11,2
2040	12,64	43,77	8,73	14,12
Transatlar	itic Market (TM)			
	VoT commuting	VoT business	VoT other persons	VoT all motives
Year	(Euro per hour)	(Euro per hour)	(Euro per hour)	(Euro per hour)
2010	8,98	31,09	6,2	10,03
2020	10,01	34,65	6,91	11,18
2040	12,73	44,07	8,79	14,21
Global Eco	onomy (GE)			
	VoT commuting	VoT business	VoT other persons	VoT all motives
Year	(Euro per hour)	(Euro per hour)	(Euro per hour)	(Euro per hour)
2010	9,09	31,47	6,28	10,15
2020	10,44	36,17	7,21	11,67
2040	14,11	48,86	9,47	15,76

Table 22. Value of Time (all scenarios)

- Regional Communities: emphasis on national sovereignty and public responsibilities.
- Strong Europe: emphasis on international cooperation and public responsibilities.
- Transatlantic Markets: emphasis on national sovereignty and private responsibilities.
- Global Economy: emphasis on international cooperation and private responsibilities.

Appendix C. Additional Tunnel Specifications

1. Asphalt

Assumption is that the coating (PAC) of the right lane after 12 years should be replaced and after 17 years the entire coating must be replaced. The single-layer porous asphalt is then milled (50 mm) and then re-applied (50 mm). After the complete coating was replaced after 12 years will be replaced again in the right lane (50 mm off, 50 mm out) and 5 years later, the entire coating changed, but it is milled 50 mm and 50 mm and 50 mm STAB PAC made.

2. Tunnel Technical Systems (TTI)

The maintenance of the TTI includes annual maintenance and replacement costs.

Annual maintenance includes, but is clean & repair of equipment, securing wiring and maintenance of mechanical systems (preservation steel structures). This is based on BON March 2007 Object Management Regime Artworks an amount deduced to be of \leq 52.56 / m2. This is on the following basis:

- In 2006, € 116.4M maintenance and attention to artworks (including VAT). Of these, 32% spent on installations, of which 98% is spent on TTI. In total there were 568,100 m² of tunnel. It was also indicated that € 10.3 million were spent on annual maintenance and € 35.5 million on variable maintenance. That translates into annual maintenance of the TTI of:
 - Not disclosed due to sensitive information. Contact the author at <u>gerokrutz@gmail.com</u> for more details.

In the BON standards it is not clear which frequency (or timing) is used for variable maintenance, but in case of TTI it can be seen as the replacement. For this, an assumption is made that TTI after 25 years should be completely replaced. The BON standards states that TTI be replaced every 15 to 30 years. The L and U-value (quantity) are taken into account (-40% and +20%). The costs of replacements are similar to the initial construction costs. The costs of removing the TTI are included in the L-and U-value.

3. Concrete Construction

The maintenance of the concrete works include annual maintenance and major maintenance.

The cost of annual maintenance are derived from BON March 2007 Property Management Regime Works. The calculation of the TTI shows that (45.8% to 36.5%) \notin 9.3 million were committed to maintenance and concrete pavement construction. It is assumed that 20% was borne by the concrete structure.

• Not disclosed due to sensitive information. Contact the author at <u>gerokrutz@gmail.com</u> for more details.

The cost of major repairs are also derived from BON March 2007 Property Management Regime Artworks. There is an amount taken from \leq 41.47 / m2. This is on the following basis:

Not disclosed due to sensitive information. Contact the author at <u>gerokrutz@gmail.com</u> for more details.

For the replacement of the tunnel (including ramps), the assumption was made that the tunnel after the end of its lifetime (30, 50 or 100) should be replaced. In the estimation of the L-and U-value, the demolition costs are included.

Scope Exclusions

Below are the items listed that are not included in the estimate (out of scope):

- Modifications to the underlying road network due to the construction of the tunnel
- Administrative and operating costs for the tunnel
- Costs for the traffic
- Cost of energy installations and lighting bored
- Investment and management & maintenance for toll
- Residual value of infrastructure beyond the technical lifetime
- Internal (management) costs

Appendix D. Drawings

Not disclosed due to sensitive information. Contact the author at <u>gerokrutz@gmail.com</u> for more details.

Appendix E. User type multiplier

	Year	RC	SE	ТМ	GE
Commuting	2000	1,16	1,16	1,16	1,16
	2006	1,14	1,14	1,14	1,14
	2020	1,12	1,11	1,11	1,10
	2040	1,12	1,10	1,10	1,09
Business	2000	1,12	1,12	1,12	1,12
	2006	1,11	1,11	1,11	1,11
	2020	1,12	1,11	1,11	1,10
	2040	1,09	1,08	1,08	1,07
Others	2000	1,54	1,54	1,54	1,54
	2006	1,50	1,50	1,50	1,50
	2020	1,43	1,39	1,42	1,40
	2040	1,43	1,36	1,36	1,33

 Table 23. User Type Multiplier (all scenarios)

Appendix F. LCCA Results Tunnel

Not disclosed due to sensitive information. Contact the author at <u>gerokrutz@gmail.com</u> for more details.

Appendix G. Interviews

Name	Organization	Date
Bert Schilder	DHV	24-02-2012
Marco Karremans	DHV	24-02-2012
Hette van der Zwaag	DHV	24-02-2012
Martien Reniers	DHV	08-03-2012
Don de Mello	DHV	14-03-2012
Geert Fuchs	DHV	15-05-2012
François Ekkendonk	DHV	15-05-2012
Marcel Bakker	DHV	16-05-2012
Emiel van Zwet	DHV	06-06-2012
Wim Koops	RWS	09-07-2012
Jasper Schavenmaker	RWS	26-07-2012
Max ten Cate	Price Waterhouse Coopers	04-08-2012
Pieter Meulendijk-de Mol	DHV	07-08-2012
Jacek Pachocki	DHV	13-08-2012
Eric Ross	Federal Highway Agency (FHWA, USA)	Correspondence
Tineke, Wiersma	RWS	Correspondance
Paolo Rocha	Odebrecht Construction & Engineering	Correspondance

Appendix H. User delay costs calculations

Maintenance activities and user delay costs

Discount rate	2,50%			
Analysis period	36			
	cost/yr	total	NPV	term
Yearly Concrete Tunnel	€ 53.957	€ 1.942.445	€ 1.789.778	1
Yearly TTI	€ 3.938.846	€ 141.798.470	€ 130.653.789	1
Control Smoothness Road	€ 13.489	€ 485.611	€ 447.444	1
Recover Damage (2%)	€ 53.957	€ 1.942.445	€ 1.789.778	1
SUB TOTAL		€ 146.168.971	€ 78.700.554	
sweep road (10 cent / m2')	€ 4.496	€ 323.741	€ 174.309	0,5
user cost	€ 2.698	€ 194.244	€ 104.585	0,5
replace toplayer right lane of road (2 x	€ 236.061	€ 499.894	€ 257.094	17
user cost	€ 141.637	€ 299.936	€ 154.256	17
replace toplayer all lanes (50mm)	€ 500.449	€ 529.888	€ 216.147	34
user cost	€ 250.225	€ 264.944	€ 108.073	34
replace toplayer all lanes (100 mm)	€ 801.258	€ 848.391	€ 346.068	34
user cost	€ 400.629	€ 424.196	€ 173.034	34
big maintenance concrete tunnel	€ 3.107.762	€ 5.593.971	€ 1.896.577	20
user cost	€ 2.175.433	€ 3.915.780	€ 1.327.604	20
TOTAL User Costs	€ 2.970.622	€ 5.099.100	€ 1.867.553	
Agency Costs		€ 7.795.885	€ 2.890.194	
replacement TTI	€ 36.966.361	€ 16.265.199	€ 19.939.307	25
replacement ramps tunnel	€ 60.293.133	€ 21.705.528	€ 24.786.128	100
replacement tunnel	€	€ 44.359.633	€ 50.655.463	100
	123.221.203			
to be detailed maint cost		€ 23.629.522	€ 17.697.165	
Direct Maint Costs		€ 236.295.215	€ 176.971.647	
Indirect Maint Costs		€ 141.715.526	€ 141.715.526	
Risk reservation (10%)		€ 40.164.026	€ 33.638.434	
Grand Total		€ 441.804.289	€ 370.022.771	

Appendix I. User delay costs parameters

The following table shows the parameter inputs required for calculating these costs for a certain activity using the Strong Economy Scenario for year 2040. At this stage, there are no traffic control plans so the change in time (hr/day) is used from the CBA results.

Decision Point 2		Total Users			
User Costs Paramete	ers	20000			
Commuting		Business		Others	
change in time		change in time		change in time	
(hr/day)	4,74	(hr/day)	3,33	(hr/day)	6,23
value of time €/hr	12,64	value of time	34,72	value of time	6,92
		average daily		average daily	
average daily traffic		traffic		traffic	
current users	6000	current users	6000	current users	8000
new users (50%		new users (50%		new users (50%	
of current)	3000	of current)	3000	of current)	4000
n (days)	2	n (days)	2	n (days)	2
upv	1,11	upv	1,11	upv	1,11
	€		€		€
SUB TOTAL	782.265	SUB TOTAL	1.528.478	SUB TOTAL	737.409
	€				
TOTAL	3.048.152				

Appendix J. Results Level III Analysis (Monte Carlo)

for 100 year life cycle



Project Costs - most likely value (T)	€ 1.439.271.533
Skewness for Investment costs	€ 9.225.267
Skewness for Maintenance costs	€ 15.670.101
Project costs - average (μ)	€ 1.464.166.902
Variation coefficient ($\sigma / \mu^* 100\%$)	22%
99% probability of exceedance	€ 981.861.805
90% probability of exceedance	€ 1.224.181.339
85% probability of exceedance	€ 1.287.577.164
50% probability of exceedance (median)	€ 1.617.712.394
15% probability of exceedance	€ 1.973.940.080
10% probability of exceedance	€ 2.059.782.602
1% probability of exceedance	€ 2.438.712.870
Standard deviation (σ)	€ 325.651.075

Appendix K. Risk Register Checklist Samples

Risks (Construction)

Description of top events	Prob	Consequence
		(€M)
Design and specifications are of insufficient quality,	3%	1,5
delaying project initiation.		
Negative effects during execution by additional	17%	6
drainage or others, resulting in additional measures.		
Change in (detailed) design, because of late survey	10%	1,7
plans delivery		
Insufficient coordination/agreements with Pro Rail	16%	1,9
activities around the tracks		
Floppy primer under Pannerdens canal creates	10%	2,75
difficulties in implementing tunnel boring, causing		
delays		
Delays due to floods on works around canal	4%	3
Additional information about geography of the	4%	15
projects, i.e. soil conditions that lead to new		
geotechnical assessment		
Corrosion Natura 2000 area during project	2%	1,7
implementation, does not meet demands		
Construction provides more hindrance than expected	8 %	2,1
and users/residents or environmental needs are		
increased, affecting scope		
Land acquisition permits	10%	2
Other environmental permits are outstanding	3%	1,2

Risk sources (exploitation)

Internal	Management conflicts		
	Loss of potential (benefits, profit)		
	Legal, licenses, contract modifications		
External (predictable and unpredictable)	Market		
	Operational		
	Environmental and Social Impacts		
	Currency fluctuations		
	Inflation		
	Taxation		
	Natural Hazards		
	Political		
	Legislative		

Appendix L. Level II Analysis for Maintenance Activities

The limit state function (LSF) entered into VAP to determine contribution of stochastic variables (a, b, c...) to the total result (an annual budget limit) is determined by:

LSF
$$Z = 8,000,000 - a - b - c - d - e - f - g - h - i - j$$
 Equation 16

	Maintenance	Cost	Lower	Upper	mu	sigma	coeff
b	Yearly TTI	€ 141.798.470	70899235,2	212697705,6	\$ 141.798.470,4	40933693	0,987
j	replace TTI	€ 36.966.361	25876452,7	48056269,3	\$ 36.966.361,0	6402762	0,154
i	big maintenance concrete tunnel	€ 5.593.971	2796985,62	8390956,86	\$ 5.593.971,2	1614840	0,039
а	Yearly Concrete Tunnel	€ 1.942.445	971222,4	2913667,2	\$ 1.942.444,8	560736	0,014
d	Recover Damage (2%)	€ 1.942.445	971222,4	2913667,2	\$ 1.942.444,8	560736	0,014
h	replace toplayer all lanes (100 mm)	€ 848.391	509034,7991	1187747,864	\$ 848.391,3	195928	0,005
С	Control Smoothness Road	€ 485.611	242805,6	728416,8	\$ 485.611,2	140184	0,003
g	replace toplayer all lanes (50mm)	€ 529.888	317932,5092	741842,5214	\$ 529.887,5	122372	0,003
f	replace toplayer right lane of road (2 x 3,5 m1)	€ 499.894	349925,7176	649862,0471	\$ 499.893,9	86584	0,002
е	sweep road (10 cent / m2')	€ 323.741	226618,56	420863,04	\$ 323.740,8	56074	0,001

The cost uncertainties were introduced as +/- percentages yielding upper and lower boundaries. These were assumed to be uniformly distributed. P(Z<0) = 0,402

These can also be done for uncertainties in quantities of each item. This could be time consuming and a Level III analysis is better suited for an overall probabilistic estimation around all variables.

Appendix M. Annuity Calculations

The following table reflects how annuities were calculated from a net present value.

	Lifetime		30		50		100
	d		2,50%		2,50%		2,50%
	UPW		20,93029		28,36231		36,61411
	Ann		0,04778		0,03526		0,02731
Alternative 1	NPV	€	483,80	€	595,80	€	647,50
	Annuity (€/yr)	€	23,11	€	21,01	€	17,68
Alternative 2	NPV	€	338,40	€	440,20	€	555,38
	Annuity (€/yr)	€	16,17	€	15,52	€	15,17
Cost Advantage	e Alt 2 vs. Alt 1	€	6,95	€	5,49	€	2,52