Master Thesis

Decision Support System to conduct Life Cycle Cost Analysis for service life road pavement design using an object oriented model

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Abstract

Introduction and background

Current road infrastructure sector focuses more on a life cycle approach and road availability during the design life. Design evaluation becomes more complex due to incorporation of both short and long term decisions during early development stages. Life Cycle Cost Analysis (LCCA) is a methodology to compare and evaluate short and long term decisions in an objective way. None of the existing LCCA frameworks take into User Delay Costs (UDC): the costs associated with road availability. Little time is available during early development stages and currently, the main focus of the decision maker in a project is on data collection rather than on alternative creation and evaluation. An object oriented model can be used for data capturing, because this type of model focuses on reuse of information for other projects. It is investigated if information needed for short and long term decisions concerning Service Life Planning Assessment (SLPA) for road pavement design could be captured in an object oriented model, to set the decision makers focus towards alternative generation and evaluation. The study concerned the investigation on how SLPA decisions could be related to the LCCA in a mathematical model to support the decision maker during early development stages concerning execution strategy, material use and asphalt composition. This research focused on the development of a Decision Support System (DSS) for evaluate competing alternatives based on Life Cycle Costs (LCC) in the field of road pavement service life design. The research is performed using ethnographic action based research techniques to make the chance of supporting work practice high. The model is validated using sensitivity analysis to obtain understanding in the behaviour of the model when the input values change. The outcomes were discussed with practitioners to determine if the model behaves according to their expectations.

Contributions to the sector

This research proved that it is possible to relate SLPA decisions to LCCA within a mathematical way. To evaluate competing alternatives, material performance characteristics are directly used for cost allocation to the year where they occur. New equations are developed and related to existing equations to automate the decision making process. This research gives a possibility to incorporate UDC within the LCCA. So far, no LCCA framework was detected that incorporated this cost category. This study

proves that UDC significantly influences the LCC and therefore UDC must be part of LCCA. This research underpins that an object oriented model is not only suitable for data structuring but also for reuse of information to create different alternatives.

Practical contributions

Within this research a model is developed and validated in collaboration with practitioners to conduct LCCA for SLPA in the field of road pavement design. Due to collaboration with practitioners the model suits the needs of the decision maker to underpin his decisions with objective information. The incorporation of UDC in the model gives the decision maker better understanding of how certain decisions influence the availability of the road. The model gives structure for holistic decision making, since UDC is incorporated. Besides that, the model is in line with current working practices due to the collaboration between practitioners and designer in the development phase. This makes the model more likely to adopt in the decision making process. The relation between cost elements and current organizational hierarchical structures makes it possible to structure information so that the model can also be applied to other projects. This will result in the collection of historical data. This research clarified that material cost is the most important parameter in the field of road pavement design and that the focus of practitioners on data collection should be on this parameter.

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List of abbreviations

LCC	Life Cycle Cost
DSS	Decision Support System
DBFM	Design Build Finance Maintain
NPV	Net Present Value
UDC	User Delay Cost
UDH	User Delay Hours
SBS	System Breakdown Structure
OBS	Object Breakdown Structure
WBS	Work Breakdown Structure

Definitions

Construction	The activities that occur due to, removal of an existing road structure including the foundation and replacing it by the same or a different structure (with or without modification of the geometry of the road). Modifying the substructure will not be taken into account.
Design life	The number of years for which the pavement is designed
Maintenance	Activities that are necessary to keep the safety, comfort and structural performance of the road at an acceptable level during the period between of end of construction and transmission of the asset to the client
Functional maintenance	Activities that are related to ensure the safety and comfort of the road users. These activities help to slow the rate of deterioration by identifying and addressing specific pavement deficiencies so that the designed durability will be met.
Object oriented model	A model that is a collection of objects which all store different values
Parametric model	A model that allows changing the complete estimation by changing one input parameter
Structural maintenance	The act of repairing an existing pavement to reset the deterioration process by overlaying or resurfacing the upper layer for the entire road section.
Road section	A uninterrupted section of road that is expected to have the same environmental and sub base characteristics
Trace section	A uninterrupted section of road that is expected by the client to have the same travel intensity and will have the same maximum driving speed
Road pavement	The upper layer, inter layer, under layer and foundation of the road, in essence the superstructure of the road
Degradation Curve	The curve that indicates how the performance of material reduces over time
Performance	The quality of the material during the analysing period based on a certain critical degradation mode
Service life	An uninterrupted period in time where the performance of the material is higher or equal to the minimum performance level
User delay cost	the estimated cost to the traveling public resulting from the construction or maintenance work performed
Service life planning	The process to come up with a solution for a new building or structure that provides reasonable assurance that it will function at least as long as the intended design life
Minimal performance level	The minimal performance that the material should fulfil over time for a certain degradation mode

1 Introduction

The infrastructural sector performed different attempts to create Life Cycle Cost Analysis (LCCA) frameworks (Wübbenhorst, 1986; Walls, et al., 1998; Zoeteman, 2001; Kim, et al., 2010; Ugwu, et al., 2005), since there is increasing emphasis on service life design (Ugwu, et al., 2005). LCCA is an economic assessment of an item, system, or facility to compare design alternatives considering all significant costs over the design life, expressed in terms of equivalent currency units (Zoeteman, 2001). LCCA should be performed during early design phases of the project to be beneficial, even though there is little knowledge concerning the system (Wübbenhorst, 1986). LCCA steers on the design by finding explanations on cost and design parameter relations during the early development (Durairaj, et al., 2002). LCCA is used to objectively underpin decisions concerning methods and materials that influence the service life of the asset, and therefore the life cycle costs (Ugwu, et al., 2005).

Besides the fact that there is a focus towards the integration of short and long term effects to the project, there is a shift towards availability of the project (Rijkswaterstaat, 2010; Rijkswaterstaat, 2013). Purpose is to minimize nuisance to road users. Unavailability of the road is translated to User Delay Costs (UDC) (Salem, et al., 2013). UDC is defined as the estimated cost caused by the increased users' travelling time resulting from the construction or maintenance work being performed (Daniels, et al., 1999). UDC is not often incorporated within LCCA, because of a lack of availability of estimation methods (Salem, et al., 2013; Walls, et al., 1998). According to the author's knowledge, there is no LCCA model or tool available for the estimation of LCC in pavement design which integrates UDC, construction costs, and maintenance costs and relates these to the service life of the pavement design.

During early design phases, little time is available to create service life design alternatives and to evaluate them. Service Life Planning Assessment (SLPA) is the process to find a solution for a road pavement design that provides reasonable assurance that it will function at least as long as the intended design life. The assessment determines the moments when maintenance is needed. The need for maintenance is mainly based on the degradation curve of the material and the minimum performance level during the design life (Zoeteman, 2001). It is investigated if it is possible to relate SLPA to LCCA in a mathematical way to relate maintenance decisions to cost allocation. An object oriented model can be used for data capturing and structuring as it focuses on reuse of information (Watson, et al., 2004). Relating LCCA and SLPA in a mathematical model and capturing the necessary data within an object oriented model leads to the Decision Support System (DSS).

A deterministic parametric DSS is created that gives the decision maker the possibility to perform 'what-if' analysis in the field of SLPA and LCCA. The model focuses on the superstructure of the road. In the mathematical model, material and execution characteristics are used to determine the moment for construction and maintenance activities. The maintenance moments are mathematically related to the cost allocation to compare design alternatives. The focus lays on identification of influence of construction methods and material choices to the service life, and therefore the required maintenance activities and cost. Net Present Value (NPV) calculations are used to compare alternatives (Woodward, 1997).

This research identified the possibilities to relate SLPA to LCCA within a mathematical model. Decisions concerning execution and Service Life Planning (SLP) strategies are mathematically related to cost allocation. Existing LCCA models were analysed and equations are directly incorporated, modified or supplemented with new equations in the DSS. The mathematical model is related to the information captured in the object oriented model. The information and the level of detail that are needed to perform LCCA are gained using ethnographic action research techniques such as literature review, interviewing experts and practitioners and abstractions from case study project data (Hartmann, et al., 2009). This made the practical value of the model high, since observations were directly presented and discussed with practitioners. This research identified a way to incorporate UDC within LCCA. So far, no LCCA model was detected that incorporated this cost category. This study proves that UDC significantly influences the LCC and therefore UDC must be part of LCCA.

After model development, sensitivity analysis is performed to examine model behaviour. This is done by changing the input values to analyse the influence on the outcome of the DSS. The results are discussed with practitioners to determine if the outcomes meet their expectations. Another purpose of sensitivity analysis is to determine the input parameters with the highest influence to the outcome. This research identified that decisions concerning traffic lane closure and material costs influence the model outcome the most. Traffic lane closure is a project specific parameter implying that sensitivity analysis should be performed per project to set a direction for alternative creation. The first focus for data collection should be on material costs, since this influences the model outcome the most.

The structure of this report is as follows: Chapter 2 identifies state of the art literature related to Service Life Planning Assessment, Life Cycle Cost Analysis, object oriented modelling, and identifies what is not known and what will be addressed in this report. Chapter 3 explains how this has been addressed. Chapter 4 identifies the decisions and informational needs that must be captured in the DSS. Chapter 5 explains the automated SLPA process model structure and the mathematical background of the model. Chapter 6 identifies strengths and limitations of the model by applying the model in a real case. The information found fin chapter 6 is used in chapter 7 for the model validation using sensitivity analysis. The report ends with a discussion (chapter 7) and conclusion (chapter 8).

2 Points of departure

Current construction industry focuses on the design life of the project and the availability of the project during the design life. Short and long term decisions have to be made at the beginning of the project within a short period of time. Different sources of information concerning material performance, costs and execution methods should be determined to create and compare alternatives to find economically efficient pavement alternatives concerning construction and maintenance activities. Service Life Planning Assessment (SLPA) is the process to come up with a solution for a road pavement design that provides reasonable assurance that it will function at least as long as the intended design life. This assessment does not cover for the evaluation of competing alternatives. Life Cycle Cost Analysis (LCCA) can be used to quantify different alternatives by performing trade-offs between short and long term decisions to ensure optimum selection (Woodward, 1997). The decision maker should focus on creation and evaluation of Service Life Planning (SLP) alternatives instead of data collection. Object oriented modelling is a modelling technique that structures design information and focuses on reuse of available information. A Decision Support System (DSS) is a computer-based information system that supports decision-making activities. A DSS consists at least of a user interface, a data management system (DMS) and a model management system (MMS). As can be seen in Figure 2-1

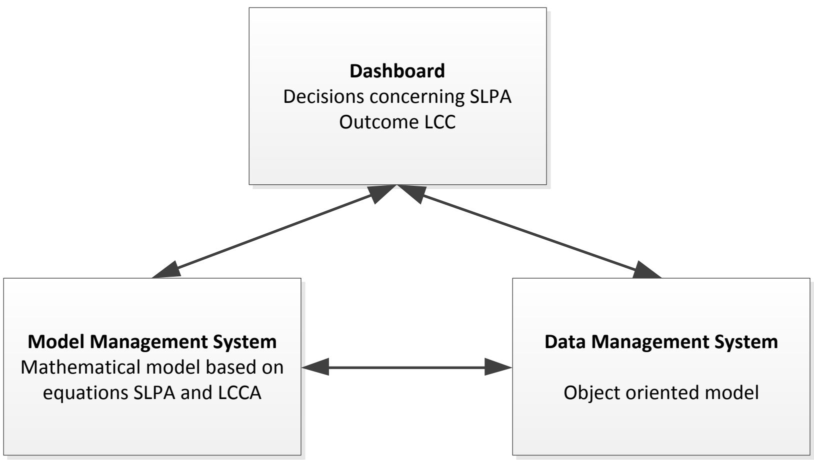


Figure 2-1 Decision Support System based on Mohemad, et al. (2010)

The dashboard gives the decision maker the possibility to use the DSS and to see how decision affect the LCC of the alternative. The DMS structures for decision making. The object oriented model could be used for the DMS, since it structures and stores available data. The MMS processes data stored in the DMS based on decisions made in the dashboard. The MMS describes the relationship between parameters mathematically and is used to present results of decisions taken in the dashboard.

This chapter first addresses what cost categories and elements should be integrated within the LCCA to perform SLPA. After this, literature is consulted to determine if current LCCA frameworks address the identified cost categories. Next to that, the current SLPA process is analysed to investigate how the need for maintenance can be related to LCCA. Object oriented modelling is discussed in more detail after this and a conclusion is given concerning the needs to create the DSS to conduct SLPA for road pavement design. All this is the input to the hypothesis, goal and research questions of this research.

2.1 Life cycle cost analysis

This paragraph is divided into life cycle cost framework and life cycle cost estimation. The framework section discusses important cost categories and elements. The estimation section identifies current LCCA models. The process of the models is discussed just as important equations and downsides of the models.

2.1.1 Life cycle cost framework

In LCCA it is important to determine the significat the cost elements and to wich cost categories they are related. Important criteria are that it supports the decision maker in performing different trade-offs and that they suit the objectives of the product and company (Woodward, 1997). Maintenance costs and construction costs have to be incorporated in the Life Cycle Cost (LCC) framework, due to focus on the design life in the construction industry. Availabillity of the road is another focus point of the current construction industry. The costs associated with availabillity are defined as User Delay Costs (UDC), the estimated cost to the traveling public resulting from the construction or maintenance work performed. UDC are time dependend, because it is related to the unavailabillity of the road due to construction or maintenance activities. The LCC framework should devide costs into time dependend and time independent to integrate UDC. Mirzadeh, et al. (2013) created a LCC framework were cost elements are categorized in time depended and energy. The focus of his research laid on the investigation of national (labour and equipment costs) and international (oil and material cost) wide interest rates wherefore these categories were sufficient. The model of Mirzadeh, et al. (2013) is adjusted to meet the purpose of this LCCA. In this research costs are categorized within construction, maintenance and UDC as can be seen in Figure 2-2. Materials are related to both the categories construction and maintenance, depended on the year where the activity takes place. The activities and asphalt layers are derived from the research organization, relating the framework to the objectives of the company.

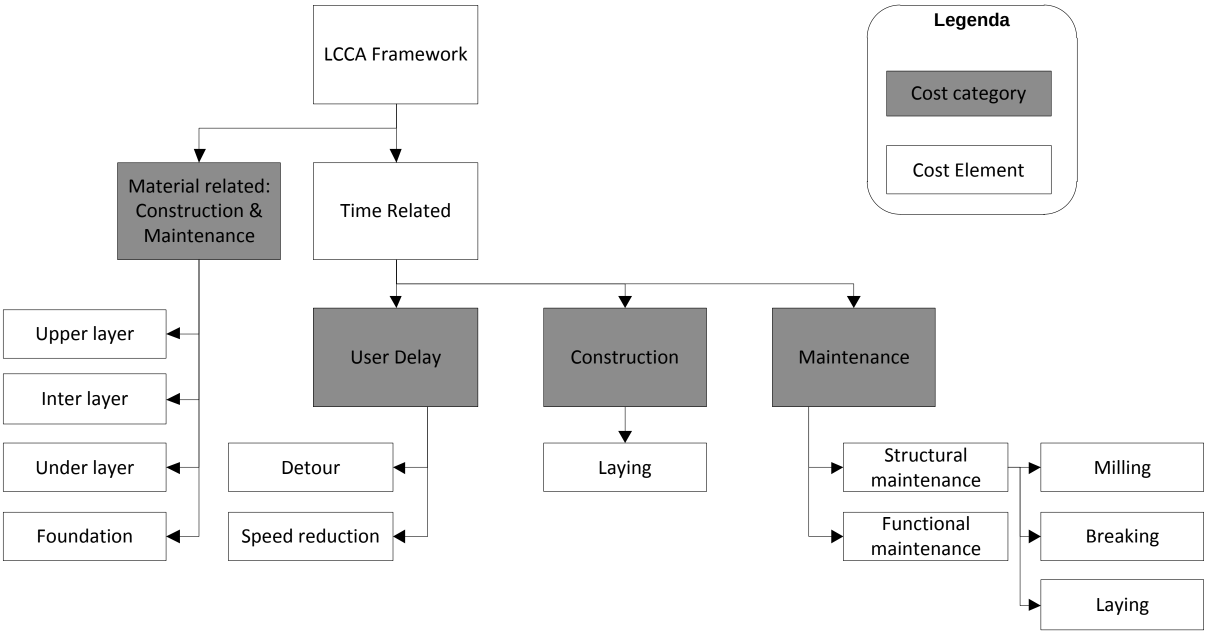


Figure 2-2 LCC framework for asphalt pavements based on Mirzadeh, et al (2013)

Construction cost is defined as the costs that occurs due to removal of an existing road superstructure and replacing the superstructure by the same or a different superstructure (with or without modification of the geometry of the road) (OCW, 2006). Modifying the substructure is not taken into account. Maintenance is defined as activities that are necessary to keep the safety, comfort and structural performance of the road at an acceptable level during the period between end of construction and transmission of the road to the client. Functional maintenance activities are related to ensure the safety and comfort of the road users. These activities help to slow the rate of deterioration by identifying and addressing specific pavement deficiencies to meet the designed durability (OCW, 2006; Scholz, 2012). Structural maintenance includes activities related to the reparation of an existing pavement to reset the deterioration process by overlaying or resurfacing the upper layer (Scholz, 2012). User Delay Cost (UDC) is defined as the estimated cost caused by the increased users travelling time resulting from the construction or maintenance work being performed. UDC primarily refers to lost time caused by any number of conditions including:

- detours and rerouting that add to travel time;
- reduced roadway capacity that slows travel speed and increases travel time (Daniels, et al., 1999).

Maintenance activities have to be performed within projects that focuses on a life cycle approach, to keep the road up to minimum requirements. UDC is a significant factor in LCCA, because it is affected by maintenance and construction activities (Krützfeldt, 2012). Despite the fact that UDC influences the costs of the project, they are not taken into account within most of the economic alternative evaluations (Krützfeldt, 2012).

To understand the estimation of UDC in a project, background of the road configuration is needed. Each project can consist of more road sections and a road section is defined as an uninterrupted section of road that is expected to have the same environmental and sub-base characteristics. Within a road section, different trace sections are allocated. These are defined as an uninterrupted section of road that is expected by the client to have the same travel intensity, traffic lanes and maximum driving speed. When it is determined that a certain road section will be constructed or maintained, a closure of trace sections is needed to conduct the activities, which result in user delay. The duration of the closure, amount of users and penalty stated within the contract determine the user delay cost for the activity and can be different per trace section due to other (expected) traffic intensities. These concepts are theoretically represented in Figure 2-3. When traffic lane 21 and 22 are closed to execute structural maintenance, the availability of the road section reduces. Users have to reduce their speed to keep a safe situation resulting in a longer duration to move from A to B.

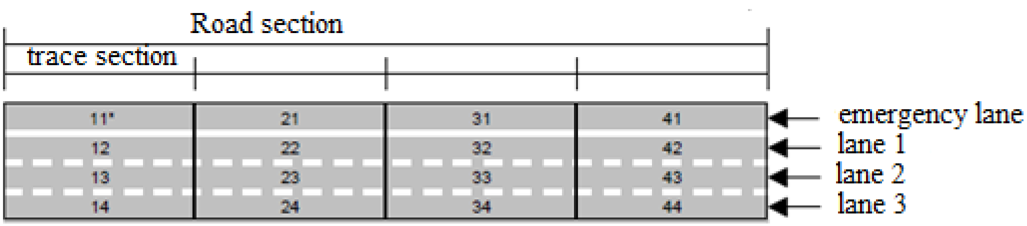


Figure 2-3 longitudinal profiles and road sections, derived from Backx (2012).

The discussed LCCA framework sets a structure of the cost elements that will be addressed within this research. The level of detail of the information needed to perform LCCA does not become clear. It is not known how the different cost elements can be determined in such a way that the decision maker can underpin his decisions. Insight in the informational needs of the decision maker to perform LCCA concerning SLP road pavement design is needed.

2.1.2 Life Cycle Cost estimation

Insufficient involvement in engineering can influence the maintenance cost negatively (Krützfeldt, 2012). A holistic view on how different decisions influence each other during early development phases is important, because at this phase the decision maker can influence the design the most (Wübbenhorst, 1986). LCC provides the theoretical concepts to balance those short-term and long-term decisions.

LCC seeks to optimise the cost of acquiring, owning and operating physical facilities over their useful lives by attempting to identify and quantify all the significant costs involved in that life (Woodward, 1997). Instead of only determining construction costs, trade-off are made between aspects that influence the cost of the road during the design life to find the optimum, lowest life cycle costs. Purpose is to facilitate the decision maker concerning competing alternatives. LCC facilitates design steering and finding explanations concerning cost and design parameter relations. (Durairaj, et al., 2002). LCC determines the costs per year, but cannot directly be used for alternative evaluation. Net Present Value (NPV) converts all costs found using LCC techniques to the present value to compare competing alternatives. Different attempts were performed to create a LCCA methodology for the construction sector. An overview of these attempts is given in Table 2-1.

One of the main differences in the process steps of the frameworks is the perspective from were the LCCA is performed. Krutzveld's (2012) framework is developed from the viewpoint of the road owner and indicates the need to determine the design life before the analysis. NPV is used in two frameworks to compare alternatives, while others not clearly define how alternatives are compared.

UDC is only specifically incorporated within one framework. System performance is used in two frameworks for determination of need for structural maintenance.

Author	Analysing process	User, phase and system	Remarks
Walls & Smith	1. Establish pavement design strategies 2. Determine performance periods 3. Estimate agency cost 4. Estimate user cost 5. Develop expenditure stream diagrams 6. Compute NPV 7. Re-evaluate design strategies	**User:** Road owners **Phase:** Initiation **System:** Road pavement	• Considers maintenance strategies based on performance periods • Considers uncertainty
Krützfeldt	1. Establish period 2. Determine activity timing and performance periods 3. Estimate agency costs 4. Estimate user costs 5. Perform qualitative and quantitative analyses 6. Develop expenditure stream diagrams 7. Compute net present value 8. Analyse results	**User:** Road owners **Phase:** Initiation **System** Infrastructure projects	• Considers user delay cost • Considers risks
Zoeteman	1. Determine functionality and performance 2. Identify conditions for financing, construction and maintenance 3. Perform quantitative feasibility analysis 4. Implement alternative 5. Develop detailed design and maintenance strategy	**User:** Contractor **Phase:** Tender **System:** Rail infrastructure	• Considers durability assessment • Considers performance fee • Considers uncertainty
Kim et. al	1. Conception of LCCA objective and alternatives 2. Input of hypotheses for the LCCA and cost related data for alternatives considered 3. LCC estimate 4. Comparison of alternatives and Sensitivity Analysis 5. Selection of alternative and decision making	**User:** Contractor **Phase:** Pre- and post-design phase **System:** Light rail transit infrastructure	• Considers different levels of detail • Estimation based on a hierarchical decomposition of the system
Ugwu et. al	1. Estimate construction cost 2. Identify recurrent cost 3. Compute cost with risk assessment 4. Identify operational cost and recurrent cost relationships 5. Durability assessment 6. Compute life cycle cost	**User:** Contractor **Phase:** Project design **System:** Highway Bridge	• Based on object oriented representation of data • Considers durability assessment

Table 2-1 LCC analysing procedures

A LCCA framework for pavement design is created by Walls & Smith (1998) for the State Highway Agency (SHA). Structural maintenance is related to the service life of the road. Changes in design parameters in relation to the life cycle cost can be analysed in this way. How construction and maintenance activities are related does not become clear, making it hard to relate LCC to SLPA. UDC is not considered as individual cost category, making it hard to make decisions based on both execution strategy and material use as can be seen in Equation 1.

$$NPV = Initial\ cost + \sum_{k=1}^{N} Rehab\ Cost_k \frac{1}{(1+i)^{n_k}}$$ **Equation 1**

Where:

i =	discount rate
n =	year of expenditure

Construction costs are not discounted during alternative evaluation. In larger projects where the construction period can take several years, the assumption that money today is worth more than tomorrow will influence the alternative comparison.

A probabilistic LCC framework for infrastructure projects in the Netherlands is set by Krützfeldt (2012). Equations are determined to estimate UDC from the perspective of the road owner as can be seen in Equation 2 and Equation 3.

$$UDC = \left(VoT_o * \Delta ATT + \frac{1}{2} * (VoT_1 - VoT_0) * \Delta ATT\right) * ADT$$ **Equation 2**

Where:

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

$$\Delta ATT = \left(\frac{L}{V_m} - \frac{L}{V_N}\right) * n * upv$$ **Equation 3**

Where:

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

Detours due to complete closure of the road are not integrated, even though it is indicated that the change in average travel time is dependent on lane closure, road length, working hours, type of users, urban or rural area, etc. NPV is estimated using Equation 4.

$$NPV = C_{inv} + C_{res} + \sum [PV(C_{o\&m}) + PV(C_{risk})]$$ **Equation 4**

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 costs of failure

UDC is not incorporated within the LCCA framework, even though equations are identified to estimate UDC. The purpose of Krützfeldt's research is to estimate agency cost and not to include society cost. Incorporation of UDC in LCCA must be done when availability of the road is important. Furthermore, no indication is given how the different cost categories are translated to the present value.

A framework to conduct LCCA for rail infrastructure is set by Zoeteman (2001) Performance of the system is related to the need for structural maintenance based on different degradation modes. Degradation is related to the amount of tonnage passing the track can be seen in equation (5).

$$RQ_{y,a} = Q_a * P_{y,a}(T_f \geq TH_a)$$ **Equation 5**

Where:

$RQ_{y,a}$	quantity of maintenance in year y for activity a
Q_a	total quantity under investigation, for instance total road length
$P_{y,a}$	part that has to be maintained
T_f	notional tonnage
TH_a	threshold

This equation relates the need for structural maintenance to decisions taken before determinations of the amount of work that has to be performed. This information is used to determine duration to perform the activities as can be seen in Equation 6.

$$S_{y,a} = roundup\left(\frac{RQ_{y,a}/PS_a}{TPP_y - L_a}\right)$$ **Equation 6**

Where:

$S_{y,a}$	amount of shifts to perform activity an in year y
$RQ_{y,a}$	amount of maintenance that has to be performed with activity an in year y
PS_a	production speed to perform activity a

TPP_y	track possession period
L_a	time lost due to set up and finishing of the work

Activity costs are related to activity duration and amount of work to be done. Duration is used for estimation of activity costs and determination of rail unavailability. Rail unavailability is used for UDC estimation. The framework is set for rail infrastructure which implies that the track will be completely closed while for road infrastructure a partial closure is also possible, making it impossible to directly integrate the framework in road pavement design LCCA.

All frameworks described above are set for line infrastructure and do not clarify how different cost elements are structured and related to the LCC estimation. Information in the relationship is important to conduct LCCA in a structured way. A LCCA framework that uses a hierarchical information structure to conduct LCCA is created by Kim Et al. (2010). LCC estimations are made at different moments in the design process using information from different hierarchical levels. Cost categories are related to parameters as used materials, resources and to the expected service life, as stated in Equation 7:

$$E[C_{tot}(X,T)] = C_{ini}(X,t) + \sum_{t=1}^{T} \frac{1}{(1+q)^t} \{E[C_{mai}(X,t)] + E(C_{dis}(X,t)]\} \quad \textbf{Equation 7}$$

Where:

C_{tot}	total life cycle cost
C_{ini}	initial construction cost
C_{mai}	maintenance cost
C_{dis}	dismantlement / disposal cost
t	a given period of time during the design life
X	used materials and resources
q	discount rate
T	design life

The relation between construction and maintenance activities and service life do not become clear within this equation and UDC is not taken into account. Next to that, construction cost are not discounted.

A LCCA framework for highway bridges is set by Ugwu, Et al. (2005). Hierarchical breakdown structures are used to structure needed information. The framework consists of the cost categories design and maintenance, where UDC is part of maintenance cost. The framework structures information, data and processes concerning service life and LCC using object-oriented representation. It is set up as a parametric model to perform overall estimations where a mathematical model allows changing parameters to identify the influence of different decisions. Downside is that it is set up for an object (Highway Bridge) instead of line infrastructure. Besides that, the equations stated are general and no indication is given on how material service life relates to the moment of structural maintenance. Nevertheless, this methodology identifies possibilities to conduct LCCA during the design process based on objective decision making, because input values are traced back to the mathematical relations and the use of object oriented knowledge representation.

This paragraph clarified different created LCCA models within the infrastructural sector. What does not become clear is what information is needed to perform the LCCA and what the level of detail of the information must be. Another problem in current LCCA models is that none incorporates UDC as an independent cost category. This makes it hard to evaluate the impact that that the alternative has on the availability of the road. The use of an object oriented model is proven to be valuable in LCCA, but has not been used to perform LCCA for road pavement design. Research is needed to determine how information should be structured and captured within the object oriented model to conduct LCCA for road pavement design. The principle of LCC is based on the assumption that all relevant cost during the design life must be identified and examined. Besides the model of Zoeteman (2001), none of the models clarifies how the need for maintenance can be determined so that it can be related to the LCC. This model is furthermore designed for rail infrastructure and can therefore not directly be used for road pavement LCCA. Knowledge is needed on how maintenance in road pavement is determined and how this can be related to LCCA to create a DSS.

2.2 Service life planning assessment

Service life planning assessment (SLPA) is the process to come up with a solution for a road pavement that provides reasonable assurance that it will function at least as long as the intended design life. With this assessment construction and maintenance decisions will be made together to find a solution to meet the design life. Service life planning is the sum of both structural maintenance and construction activities. The service life of the road determines the critical moment for structural maintenance and can be used for cost allocation to the design alternative (Zoeteman, 2001).

During construction and maintenance, the road is built to meet the performance requirements. Factors and relationships influencing the performance of the road infrastructure have to be identified to estimate LCC. Degradation in system performance is the driving force causing structural maintenance (Zoeteman, 2001). Service life is determined by material degradation and minimum performance. Service life of asphalt is influenced by dynamic vehicle load, asphalt stiffness, environmental factors, pavement structure, thickness (Abdollahipour, et al., 2013) and summer or winter construction (Mohan, 2010). Next to that functional maintenance can influence the performance of the pavement durability (Zoeteman, 2001) (VBWasfalt, 2005).

Service life of the pavement must be determined to create a maintenance strategy (Walls, et al., 1998). Degradation curves are used to determine service life. They indicates how material performs over time. The service life of the system is determined by the critical degradation mode (Zoeteman, 2001). This is visualized in Figure 2-4 for a hypothetical degradation mode. In this case, structural maintenance is needed to keep the performance of the road above the minimum performance level to achieve the design life. Costs can be allocated to the moment of structural maintenance.

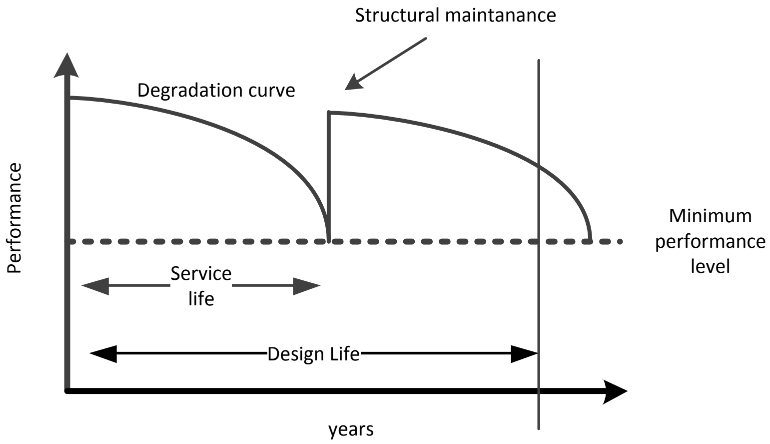


Figure 2-4 hypothetical degradation curve for a pavement design alternative based on Walls, et al. (1998)

This principle clarifies that service life is different for each project, due to different minimum performance levels per project. Defining the degradation curve of the materials for the most prevalent degradation modes, results in the maintenance strategies when the projects minimum performance levels are known (Walls, et al., 1998).

Degradation curves can be determined in different ways. Historical data is one of them (Walls, et al., 1998). Historical data can only be used for the same type of asphalt and practice, implying a solid understanding by local agencies and contractors of the degradation of asphalt pavements. They should create their own data to get competitive advantage over others. Mathematical models are another mean to determine service life such as RAAV (Tolman, et al., 2006) estimates the service life based on pre-defined parameters. Backx (2012)created two equations to determine the service life based on conditions in a certain year, conditional change and the minimum performance level as can be seen within Equation 8 and Equation 9.

$$C_t = C_{t-1} - \Delta C \qquad \textbf{Equation 8}$$

$$\Delta C = (C_0 - C_w)/L_1 \qquad \textbf{Equation 9}$$

Where:

C_t	change in condition in year t (%)
ΔC	condition change per year (%/year)
C_0	starting condition (%)
C_w	warning condition (%)
L_1	service life expectancy (years)

The equations use starting condition, changing condition per year and minimum performance to determine the service life of the asphalt. What these equations do not clarify is how earlier performed construction or maintenance activities are related to the service life or SLP. The last method to determine the degradation curve is using expert opinion. A disadvantage of this strategy is that their opinion can be biased and it is hard to clarify the level of knowledge of the experts (Ugwu, et al., 2005).

This paragraph described how the moment for structural maintenance in road pavement design is determined. Information concerning material degradation and minimum performance is needed to determine the service life. Factors influencing the service life are identified, but is not known which of these factors have to be incorporated within the decision making process according to the decision maker. This is valuable knowledge, because it makes it possible to create the DSS were the service life is determined based on the important influence factors. Equation 8 and Equation 9 can be used to relate the need for structural maintenance to the LCC, but they do not relate to earlier performed activities. Research is needed to investigate how earlier performed activities can be related to SLP and be incorporated in the DSS.

2.3 Object oriented model

Information is required to perform LCCA and SLPA. Currently, decisions are made based on a defragmented analysis to see if it fulfils the requirements (Bank, et al., 2010). Systems Engineering can be used to capture and structure the decision making process. Systems Engineering (SE) treats a project, contract or design as a system that can be divided into smaller parts, so called subsystems, which are intertwined with each other in a hierarchical way. Breakdown structures are used to visualize the decomposition of the subsystems. Breakdown structures are “hierarchical breakdowns or tree structures which are an instrument to get an overview of the whole and the parts of a system, set of requirements, activities or functions” (Gelderloos, 2010 p. 32). Decomposing a system is something that is often done in complex civil engineering projects (Gelderloos, 2010).

LCCA and SE are based on holistic decision making. This results in an incentive to come up with methods that support holistic decision making. Building information models (BIM) can be a mean to do this, because it reduces the amount of work required to evaluate alternatives (Bank, et al., 2010). BIM is also referred to as an object oriented model (Ahn, et al., 2010) This is a computerized approach that describes and displays information necessary for design creation. Different threads of information are integrated in one system that results in holistic data collection (Krigsvoll, 2008). SE can be the basis for structuring the information. It consists of geometric and non-geometric information such as schedule, cost, and material related information. It is not limited to physical elements in reality, but anything can be modelled in an object oriented model (Ahn, et al., 2010). An object oriented model captures, structures and updates available information during early development stages to gain more insights as time passes. An object oriented model consists of building objects and of a set of parameters and rules. This relates to LCCA, since this theory distinguishes between elements and relations and can therefore be used input for LCCA. One of the main strengths of object oriented models is that focuses on reuse of information (Watson, et al., 2004). Another benefit of using a model is that they visualize the impact that certain trade-offs have on the road to overcome uncertainty during the early development (Aughenbaugh, et al., 2004). Simulation can be seen as "a tool to evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time" (Maria, 1997 p. 3). A model simplifies the reality while simulation is used to see how certain trade-offs will influence the expected reality.

The outcome of the model is dependent on the input values that are integrated within the model. Within a perfect world, there would be complete information about the input values, given the decision maker complete certainty about the outcome (Kim, 2010). Unfortunately, in reality this is not all known resulting in decisions that have to be made under uncertainty. The values used to make a decision could change over time or have been created based on wrong assumptions or sources. The decision maker does not know till which extend he takes decisions under uncertainty, because he has no information on how the input parameters affect and interact with each other and to the outcome of the model. Sensitivity analysis is seen as a good tool for model validation (Hamby, 1995). In a model, all the input parameters and the assumptions of the model structure are subject to error (Pannell, 2013). There is uncertainty about the current input values, but even more uncertainty about future values concerning for instance costs, material deterioration, traffic intensity and productivity (Pannell, 2013). With sensitivity analysis, the potential errors and the impacts to the outcome will be investigated. The results found are used to indicate unlikely model behaviour, indicate important assumptions, simplify a model, guide future data collection efforts, allocate resources (Eric D. Smith, 2008), under which circumstances this alternative will change and how this alternative will change (Pannell, 2013).

This paragraph indicated the use of SE to structure the design and decision making process. This structure can be used within an object oriented model to support holistic decision making. It is not known what information must be incorporated in the object oriented model. Even if it was clear what information must be captured in the object oriented model, literature does not indicate how the information should be captured in the model. Research is needed to investigate how information needed to perform LCCA for road pavement service life planning should be structured in the object oriented model.

2.4 Gap analysis

Many LCCA frameworks for different infrastructural purposes using mathematical models are created. The relation between costs and decisions concerning SLP does not become clear within these frameworks. The relationship between quality, structural maintenance need and life cycle cost is not identified making it impossible to create a DSS. It is known what cost categories and elements must be addressed in LCCA for road pavement design, but not how decisions affect the cost over the design life. Next to that, it is not known what kind of information decision makers use to estimate the different cost elements. It is not known how this can be captured and used to conduct LCC analysis for road pavements in a short period of time. Besides that, literature states that many factors influence the service life of asphalt and life cycle cost. Due to the limited available time, the focus of the decision maker should not lay on the collection of data, but on alternative generation and evaluation. So far, there is not a LCCA framework that integrates UDC to perform life cycle cost decision making in the field of service life road pavement design. Since many factors influence the service life of asphalt and life cycle costs, information on how these factors influence the service life and life cycle is beneficial for decision makers for setting a focus within a project, but also for data collection activities for increasing the knowledge base for the most important factors.

2.5 Hypothesis

The use of an object oriented model to capture and structure information concerning service life planning assessment and life cycle costs to objects should give the decision maker the needed information for decision making. This way the decision maker focuses on alternative generation and evaluation based on captured historical data in the model.. Setting a formalized LCCA for service life planning pavement design should result in an objective methodology to compare design alternatives that can be used for decision making. It is expected that this leads to better decision making. Relating the object oriented model to the LCCA estimation should result in a tool that can be used by the decision maker to compare competing alternatives within a short time span. Relating the moment of need for structural maintenance to the life cycle cost using an mathematical model should make it possible to use the object oriented model as input for life cycle cost decision making. Besides that, since there is little historical information available, it is expected that this research will indicate the influence of different input parameters to the life cycle costs. It is expected that this information will be valuable for making a start of data collection activities and for further research, focussing on the parameters that has high influence on the life cycle costs.

2.6 Goal

The first objective of this research is to clarify what information is needed to perform the LCCA for road pavements. The second objective is to gain insight in how this information should be captured within the object oriented model. The last objective is to implement the object oriented model within a DSS to conduct LCCA during the early development stages. In total, one main objective can be stated:

Study the Life Cycle Cost Analysis (LCCA) process for service life planning road pavements designs and create a process to store, structure and update information within an object oriented model that can be used within a DSS to conduct automated LCCA.

2.7 Research question

The objective as presented in chapter 2.6 is translated into one main question and supporting sub questions to come to answer:

How should an object oriented Decision Support System (DSS) look like to conduct Life Cycle Cost Analysis (LCCA) for service life road pavement design and how do the input parameters relate to the life cycle costs?

Sub questions:

1. *What information is needed to perform road pavement LCCA?*
2. *What are important decisions that should be integrated within the DSS according to the decision maker to come to reliable decisions?*
3. *How should the object oriented model be structured to perform the LCCA?*
4. *How can this information be used to create a parametric decision support model?*
5. *What are the strengths and limitations of the model?*
6. *Which parameters influence the life cycle costs the most?*
7. *What is the interaction between the input parameters?*

3 Research method

The model is developed using ethnographic action based research techniques and performed within a large Dutch construction firm. Purpose of this methodology is to observe the current working methods from inside and to use this insight to develop the model in iterative circles as can be seen in Figure 3-1. The model is developed closely to current practices making the change of supporting work practice high, but also to empirically test the model by directly propose observations to practitioners' views.

The developed model is designed and tested in a large infrastructural tender located in the Netherlands. The contractor becomes responsible for the design, construction, financing and maintenance of overlaying and underlying road network, land tunnel, various viaducts, overpasses, traffic signs, ecological features and information systems. Main reason for selecting this case was the possibility for the researcher to participate within the project. The researcher became part of the tender team of the contractor. The research focuses on project life cycle aspects that are not project specific, but are included within each road construction project. By creating a DSS that is flexible, project specific requirements as well as quality aspects can be implemented per project to make the DSS suitable for other projects.

The tender team was located at a central location and the researcher was located there for four months. Different disciplines were part of the team and the composition changed over time based on the needs at that moment in time. Before the researcher started working on the project, he gained knowledge concerning Life Cycle Costing, object oriented modelling and asphalt service life planning. This gave him the required background to observe the current practices within the tender to develop the model. This observations were cross checked with tender team participant as design engineers, maintenance engineers, traffic engineers and financing engineers to validate the model. In total, six participants individually took place within individual interactive sessions. In these sessions the DSS was discussed just as the outcome of the sensitivity analysis. Besides that, two external experts in the field of asphalt service life were consulted to validate both the equations that formed the input for the model and the model itself. This way, the model was also externally validated.

Data used came from sources like observations, informal talks, contract documents, organizational wide documents, literature, and interactive sessions. Input values concerning costs were determined by an expert. Service life values determined through an expert session were used for the determination of structural maintenance moments. By estimating all the alternatives that were created by the tender team and simulating this in the DSS, errors could be found and removed from the model by comparison of their outcome to the outcome of the DSS.

Figure 3-1 indicates the iterative ethnographic action based research cycles that is performed in this research and which steps will give answers to sub questions stated in chapter 2.7. The cycle is directed from outside to inside, or from rough to detailed. This was also done in this research identifying the roughest processes and then fine tuning them. At thirst the current practice is observed by reading contract documents, created tender documents and informal talks with participants. This is analysed by comparing it to relevant literature to identify the current work routines and what the important considerations are in life cycle cost decision making for service life road pavement design. The obtained information from these steps was used to develop or update the computer model that is developed in Microsoft Excel. Using the approach from rough to a detailed level allowed the researcher to gain more in depth understanding in what information is needed and which important decisions have to be made. The first focus was to identify the cost categories that should be incorporated within the model. Based on practitioners' views and contract documents it became clear that that the focus lays on construction cost, maintenance cost and user delay cost. Besides that it was observed how design alternatives were made and compared. Data concerning costs and service life expectations were collected and analysed. This was used to create a first prototype where the life cycle costs were related to the service life of upper layers with of different asphalt types and to the traffic speed during activity execution. After talks with practitioners it became clear that factors influencing the service life are important decisions to incorporate in the model. Besides that, the closure of traffic lanes during activity execution was considered an important decision which was initially not incorporated in the model. Literature and recommendations of the practitioners were used to update the model. The last iterative cycle performed, was based on the opinions of both tender team participants and external experts. Tender team participants indicated that for the estimation of user delay hours, in the case of a detour, only the two trace sections with the highest traffic intensity are used to estimate the user delay hours. Besides that, external experts indicated the importance of the incorporation of cumulative costs in the dashboard.

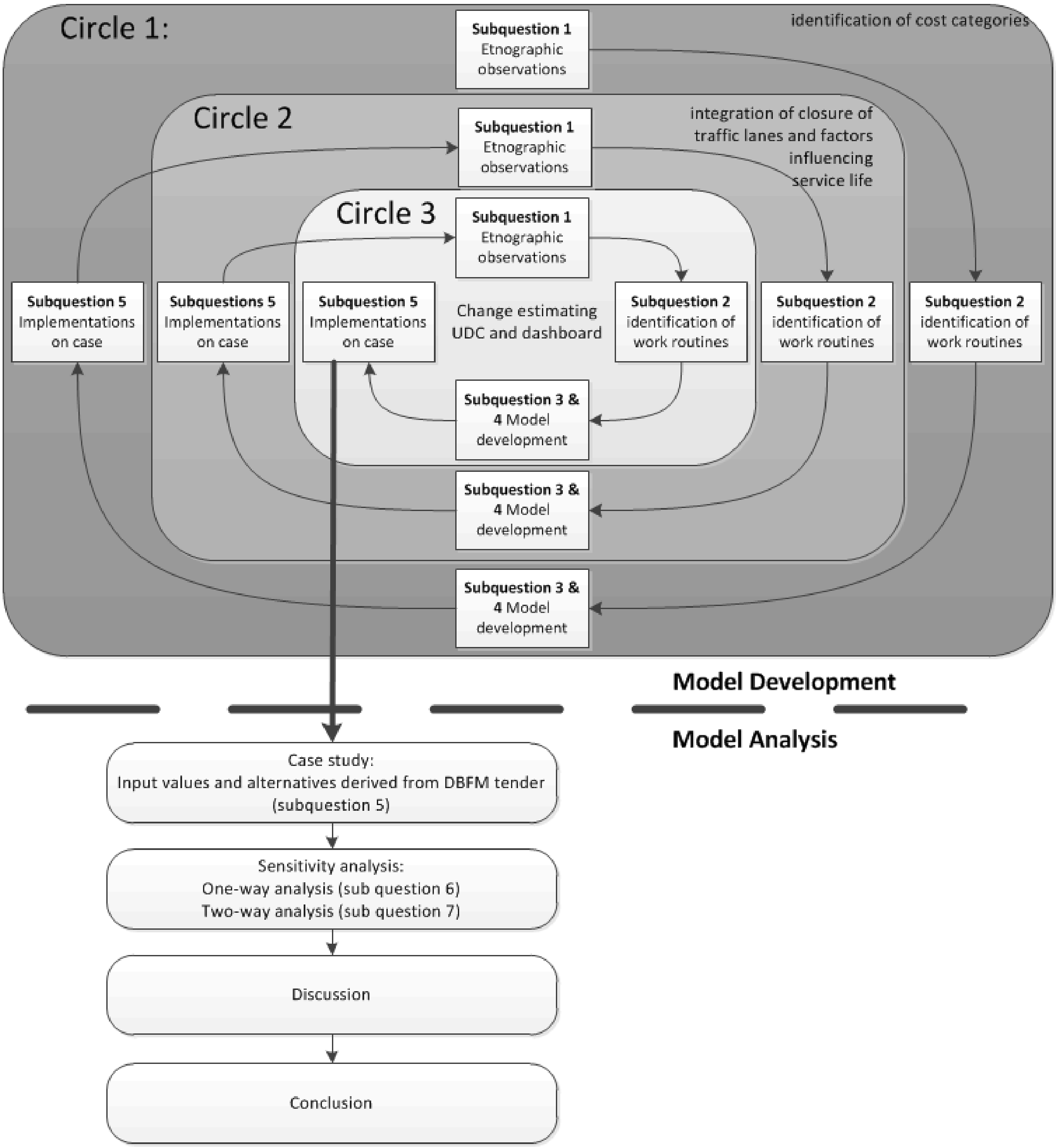


Figure 3-1 Schematic overview of research method

The developed model is presented using three schemas the process model; the class diagram, and the estimation model. The process model describes how information captured in the class diagram is used to perform LCCA. The class diagram describes what information is captured in the model and how this is structured to perform the LCC estimation. The estimation model describes the relationship between the different developed equations and the class diagram and is related to the investigated equations in chapter 2 and indicates what is changed in order to perform LCCA for road pavement design.

The strengths and limitations of the model will be tested within the base case as described before. This will be done by simulating alternatives that where created by the tender team within the DSS. The alternative with the lowest NPV is used to conduct sensitivity analysis to validate the model analytically. Sensitivity analysis gives insight in the question if the right problem is addressed by the Decision Support System (DSS) (Assakhaf, 2003) and helps identifying the specific issues that matter in decision making. The outcome of the sensitivity analysis is used to examine unexpected model behaviour. If the DSS responses reasonable to the problem from an intuitive or theoretical perspective, then the decision maker may have some comfort with the qualitative behaviour of the model even if the quantitative precision or accuracy is unknown (Frey, et al.). Analysing the outcomes of the sensitivity analysis with experts is used to validate the Decision Support System (DSS) to see if it approaches reality. The sensitivity analysis itself does not validate the model, but the outcome is used for validating experts opinions about the DSS with the reality. Two types of sensitivity analyses techniques are used in this research, one-way and two-way sensitivity analyses. The first methodology creates a quantitative image of the influence of different factors and gives answer to sub question 6. Downside of this methodology is that interactions between parameters do not become visual and that decisions are strongly dependent on the base case values. Two-way sensitivity analysis is used to visualize the relation between input parameters and gives answer to sub question 7. With this technique the value of two input parameters will be changed, keeping the others constant to see the influence it has on the NPV. The software that is used to perform sensitivity analysis is Microsoft excel and is performed using the ‘What-If’ analysis option. It is decided to use this program, because the model is also created in Microsoft Excel.

4 Decision support system requirements

This chapter points out the information needed to perform Life Cycle Cost Analysis (LCCA) for Service Life Planning Assessment (SLPA) for road pavement design. At first an introduction is given to the selected case were information is obtained. After that, requirements from the tender team, that were obtained by informal talks, document study and validation afterwards, are presented. The requirements are related to the level of information that must be captured within the DSS and the decisions that the model should support.

4.1 Base Case

The selected case is located near Amsterdam and is part of the larger Rijkswaterstaat plan to upgrade the highway between Schiphol Amsterdam Airport, Amsterdam and Almere. In total, 63 kilometre of road will be widened to increase traffic capacity. Another goal is to increase liveability by constructing a tunnel, aqueduct, acoustic barriers and bicycle trails. The location of the case is indicated in purple in Figure 4-1.

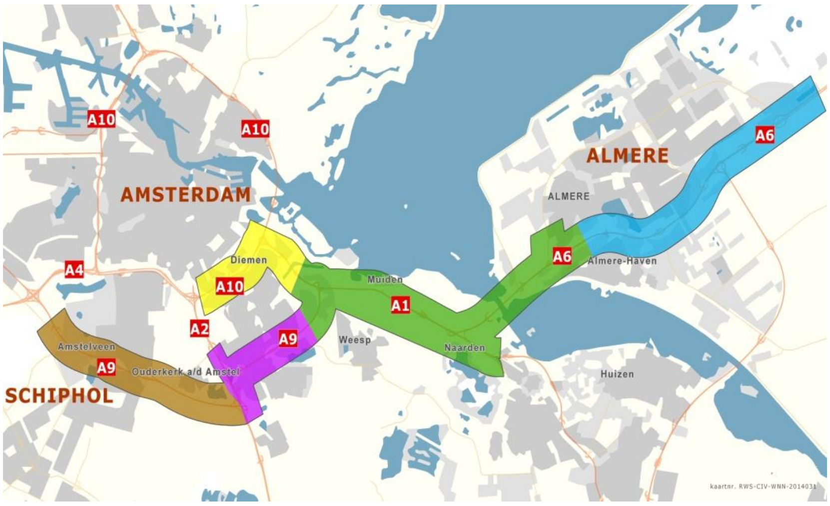


Figure 4-1 A9/A10/A1/A6 Schiphol - Amsterdam - Almere

During research, the project was in the tender stage, which started halfway 2013 and finished in May 2014. Construction activities are planned to start in 2015 and construction to finish in 2020. This project is put on the market as a Design Build Finance Maintain (DBFM) contract. It consists of the building, financing and maintaining of the Gaasperdammerweg trace (SAA-A9, junction Holendrecht - Diemen). The highway section is approximately 6 km long. The contractor becomes responsible for designing, building, financing and maintaining the underlying road network with several engineering structures (tunnels, bridges) and with associated traffic signs, ecological features and information systems. It was estimated that the project consists of approximately 94 km of asphalt lanes.

4.2 Model information

LCCA is founded on the assumption that money today is worth more than tomorrow. A discount factor accounts for this assumption indication how the value of money over time changes. With a design life focus, short and long term decisions are compared. There is more uncertainty concerning the value of money over 20 years than over two years, because it is not known how the world will change. Different discount factors are needed to influence the expectations of how money will change over time for long and short term decisions.

Main focus of LCCA is to evaluate alternatives based on competing trade-offs. Therefore, the model focuses on decisions and activities that are not alternative overarching. For instance, daily inspection has to be performed for all of the alternatives. During alternative evaluation, the main focus is on not overarching decisions, to find the optimum solution. Afterwards, more detailed estimation can be performed for overarching solutions. One of the main focus points in road pavement decision making is the composition of the asphalt structure. The system asphalt structure consists of an upper layer, inner layer, under layer and foundation. Different compositions and layer thicknesses can be set determined which all influence the service life and the life cycle costs. The asphalt structure can be modified the maintenance period to fulfil the requirements. For instance, it is possible to construct during an inner layer and an upper layer where at first the upper layer was constructed directly on the under layer. The model should give the decision maker the possibility to select the composition of the asphalt structure during construction, but also to change the composition later on. Only this way the decision maker can evaluate the alternative based on SLP and LCC.

The moment the layer was constructed, the traffic intensity and the environment were identified as factors influencing the service life of the upper layer. This research confirmed that these factors influences the service life of the upper layer, but also identified prolonging maintenance as a factor. Service life indicates the latest year for structural maintenance to keep the road performance above the minimum performance level. Practitioners indicate that structural maintenance is sometimes performed before the end of the service life. Main reason is to create more certainty that the road performs to its minimum requirements. Another reason is the possibility to combine asphalt maintenance with maintenance to other subsystems of the road to decrease the unavailability of the road. The model should give the decision maker to possibility to set the year to perform structural maintenance based on the estimated service life.

Traffic intensity is a project specific factor, and is the same for all different alternatives in the project. Service life could be determined using traffic intensity, but this would set to much burden to the decision maker. Therefore, this factor is not incorporated in the model. The relationship between construction period and service life was already determined by Mohan (2010) and confirmed in this research. Practitioners indicate that as a rule of thumb, summer construction will increase the service life with one year over winter construction. Incorporation of this decision in the model is essential to relate to the overall planning of the project. Activity implementation can be examined to the overall project planning and project LCC. Environmental factors are expected to have the same impact on all alternatives. However, the sub base characteristics or the vegetation around the road can be different for different sections of roads, influencing the service life. The model should differentiate between road sections, since environmental factors influence the service life. Practitioners indicate that prolonging maintenance increases service life two years. Performing prolonging maintenance activities are less expensive than structural maintenance activities and can therefore be an interesting option for the decision maker. Downside is that road closure is needed to perform the activity, increasing the User Delay Costs (UDC).

Decisions indicated above are directly related to the service life, but also to the LCC. Decisions concerning used material and thicknesses of the layer determines the service life, but also the costs related to it. Width and length of the road section is information that is needed to estimate material costs. Time dependent costs like labour and equipment need to be estimated as well. Crew is defined as the amount of labour and equipment needed to perform the activity. Crew costs are related to the execution of activities, e.g. fraying of the upper layer or the execution of functional maintenance. Activity duration determines crew costs and depends on crew speed to perform the activity and the way the road section is closed during activity execution. When the complete road is closed to perform the activity, more crews work parallel or larger equipment is used. The duration of the activity decreases, but unit prices are higher. The incorporation of crew speed per traffic lane and crew cost per hour in the model is needed, giving the decision maker the possibility to make decisions concerning closure of traffic lanes.

Traffic speed per traffic lane is an important factor in UDC estimation. During complete trace section closure, UDC depends on the detour times and the duration of the trace closure. The model must support the analysis of the influence of detour times to the LCC. UDC also depends on the reduced roadway capacity. During activity execution, traffic speed must be reduced to create a safe working environment (CROW, 2013). The activities are executed to keep the performance of the road above the minimum performance level. Traffic lane closure and traffic speed during activity execution are decisions needed within the model to estimate UDC. Regular traffic speed, traffic intensity, value of time and detour times per trace section are sources of information needed in the model to estimate UDC.

This chapter identified different sources of data and decisions needed to perform LCCA and SLPA. The data and decisions need to be integrated within the Decision DSS. It consists of project specific information as the value of time, traffic intensity and detour times and project unspecific information as material degradation curves, labour costs and material costs. This information should be captured and structured so that it relates to the mathematical algorithm that is part of the DSS. It became clear that the focus of the decision maker during alternative evaluation is on those trade-offs that are not alternative overarching. Important decisions that have to be taken are related to material use, execution strategy, service life and executed work as can be seen in Table 4-1.

Category	Parameter
Material use	Layer (upper layer, inner layer, under layer, foundation)
	Material used
	Thickness of the layer
Execution strategy	Closure of traffic lanes during activity execution
	Traffic speed during activity execution
Service life	Summer or winter construction
	Prolonging maintenance yes or no
	Year to perform maintenance
Value of money	Discount factor
Executed work	Activity (laying, fraying, functional maintenance, breaking)

Table 4-1 important decisions

5 Decision support system description

Model goal is to support the decision maker concerning short and long term decisions in the field of Service Life Planning Assessment (SLPA) focussing on the Life Cycle Costs (LCC). The model takes decisions for one road section at a time. Unplanned maintenance is not incorporated within the model. The model Focuses on tangible costs as labour, materials and equipment and not on intangible costs as salvage and quality loss. The model estimates the LCC for the road superstructure and does not estimate the substructure of the road. It is a deterministic parametric model, changing the complete LCC estimation by changing one input parameter (Obergrießer, et al., 2011). A deterministic approach is used due to the availability of information concerning LCC and service life. The model is developed within Microsoft Excel, because it is a program known by the researcher and many other people in the field. The next paragraphs explains the automated SLPA process, how the information found in chapter 4 is structured in the object oriented model, how the information is processed in the model and what information and decisions can be made within the Decision Support System (DSS) dashboard.

5.1 Process model

The decision making process for SLPA and LCC is presented in Figure 5-1. It shows the sequencing of tasks in combination with the used data to perform those tasks. The grey data boxes relate to the class diagram objects explained in paragraph 5.2. The dotted line indicates a loop when service life (planning) is estimated to be shorter than the required design life. Despite the self-explanatory character of the model, it does not become clear how decisions between construction costs, User Delay Costs (UDC) and maintenance costs interact within the model.

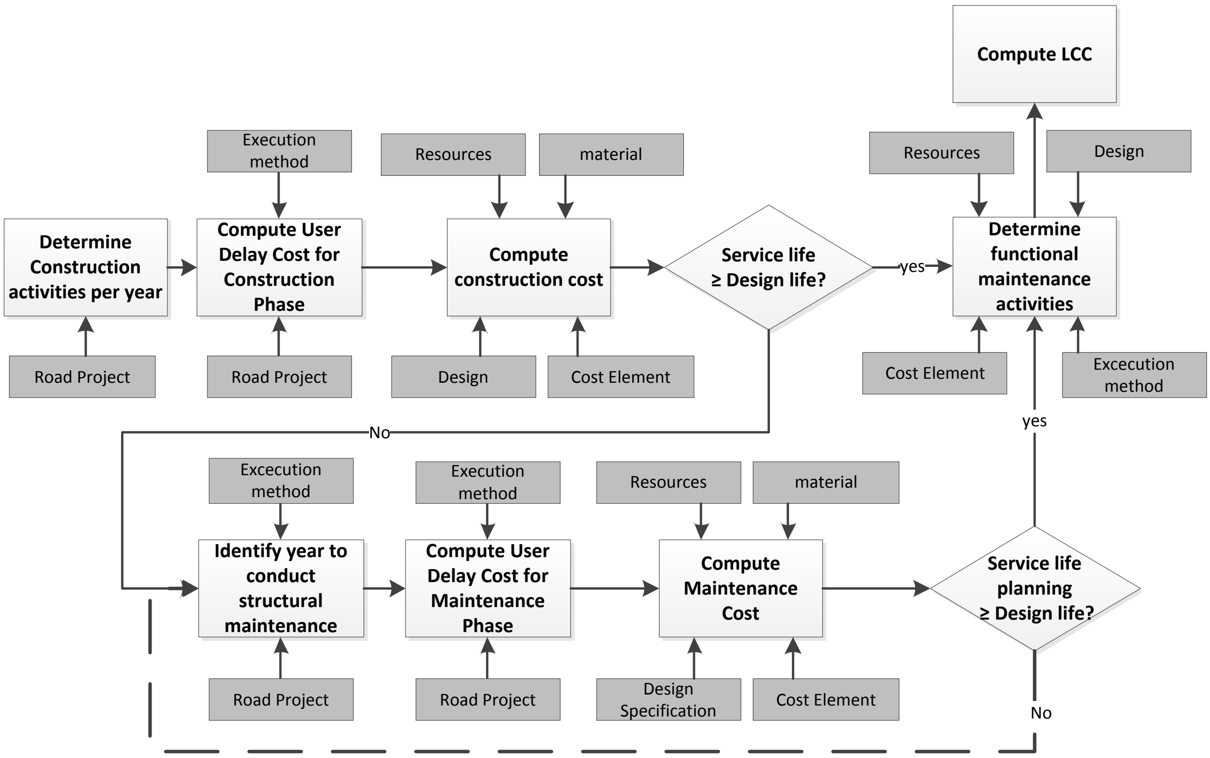


Figure 5-1 process model

5.2 Data management system

The class diagram presented in Figure 5-2 explains the relation and incorporation of the cost elements and attributes in the object oriented model. These elements and attributes represent different types of data, information and knowledge which are allocated to different objects. The object oriented model captures data like asphalt surface area and type of the layer material. Besides that, information as degradation curves per type of asphalt and activity speed to perform an activity are incorporated. The estimation process is processes the data true predefined relationships to create information as service life and activity costs. The model integrates project specific information objects (road project and design), generic organizational objects (material resources, cost element, system breakdown structure and activity breakdown structure) and processing objects (component and cost category. Organizational hierarchical structures are used to collect and structure historical data concerning the other organizational wide databases that can be used in further projects. This relates organizational goals to the model. The model incorporates objects upper layer, interlayer, under layer and foundation. The incorporated activities are applying, milling, breaking and functional maintenance of the different objects. The class diagram does not indicate how the processing object generates information used for decision making. This will be explained in the next paragraph.

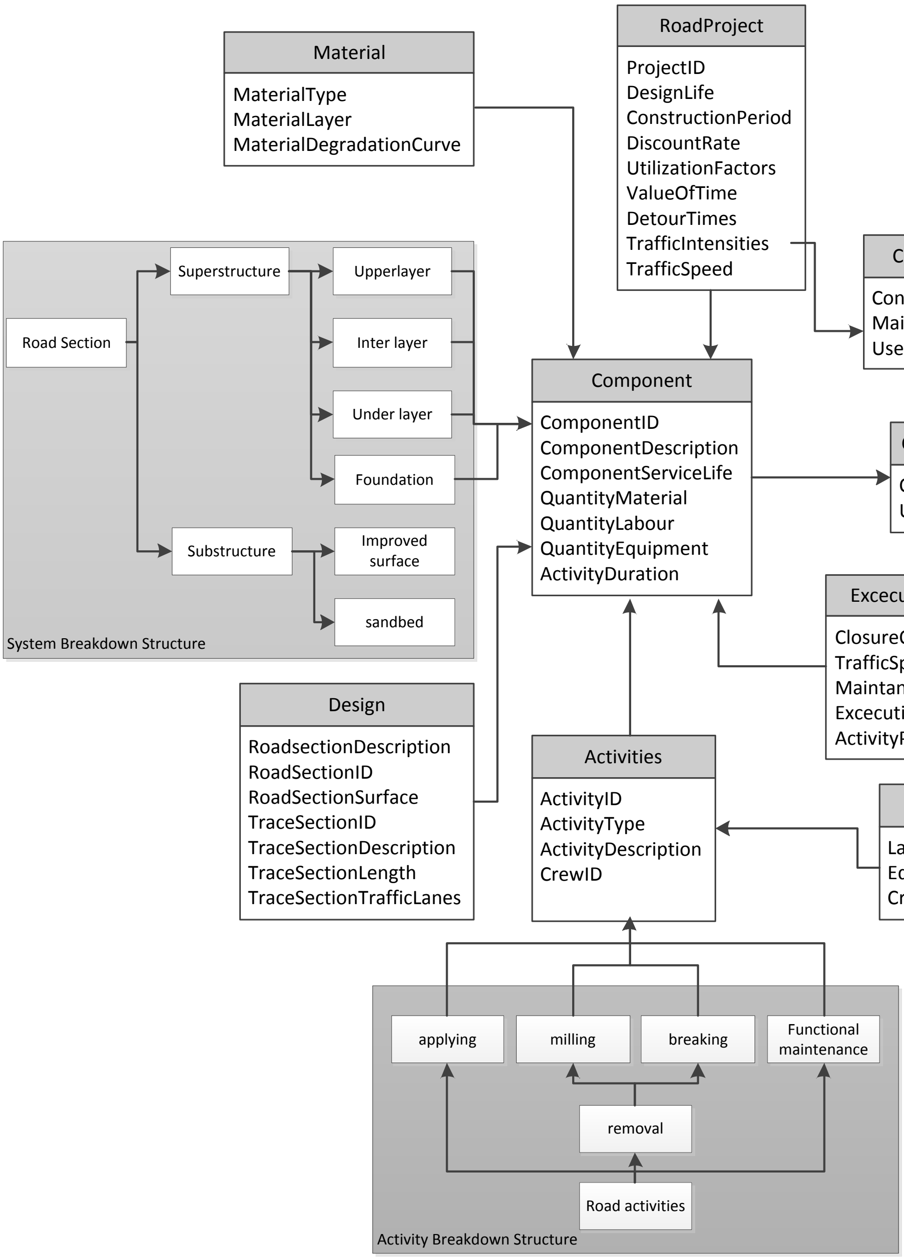


Figure 5-2 Class diagram

5.3 Model management system

The algorithm for LCC for road pavement is based on design, execution and maintenance decision making parameters. This paragraph explains the created algorithm that is used to relate decisions to the objects captured within the object oriented model ea. the data management system. The equations are stated within an overview in Appendix I. Appendix II gives an alphabetic overview of all the acronyms and where they stand for. Appendix III gives an overview of how the equations from chapter 2 are used to come to the equations within the next paragraphs. Figure 5-3 represents the model management system. It visualises how equations, decisions and contract requirements are intertwined with each other. The blocks indicate the different estimation modules that are explained within the next paragraphs.

5.3.1 Duration

The duration estimation is derived from Equation 3. It is modified to estimate activity costs and UDC. Amount of shifts is the outcome of Equation 3. In the DSS the amount of hours is estimated. This is done to relate duration to the estimation of UDC or activity costs. Equation 3 assumes that duration of activities depends on the amount of work and the speed to perform the work. In the case of rail infrastructure, the track section is either closed or open. Roads can be closed per traffic lane, dependent on the configuration of the trace section. This influences the duration of the activity, because in the case of closure of one traffic lane, less crews work side by side. Equation 3 is modified making the duration dependent on speed of the crew, the closure of traffic lanes and length of the trace section. Based on the amount of traffic lanes closed, a trace section is completely or partial closed and the DSS processes this information using Equation 10 or Equation 11 to estimate the hours to conduct the activity on that trace section.

$$d_{ts} = l_{ts} / S$$ **Equation 10**

Where:

d_{ts}	duration to perform activity on trace section (h)
l_{ts}	length of trace section (m)
S	speed to perform activity (m/h)

$$d_{ts} = \frac{l_{ts}}{S} + (ts_{tl} - CL_{tl}) * (\frac{l_{ts}}{S})$$ **Equation 11**

Where:

d_{ts}	duration to perform activity on trace section (h)
l_{ts}	length of trace section (m)
S	speed to perform activity (m/h)
ts_{tl}	amount of traffic lanes that the trace section has ()
CL_{tl}	amount of closed traffic lanes ()

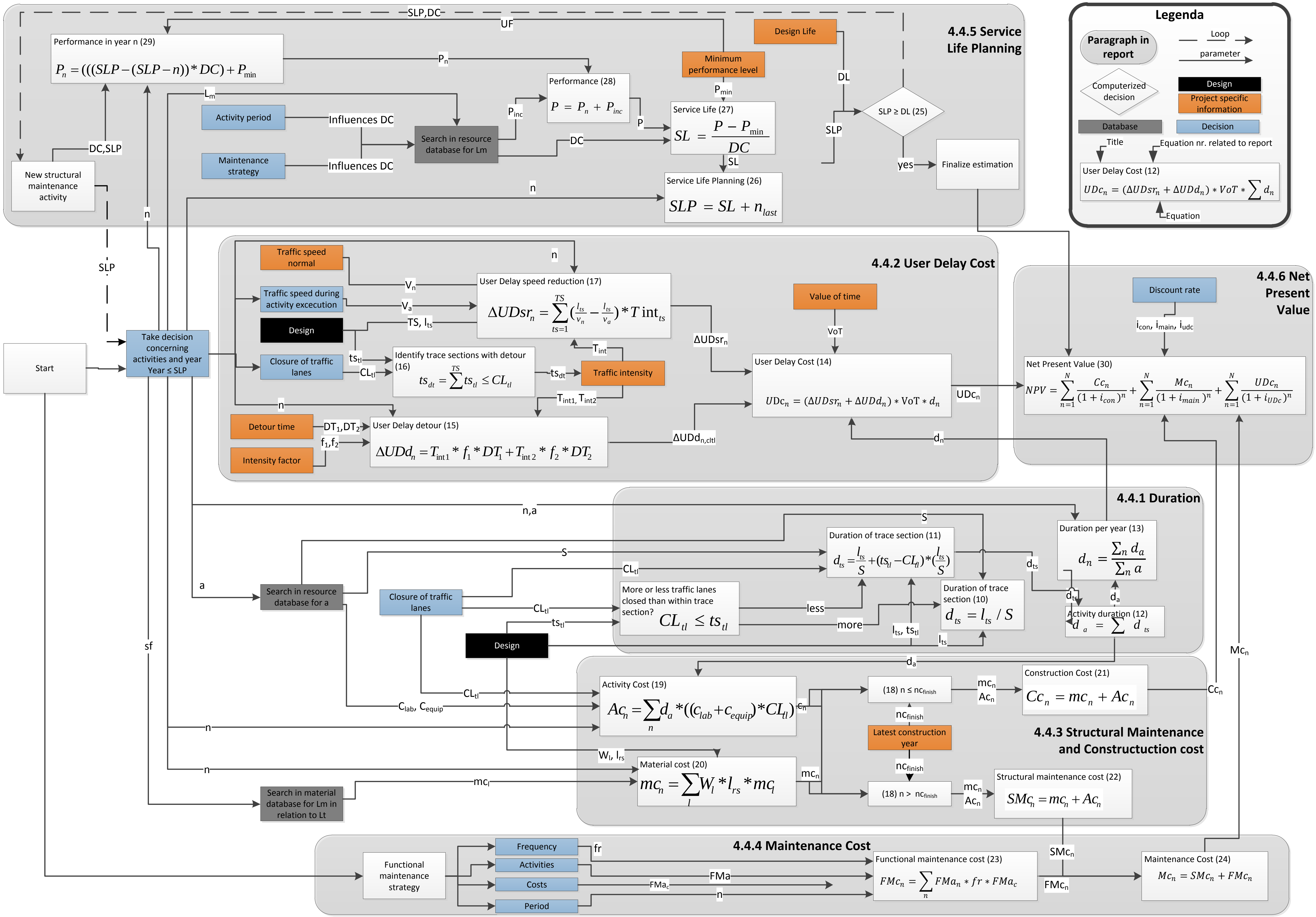


Figure 5-3 Estimation Model

The duration to perform the activity on the trace section is used within Equation 12 to estimate the amount of hours to conduct the activity over the entire road section by summing the durations to perform the trace sections within the road section.

$$d_a = \sum d_{ts}$$ **Equation 12**

Where:

d_a	duration to perform the activity on the complete road section (h)
d_{ts}	duration to perform activity on trace section (h)

The duration of the activities is used to estimate crew costs and is explained in chapter 5.3.3. Duration is also used to estimate UDC. The DSS assumes parallel execution for activities executed in the same year. The DSS sums all the activities executed in the same year and divides it by amount of activities executed in that year using Equation 13.

$$d_n = \frac{\sum_n d_a}{a_n}$$ **Equation 13**

Where:

d_n	duration to perform all activities in year n (h)
n	year under investigation ()
d_a	duration to perform the activity on the complete road section (h)
an	activities in year n ()

5.3.2 User delay cost

The estimation of user delay cost is derived from Equation 2 and represented within Equation 14.

$$UDc_n = (\Delta UDsr_n + \Delta UDd_n) * \text{VoT} * d_n$$ **Equation 14**

Where:

UDc_n	User delay cost in year n (€)
$\Delta UDsr_n$	average user delay per hour due to speed regulation in year n (delay/h)
ΔUDd_n	average user delay due to detour in year n (delay/h)
VoT	Value of time (€)
d_n	duration to perform all activities in year n (h)

As indicated in Chapter 2, Equation 2 estimates UDC using change in traffic time and user delay based on rerouting. Equation 14 takes both into account. The estimated user delay per hour is multiplied by the value of time and the duration to perform all activities in year *n* resulting in costs per year needed for cost discounting.

User delay time due to complete closure of a trace section is estimated with Equation 15:

$$\Delta UDd_n = Tint_{tsdt\,1} * f_1 * DT_1 + Tint_{tsdt\,2} * f_2 * DT_2$$ **Equation 15**

Where:

ΔUDd_n	in year n (delay/h)
$Tint_{tsdt1}$	completely closed trace section with the highest traffic intensity (cars/h)
f_1	traffic intensity factor (%)
DT1	detour time of trace section with highest traffic intensity (h)
$Tint_{tsdt2}$	completely closed trace section with the second highest traffic intensity (cars/h)
f_2	traffic intensity factor (%)
DT_2	detour time of trace section with second highest traffic intensity (h)

The two trace sections with the highest traffic intensity are used for UDC estimation, since this was also done by the model of Rijkswaterstaat. Only the trace sections with the highest traffic intensity are used for the estimation of average user delay due to detour, just as the detour time and the factor of cars.

Information concerning traffic lanes per trace sections and the closure of traffic lanes is needed to determine which trace section is completely closed. This information is processed using Equation 16:

$$ts_{dt} = \sum^{TS} tl_{ts} \leq CL_{tl}$$ **Equation 16**

Where:

ts_{dt}	trace sections which are going to be closed during activity execution
TS	trace sections
tl_{ts}	traffic lanes per trace section
CL_{tl}	closure of traffic lanes ()

This equation considers all trace sections within the road section under investigation and determines per trace section the amount of traffic lanes, including the emergency lane. Based on the decision concerning closure of traffic lanes, Equation 16 divides the trace sections to completely or partial closed. The group of closed trace sections is used in Equation 15 to for user delay estimation due to rerouting.

Besides delay due to rerouting, user delay occurs due to traffic speed reduction. Equation 17 addresses this is derived from Equation 3.

$$\Delta UDsr_n = \sum_{ts=1}^{TS} \left(\frac{l_{ts}}{V_a} - \frac{l_{ts}}{V_n} \right) * Tint_{ts}$$ **Equation 17**

Where:

$\Delta UDsr_n$	average user delay per hour due to speed regulation in year n (cars/h)
TS	trace section
l_{ts}	length of trace section (m)
V_a	traffic speed during activity execution (km/h)
V_n	traffic speed during normal conditions (km/h)
$Tint_{rs}$	traffic intensity (cars/h)

The user per vehicle type is used as input in Equation 3. For the estimation of user delay cost, there is no differentiation in road users as busses, cars and trucks. Therefore, the total traffic intensity per hour is used instead of the different categories of road users.

5.3.3 Construction and structural maintenance costs

Construction costs and structural maintenance costs are two different cost categories, but have an overlap in cost elements. These are labour, material and equipment costs. The activities are different, but the cost elements are identical. Distinction lies in the year where the costs occur. Cost allocation depends on the construction deadline. Therefore, material and crew costs are estimated in the model and thereafter allocated to the cost category using Equation 18.

$$SM_n = n > c_{finish}$$
$$C_n = n \leq c_{finish}$$ **Equation 18**

Where:

C_n	construction in year n ()
SM_n	structural maintenance in year n ()
n	year under investigation ()
c_{finish}	year when construction should be finished ()

For activity costs estimation, activity execution duration is essential. Together with the cost per hour of labour and equipment the activity costs per year is determined by Equation 19.

$$Ac_n = \sum_n d_a * (c_{lab} + c_{equip})$$ **Equation 19**

Where:

Ac_n	Activity cost in year n (€/year)
d_a	duration to perform the activity on the complete road section (h)
c_{lab}	labour cost in to perform activity a (€/h)
c_{equip}	equipment cost to perform activity a (€/h)

Information concerning labour and equipment cost per hour is essential within Equation 19 and is therefore integrated in the resource object. Construction and structural maintenance costs also have material costs. Material costs are costs of resource that become part of the road. A road pavement consists of different layers which have different thicknesses. Equation 20 determines the material costs per year.

$$\mathrm{mc}_n = \sum_l L_w * l_{rs} * mc_l \qquad \textbf{Equation 20}$$

Where:

mc_n	material cost in year n (€/year)
l	layer
L_w	layer width (m)
l_{rs}	length of road section (m)
mcl	material cost of layer (€/m^2)

The width of the layer and the length of the road section are needed. The thickness of the layer of the material is not incorporated in the equation as an individual factor, but is incorporated in object cost element.

Depended on the year of activity execution, either Equation 21 or Equation 22 is used for cost allocation to the cost category.

$$Cc_n = mc_n + Ac_n \qquad \textbf{Equation 21}$$

Where:

Cc_n	Construction cost in year n (€/year)
mc_n	material cost in year n (€/year)
Ac_n	Activity cost in year n (€/year)

$$SMc_n = mc_n + Ac_n \qquad \textbf{Equation 22}$$

Where:

SMc_n	Structural maintenance cost in year n (€/year)
mc_n	material cost in year n (€/year)
Ac_n	Activity cost in year n (€/year)

5.3.4 Maintenance costs

The purpose of functional maintenance is to slow the deterioration process of the upper layer by identifying and addressing specific pavement deficiencies so that the designed service life will be met (OCW, 2006) (Scholz, 2012). Typical functional maintenance activities are for instance patch repairs of potholes or cracks with cold-mix asphalt. In the model, the functional maintenance activities are not related to the service life, because there was no data on how functional maintenance strategies help slowing the deterioration process. Nevertheless, functional maintenance is incorporated, because it influences the life cycle cost. In the model, functional maintenance cost is not taken into consideration for the estimation of UDC. Input for functional maintenance costs is the period over time when functional maintenance is executed, the frequency per year and the costs to perform the activity as stated in Equation 23.

$$FMc_n = \sum_n FMa_n * fr * FMa_c$$

Equation 23

Where:

FMc_n	Functional maintenance cost in year n (€/year)
n	year under investigation ()
FMa_n	functional maintenance activities that are performed in year n ()
fr	frequency per year ()
FMa_c	cost to perform the functional maintenance activity a (€)

Total maintenance cost per year is estimated using the outcome of Equation 22 and Equation 23 within Equation 24.

$$Mc_n = SMc_n + FMc_n$$

Equation 24

Where:

Mc_n	maintenance cost in year n (€/year)
SMc_n	structural maintenance cost in year n (€/year)
FMc_n	Functional maintenance cost in year n (€/year)

5.3.5 Service life planning

The year for activity is part of most of the equations stated in the previous paragraphs. Most of the in chapter 2 analysed LCCA frameworks, do not indicate the determination of this moment and is seen as one of the major drawbacks of existing LCCA models. The only LCCA model describing the amount of maintenance works per year is set for rail infrastructure (Zoeteman, 2001). SLPA equations are used for service life estimation and identification of moment of structural maintenance. The service life planning is the sum of construction and structural maintenance activities that gives reasonable assurance that the pavement functions according to the minimum stated performance over the intended design life. Determination of the need for a structural maintenance is dependent on the sum of the earlier executed construction and maintenance activities. Equation 25 determines the need for a structural maintenance activity.

$$SLP < DL = \text{new structural maintenance activity} \quad \textbf{Equation 25}$$

Where:

SLP	Service life planning (year)
DL	Design Life (year)

When the estimated service life planning is shorter than the design life, additional structural maintenance is needed to meet the performance requirements. When the estimated service life planning is longer or equal to the design life, the performance requirements over the design life are met with the selected strategy. The LCCA estimation is finished and the Net Present Value of the alternative is estimated. The service life planning is determined using Equation 26.

$$SLP = SL + n_{last} \quad \textbf{Equation 26}$$

Where:

SLP	Service Life Planning (year)
SL	Service Life (year)
n_{last}	year where latest activity will be executed (year)

The service life indicates how many years the upper layer fulfils the minimum performance requirements. It is assumed that the upper layer of the asphalt pavement either completely fulfils the requirements in a certain year or not. not. Equation 27 identifies the service life using minimum performance level, upper layer performance and the degradation curve of the selected upper layer material.

$$SL = \frac{P - P_{\min}}{DC} \quad \textbf{Equation 27}$$

Where:

SL	Service life (year)
P	upper layer performance (%)
P_{min}	minimum performance level (%)
DC	Degradation curve (%/year)

The degradation curve is based on the selected upper layer material and influenced by decisions concerning use of prolonging maintenance and activity execution period. The degradation curve values and the influence of certain decisions are based on expert opinions. The data is collected and integrated in the execution method and material object of the object oriented model. The performance of the upper layer is estimated using Equation 28.

$$P = P_n + P_{inc}$$ **Equation 28**

Where:

P	upper layer performance (%)
P_n	layer performance in year n (%)
P_{inc}	performance increase (%)

The performance increase is based on used upper layer material. Values were determined by an expert session and incorporated in the object material. The model sets a performance limit of 100% to meet reality. Material performance in year *n* is based on previous executed activities. Selecting an upper layer for a new road construction, the performance of the upper layer is 0%, because there is none yet. For material performance estimating during structural maintenance, Equation 29 is used.

$$P_n = (((SLP - (SLP - n)) * DC) + P_{\min}$$ **Equation 29**

Where:

P_n	layer performance in year n (%)
n	year were activity will be performed (year)
SLP	Service life Planning (year)
DC	degradation curve (%/year)
P_{min}	minimum performance level (%)

The service life planning must be equal or longer than the design life. When this is not the case, the strategy does not fulfil the requirements and additional structural maintenance is needed. This can be executed in the same year or before the year when the SLP will not meet the performance requirements anymore. The model supports the possibility to execute structural maintenance before the year where the road does not fulfil the requirements. The quality of the upper layer will be higher in that year than the quality at the end of the estimated service life. This is theoretically represented in Figure 5-4. In this case, n_2 represents the latest year for structural maintenance to meet the performance requirements. The rest performance P_{n2} is at this moment the same as the minimum performance level. Executing structural maintenance before year n_2, in year n_1, then the remained performance P_{n1}, is higher. This remained performance is used in the DSS.

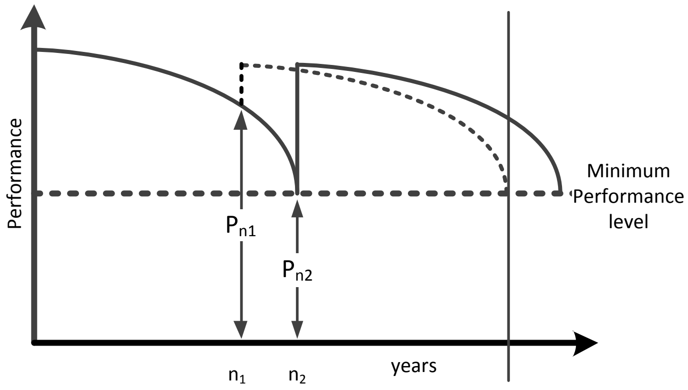


Figure 5-4 theoretical example of service life in relation to moment of performing structural maintenance

5.3.6 Net present value

Determination of the year where costs occur is presented paragraph 5.3.5. This enables the model to automate the estimation of NPV to evaluate competing alternatives. The model discounts the different cost categories to the present value using different discount rates per cost category using Equation 30:

$$NPV = \sum_{n=1}^{N} \frac{Cc_n}{(1+i_{con})^n} + \sum_{n=1}^{N} \frac{Mc_n}{(1+i_{main})^n} + \sum_{n=1}^{N} \frac{UDc_n}{(1+i_{UDc})^n} \qquad \text{Equation 30}$$

Where:

NPV	Net Present Value (€)
N	period under investigation ()
Cc_n	Construction cost in year n (€/year)
i_{con}	discount rate for construction cost (%)
Mc_n	maintenance cost in year n (€)
i_{main}	discount rate for maintenance cost (%)
UDc_n	User delay cost in year n (€)
i_{UDc}	discount rate for user delay cost (%)

What this equation allows is to differentiate between the cost categories construction cost, maintenance cost and user delay cost and sets different discount rates for those cost categories. This way, uncertainty concerning the value of money over time can be set for different periods, short term (construction cost) and long term (maintenance cost). Next to that, this equation can discount the UDC, which can be part of a project.

5.4 Dashboard

The algorithm described in paragraph 5.3 gives the decision maker the possibility to perform 'what if' analysis to see how a certain decision influences the LCC of the project pavement design. The decisions are made within the dashboard of the DSS. The decisions that the decision maker can make in this model are represented in Table 5-1 and are based on the outcome of the etnographic research as described in chapter 4.

Category	Parameter
Material use	Layer (upper layer, inner layer, under layer, foundation)
	Material used
	Thickness of the layer
Execution strategy	Closure of traffic lanes during activity execution
	Traffic speed during activity execution
Service life	Summer or winter construction
	Prolonging maintenance yes or no
	Year to perform maintenance
Value of money	Discount factor
Work performed	Activity (laying, fraying, functional maintenance, breaking)

Table 5-1 model decisions

The impact that the decisions has on the project are graphically represented within graphs and tables. The DSS visualises the life cycle costs, the cumulative costs, nominal costs, net present value and service life planning. How they are represented is indicated within Table 5-2, and an example of the dashboard is given in Figure 5-5. The numbers in brackets in Table 5-1 correspond to the numbers within Figure 5-5.

Output variable	Represented within the DSS	
Discounted costs	Cumulative cost	**(1)**
	Life Cycle Costs	**(2)**
	Total Net Present Value and per cost category	**(3)**
Nominal costs	Total costs and per cost category	**(3)**
	Costs divided per activity and cost element	**(4)**
Material Performance	Service Life Planning	**(5)**

Table 5-2 the way that output variables are represented within the DSS

The graph presenting service life planning visualises the performance of the upper layer during the design life, including the moment of construction and structural maintenance. Based on this curve, the discounted costs are estimated and represented as life cycle cost, cumulative costs and net present value. The life cycle cost visualizes the costs per year per cost category. The net present value presents the discounted costs for the total cost and the cost elements and categories. The cumulative cost graph visualises how the costs flow from the beginning to the end of the project for the different cost categories and the total cost. Besides that, the nominal costs are represented in two ways in the dashboard. Nominal total cost is broken down to cost category and elements. Next to that, nominal costs per activity are represented. The costs per activity can be reused in other projects, due to the use of the organizational breakdown structures. These structures are used in other projects as well, making it easy for reuse.

Project	A9 Gaasperdammerweg	**Te analyseren Weg sectie**	**2** **Buiten Tunnel**
Start Datum	1-1-2015	oppv totaal	173.880 m2
Eind Constructie Periode	1-1-2019	oppv overig rijstrook	108.360 m2
Eind onderhoudsperiode	2039	opp rechter rijstrook	65.520 m2
		analyse datum	16-7-2014

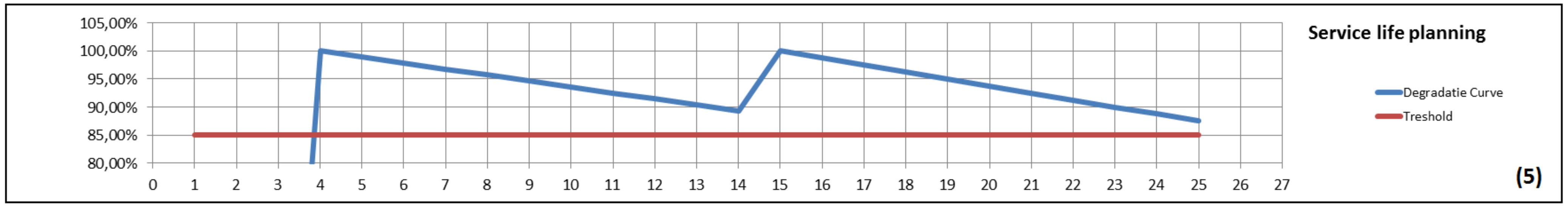
Act. ID		Uiterlijk jaar	Jaar Toegepast	Periode	Fase	Activiteit	Object	Materiaal	Uitgangspunt levensduur	Dikte	eenheid	max. snelheid tijdens uitv.	max. afsluiting rijstrook	Levensduur	Degradatie	Opwaardering
1		**2019**	2018	Zomer	**Construction**	**aanbrengen**	**Deklaag**	ZOABplus	Vroeg onderhouden	50	**mm**	70	1	**14**	**1,07%**	**100,00%**
1	1	2019	2018		Construction	aanbrengen	Tussenlaag	AC_bin_30_45	Vroeg onderhouden	60	mm					
1	2	2019	2017		Construction	aanbrengen	Onderlaag	AC_22_base_30_45	Vroeg onderhouden	65	mm					
1	3	2019	2017		Construction	aanbrengen	Onderlaag	AC_22_base_30_45	Vroeg onderhouden	70	mm					
1	4	2019	2016		Construction	aanbrengen	Fundering	Menggranulaat_31_5	Vroeg onderhouden	250	mm					
2		**2033**	2029	zomer	**Onderhoud**	**aanbrengen**	**Deklaag**	ZOABplus	Vroeg onderhouden	50	**mm**	70	1	**12**	**1,25%**	**15,00%**
2	1	2033	2029		Maintenance	frezen	Deklaag	ZOABplus	Vroeg onderhouden	50	mm					

Functioneel Onderhoud

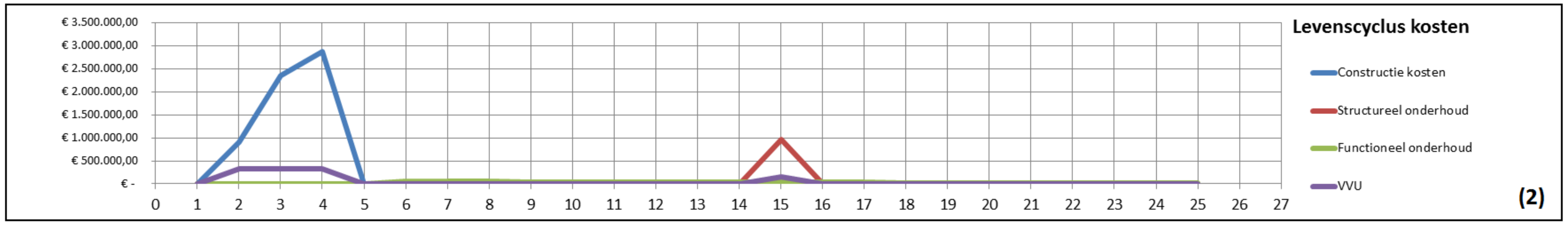
	Start jaar	Eind Jaar	frequentie per jaar	activiteit	Actie	max. snelheid tijdens uitv.	max. afsluiting rijstrook
1	2020	2039	1	Functioneel_Onderhoud	pref onderhoud	130	0

	NPV		Nominaal	
Totale Kosten	€	**8.877.457**	€	**10.619.656**
Constructiekosten	€	**6.111.572**	€	**5.859.756**
materiaal	€	6.111.572	€	5.859.756
arbeid	€	-	€	-
materieel	€	-	€	-
Onderhoudskosten	€	**1.646.515**	€	**3.800.440**
Struc. Ond. Kosten	€	**967.359**	€	**2.260.440**
materiaal	€	967.359	€	2.260.440
arbeid	€	-	€	-
materieel	€	-	€	-
Func. Ond. Kosten	€	**679.155**	€	**1.540.000**
materiaal	€	-	€	-
arbeid	€	-	€	38.500
materieel	€	-	€	38.500
Voertuig Verlieskosten	€	**1.119.370**	€	**959.460**

(3)

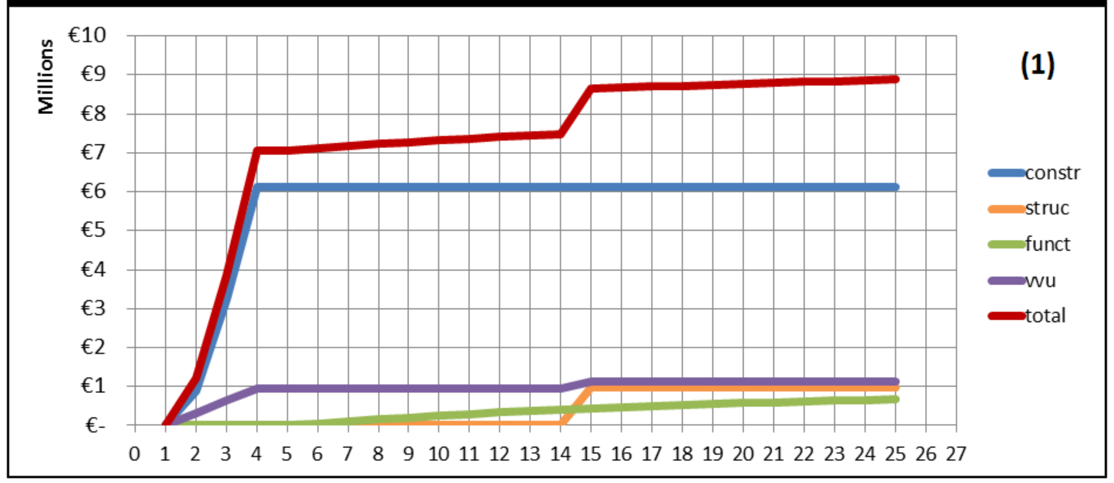


(5)



(2)

Cummulatieve kosten



(1)

Nominale kosten

Materiaal	materiaalkosten		arbeidskosten		materieelkosten		vvu kosten		totale kosten	
⊟c	€	**7.042.140**	€	-	€	-	€	**959.460**	€	**8.001.600**
⊟aanbrengen	€	**7.042.140**	€	-	€	-	€	**959.460**	€	**8.001.600**
⊟Deklaag										
ZOABplus_50mm	€	2.260.440	€	-	€	-	€	159.910	€	2.420.350
⊟Fundering										
Menggranulaat_31_5_250mm	€	956.340	€	-	€	-	€	319.820	€	1.276.160
⊟Onderlaag										
AC_22_base_30_45_65mm	€	1.269.324	€	-	€	-	€	159.910	€	1.429.234
AC_22_base_30_45_70mm	€	1.373.652	€	-	€	-	€	159.910	€	1.533.562
⊟Tussenlaag										
AC_bin_30_45_60mm	€	1.182.384	€	-	€	-	€	159.910	€	1.342.294
⊟F_U	€	-	€	**38.500**	€	**38.500**	€	-	€	**1.540.000**
⊟Functioneel_Onderhoud	€	-	€	**38.500**	€	**38.500**	€	-	€	**1.540.000**
⊟Deklaag										
pref onderhoud	€	-	€	38.500	€	38.500	€	-	€	1.540.000
	€	**7.042.140**	€	**38.500**	€	**38.500**	€	**959.460**	€	**9.541.600**

(4)

Figure 5-5 Dashboard

6 Decision support system application

The DSS is used to perform Service Life Planning Assessment (SLPA) and Life Cycle Cost Analysis (LCCA) in a Dutch DBFM tender, where the contractor will become responsible for the design, construction, financing and maintenance of overlaying and underlying road network with several engineering structures (land tunnels, bridges) and belonging traffic signs, ecological features and information systems. The construction period was set at 5 years. The contractor becomes responsible for the maintenance of the road for 20 years after construction. The value of time is stated at 15 €/h the performance of planned maintenance and construction activities. When unplanned maintenance occurs, the value of time is 25 €/h. Per trace section, the detour times, road configuration and traffic intensities were given in the contract. The required asphalt performance is stated in the standard of Rijkswaterstaat and is part of the contract (Scheepvaart, 2011). The discount factor was a strategic decision, because the contract did not prescribe this.

Based on these preconditions, the tender team divided the road into inside and outside the land tunnel. This was done due to different substructure characteristics that influence the service life of the asphalt. Seven competing alternatives are determined for the road section located outside the land tunnel. Alternatives differentiate concerning moment of construction, maintenance and used material. All alternatives are within Appendix IV. The design alternatives are simulated within the DSS to examine material performance and Life Cycle Cost estimation. What stands out is that the composition of the complete superstructure is different for all alternatives, rather than the thickness and used material of the upper layer. Besides that, differentiation in alternatives is based on the use of prolonging asphalt and the year when structural maintenance will be performed.

The results of the SLPA for all alternatives are represented In Figure 6-1, indicating the expected performance of the upper layer over the design life and the moments when structural maintenance will perform.

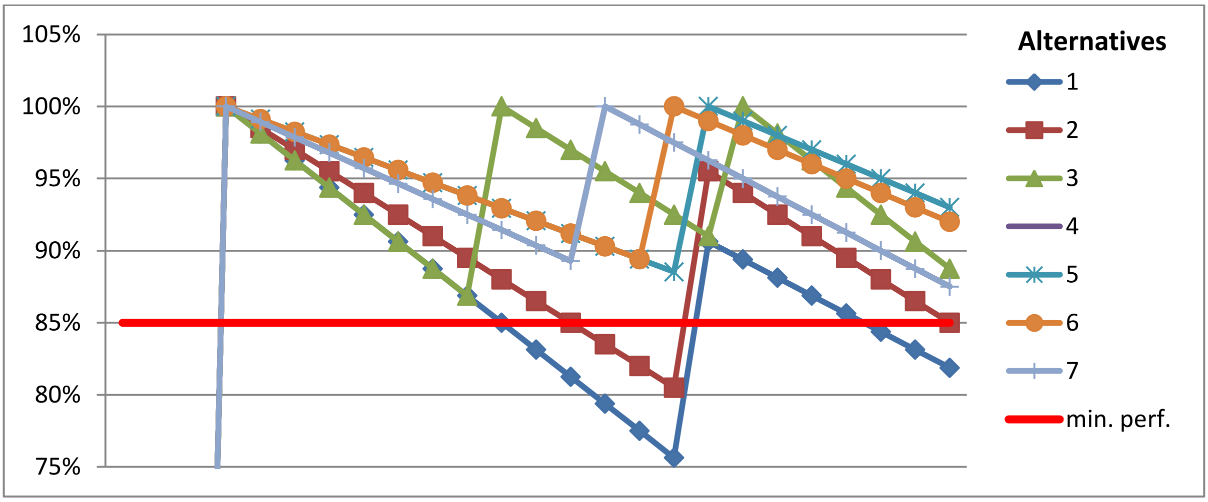


Figure 6-1 Service Life Planning Design Alternatives

Except for alternative 1 and 2 all alternatives meet the minimum performance requirements. There is a high change that unexpected maintenance is needed to keep the performance of alternative 1 and 2 above the minimum performance. This results in contractual fines due to non-functioning of the road and additional user delay cost, because the value of time for unexpected activities is higher than that for planned activities. The other strategies determined a regime that suits the minimum performance, including moments for structural maintenance. The moments for structural maintenance were set before the end of the service life, resulting in additional certainty that the alternative meets the minimum performance requirements. Alternative 3 has three moments for structural maintenance to meet the requirements, but no information is given concerning the LCC of the alternative.

The LCC for all alternatives are displayed as cumulative costs in Figure 6-2. It, visualizes the expenditures over the design life, giving an overview of moments when costs are made.

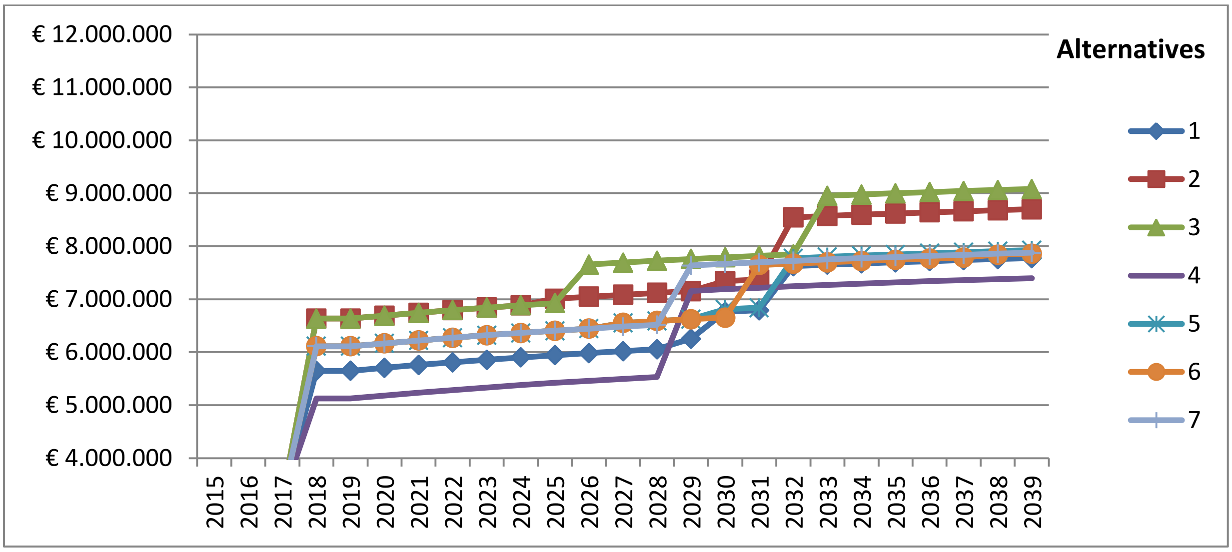


Figure 6-2 cumulative cost overview without user delay cost

Alternative 4 has the lowest estimated LCC and alternative 3 the highest estimated LCC. One of the reasons that alternative 3 has the highest LCC is the usage of an additional structural maintenance activity. Alternative 1, 5, 6 and 7 do not outrun each other significantly. Alternative 1 and 2, which do not fulfil the minimum requirements, do not have the lowest estimated LCC.

Figure 6-2 presents the presumptions of the tender team. Within the LCCA of the tender team, UDC was not incorporated. An assumption is made that during activity execution, the traffic speed is reduced to a maximum of 70km/h and one traffic lane is closed to perform the activities. This results in the cumulative cost as presented in Figure 6-3.

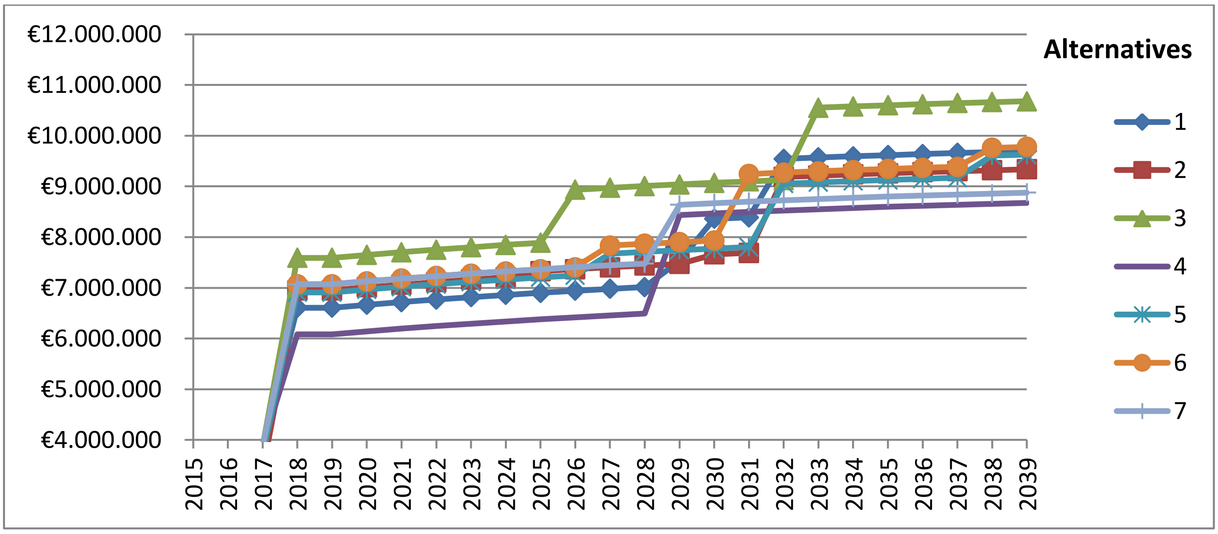


Figure 6-3 cumulative cost overview with user delay cost

Comparing Figure 6-2 and Figure 6-3 clarifies that UDC significantly influences the LCC. The NPV increases with the incorporation of UDC, but also the ranking of the alternatives change. For instance, alternative 6 has the second highest NPV when taking UDC into account, while without the incorporation of UDC, there is not a significant difference between alternative 6 and alternatives 1,5,6,7. Reason for this is that this alternative examines the possibility to use prolonged maintenance to help slowing the deterioration process of the upper layer. This way, a cheaper construction material is used and in combination with the prolonged maintenance activity, the service life can be the same as for a more expensive construction material. With this DSS, the impact that prolonged maintenance has on the LCC where UDC is part of the analyses becomes clear. This DSS gives the decision maker a tool to underpin his assumptions using uniform, transparent and complete information.

This case study indicates the importance of incorporating UDC in LCCA. The LCC of the alternatives changes significantly when UDC is accounted in the analysis. The DSS supports incorporation of UDC within LCCA by the incorporation of activity execution strategy. The incorporation of UDC in the DSS is one of the main strengths of the model, because this case study revealed that UDC has a significant influence on the LCC. When availability of the road is not one of the steering mechanisms, the DSS gives the decision maker the possibility to exclude this from the analysis making the DSS applicable for all projects with a design life focus. Another strength of the DSS is that it accounts for road pavement quality over the design life. The DSS warns the decision maker when an alternative is expected perform less than requirements during the design life. Relating service life decisions to LCC and automating this process is proven to be possible and beneficial. It speeds up the evaluation of an alternative on costs and quality during the design life. The case study revealed that the information captured in the object oriented model is sufficient to evaluate upper layer SLP alternatives based on LCC. The case study revealed that alternatives do not really different in upper layer material, but more in superstructure composition. Incorporating information in the DSS about the relation between asphalt layers to the service life is something that is expected to improve the DSS. Reuse of information captured in the object oriented model is proven to be possible, because all alternatives are created using the same databases. The object oriented model gives the decision maker a focus towards alternative generation and evaluation rather than on data collection.

7 Decision support system validation

The model is validated using sensitivity analysis. Sensitivity analysis examines changes in model output in response to change in input value parameters. Purpose is to ensure that the model responds to the expectations of the user (McGrath, 2006). It gives insight in the question if the right problem is addressed by the Decision Support System (DSS) (Assakhaf, 2003) and helps identifying the specific issues that matter in decision making. The outcome of the sensitivity analysis is used to examine unexpected model behaviour. Unexpected model behaviour implies that the model does not respond to reality. This can be caused by the structure of the model, or by the input values. If the DSS responds reasonable from an intuitive or theoretical perspective, then the model users may have comfort with the qualitative behaviour of the model (Frey, et al.). Analysing the outcomes of the sensitivity analysis with experts is used to validate the Decision Support System (DSS) to see if it approaches reality. The sensitivity analysis itself does not validate the model, but the outcome is used for validating experts opinions concerning the DSS with reality.

A precondition for the analysis is that the change in input value is expected to take place in reality. Therefore, input parameters are divided into two groups. One group uses an absolute scale, where values changed using exact figures. The other group uses ratio scale where the input parameters changes with steps of 5% to plus 20% and minus 20% to the base case value. Table 7-1 presents the analysed input parameters allocation to the scale group and what respectively an increase or decrease indicates. The performed analysis used data obtained from the base case. One or two parameters are changed systematically to analyse the influence to parameter(s) has on the Net Present Value (NPV).

Input parameter	Scale	Decrease	Increase
Discount factor	Ratio	lower discount factor	higher discount factor
Activity Speed	Ratio	Slower activity execution	Faster activity execution
Traffic Speed	Ratio	traffic moves slower	traffic moves faster
Degradation	Ratio	flatter degradation curve	steeper degradation curve
Material Cost	Ratio	lower cost	higher cost
Activity Cost	Ratio	lower cost	higher cost
Asphalt Surface area	Absolute	decrease in surface area	increase in surface area
Traffic Lane Closure	Absolute	less lane closures	more lane closures

Table 7-1 Parameters under investigation

7.1 Base case

The DSS is changed to analyse the effect of a different degradation curve to the NPV. The DSS determines the latest year for structural maintenance without passing the minimum performance level. This information is used to set the maintenance strategy. The maintenance strategy is not directly related to the degradation curve, but only related to the latest year to perform structural maintenance. For the sensitivity analysis, the maintenance strategy is directly related to the degradation curve in the DSS. The adjusted DSS is used for one-way and two-way sensitivity analysis. The used Service Life Planning alternative is represented in Figure 7-1 and is the same as alternative 4 indicated in chapter 6. Figure 7-2 states the service life planning and Figure 7-3 the cumulative cost of the alternative.

year	period	activity	object	material	thickness	period	traffic speed	closure traffic lanes	proloning maintenance
5	**Construction**	**Laying**	**Upperlayer**	**ZOABplus**	**50**	**summer**	**70 km/h**	**1**	**no**
5	Construction	Laying	Underlayer	AC_22_base_30_45	65	summer	70 km/h	1	no
5	Construction	Laying	Underlayer	AC_22_base_30_45	70	summer	70 km/h	1	no
5	Construction	Laying	Foundation	Menggranulaat_31_5	250	summer	70 km/h	1	no
18	**Maintenance**	**Laying**	**Upperlayer**	**ZOABplus**	**50**	**summer**	**70 km/h**	**1**	**no**
18	Maintenance	Milling	Upperlayer	ZOABplus	50	summer	70 km/h	1	no
18	Maintenance	Laying	Inter Layer	AC_bin_30_45	60	summer	70 km/h	1	no
Functional maintenance			**freq/year**		**year**	**to**	**year**		
preventive maintenance			1		2020		2039		

Figure 7-1 Base case

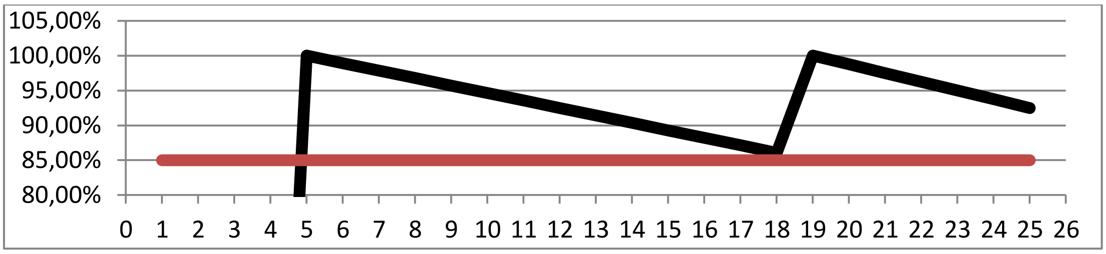


Figure 7-2 Service Life Planning

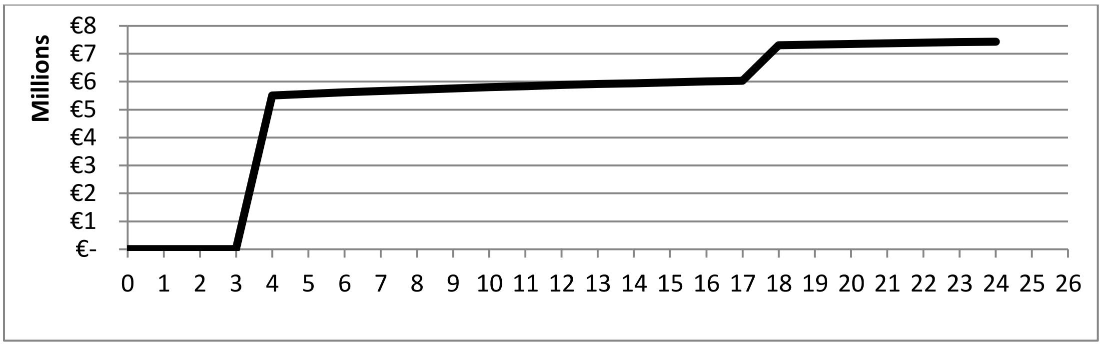


Figure 7-3 Cumulative Life Cycle Cost

7.2 One-Way sensitivity analysis

One-way sensitivity analysis creates a quantitative image of the influence of different factors. Input parameters are individually systematically changed to analyse the influence to the NPV. The outcome is used for the investigation if the outcomes approach reality by investigating if the ranking of the parameters corresponds to expectations or theoretical perspectives. One way analysis examines if a parameter makes a difference in to the decision (Khoramshahi, 2012). The one-way analysis is represented in two-ways. The spider plot visualises the relation between the input parameter to the NPV and can be used for strategic decisions (Pannell, 2013). Precondition for a spider plot is the use of the same scale and intervals. Therefore, three spider plots are created, one for the parameters that change using ratio scale and two for the parameters using an absolute scale. Next to that, for the parameters using a ratio scale, a tornado diagram is set which visualises the impact of a change of input value of plus 20% and minus 20% to the NPV base value and is presented in Figure 7-5. The wider the bar, the bigger the influence to the NPV. A decreasing effect on the NPV is seen as positive. The tornado diagram does not clarify if a certain increase in input value has the same effect to the NPV as when the input value changes using the same interval in the other direction. Besides that, the relation that the input parameter has on the NPV is not shown in the tornado diagram. The spider plot presented in Figure 7-4 and Table 7-2 give more insight in these matters. At first the different plots are represented, followed by an analysis per parameter.

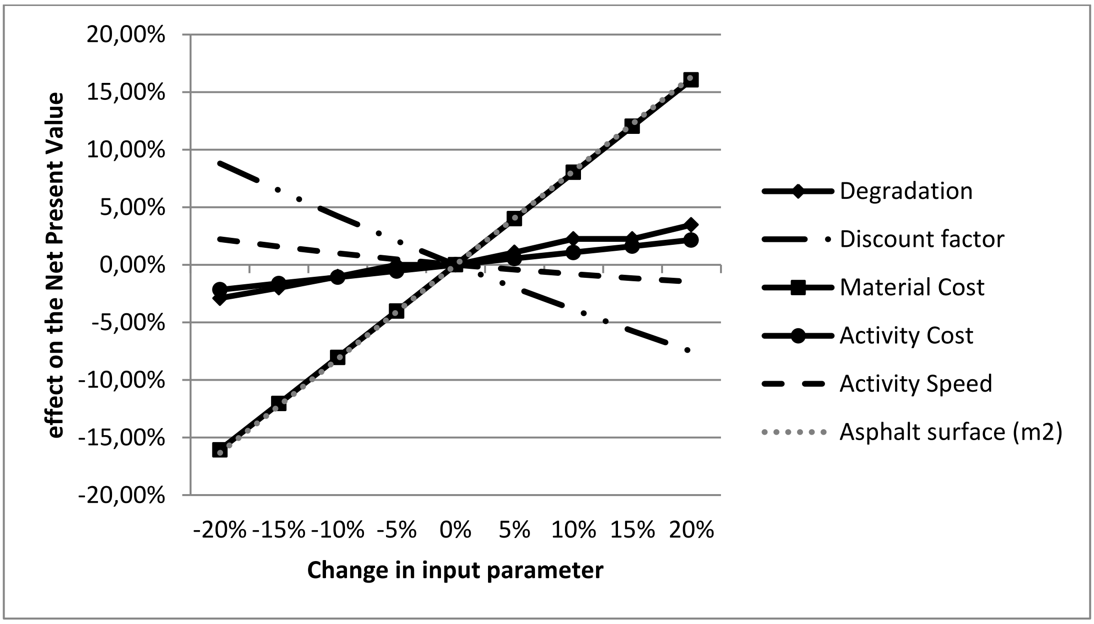


Figure 7-4 spider plot

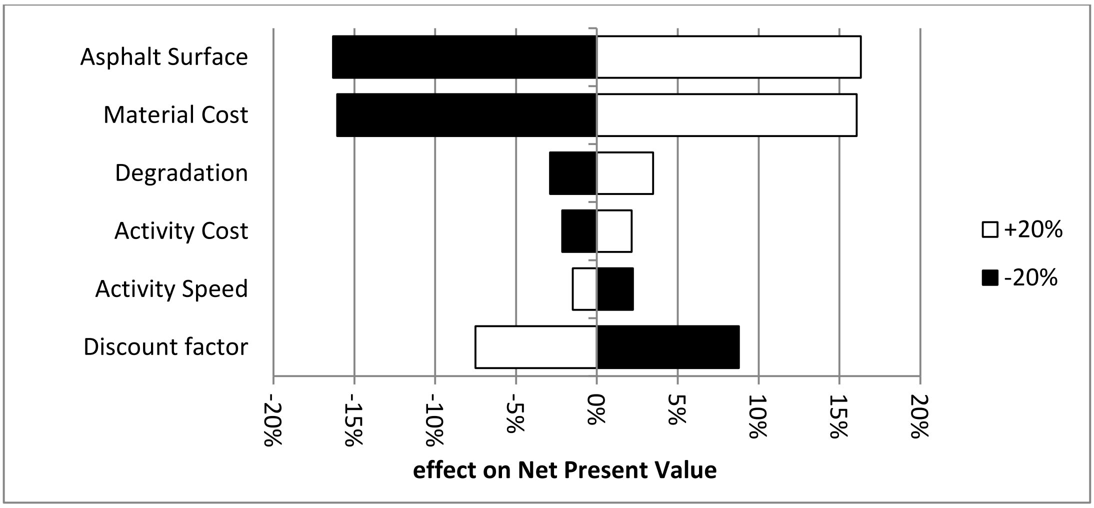


Figure 7-5 Tornado diagram

Δ	Degradation	Discount	Material Cost	Activity Cost	Activity Speed	Asphalt Surface
-20%	-2,90%	8,79%	-16,06%	-2,16%	2,23%	-16,32%
-15%	-1,99%	6,46%	-12,04%	-1,62%	1,58%	-12,24%
-10%	-1,03%	4,22%	-8,03%	-1,08%	0,99%	-8,16%
-5%	0,00%	2,07%	-4,01%	-0,54%	0,47%	-4,08%
0%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
5%	1,09%	-1,99%	4,01%	0,54%	-0,43%	4,08%
10%	2,25%	-3,90%	8,03%	1,08%	-0,81%	8,16%
15%	2,25%	-5,74%	12,04%	1,62%	-1,16%	12,24%
20%	3,48%	-7,52%	16,06%	2,16%	-1,49%	16,32%

Table 7-2 one-way sensitivity analysis for ratio scale parameters

7.2.1.1 *Asphalt surface*

Asphalt surface is the surface of road that must be constructed or maintained and is expressed in m^2. The tornado diagram in Figure 7-5 indicates that this parameter has the most influence on the NPV for the parameters changed with ratio scale. An increase in asphalt surface results in an increase in NPV. Table 7-2 and spider plot presented in Figure 7-4 indicate a linear relation between asphalt surface and NPV, and that a change in input parameter has the same effect in opposing directions.

7.2.1.2 *Material cost*

Material costs are the cost of resources that become part of the road (Al-Jibouri, 2004). In this case, the costs are related to the upper layer, inner layer, under layer and foundation where delivery to the site is part of the unit price. The tornado diagram in Figure 7-5 indicates that material cost has a large influence on the NPV. The spider plot in Figure 7-4 indicates a linear relation between NPV and material cost and that a change in input parameter has the same effect in opposing directions to the NPV.

7.2.1.3 *Degradation*

Degradation is the change of performance of the upper layer per year expressed in percentages. The faster the material deteriorates, the earlier structural maintenance is needed. This is theoretically visualized within Figure 7-6.

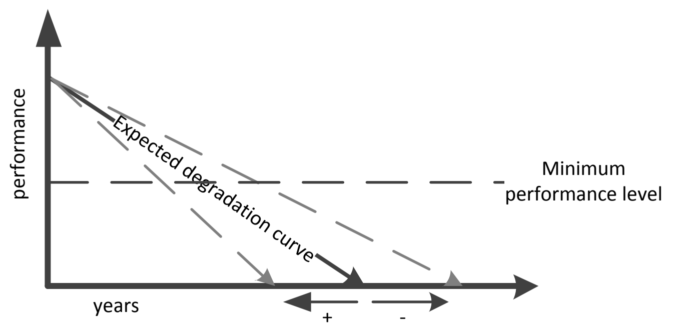


Figure 7-6 theoretical example of influence degradation curve on service life

When material deteriorates faster than expected the degradation curve becomes steeper resulting in an shorter service life resulting in earlier need for structural maintenance. In the worst case, additional maintenance activities are needed to meet the design life. When the material deteriorates slower than expected, the degradation curve becomes flatter and the service life becomes longer, resulting in later need for structural maintenance. In the best case, a fewer amount of structural maintenance activities are needed to reset the deterioration process.

The tornado diagram points out that an increase or decrease of 20% of the input parameter has little effect to the NPV (<5%). The spider plot visualizes a non-linear relation between degradation and NPV. This can be explained by the fact that for the analysis, the service life that is estimated based on the degradation curve is rounded to full years. The spider plot also visualizes that degradation has a more negative than positive effect on the NPV.

7.2.1.3.1 Activity Costs

Activity Costs are the direct costs that occur to conduct an activity. These are costs of resources that do not become part of the road, but which are needed to perform the activities. In this case, they are related to labour costs and equipment cost. Labour are the human resources needed to conduct an activity and equipment are all the machines and tools used by labourers to conduct an activity (Al-Jibouri, 2004). The tornado diagram indicates that a change of 20% of the activity costs has little effect on the NPV (<5%). The relation with the NPV is linear and has a larger negative than positive effect on the NPV.

7.2.1.3.2 Activity Speed

Activity speed is the speed of a crew to execute an activity. In this case, it is expressed in terms of amount of meters of traffic lane per hour. The speed to perform the activity is dependent on the amount of traffic lanes closed, because the model assumes that crews work parallel to each other when 2 or more traffic lanes are closed. The tornado diagram indicate that activity speed has little influence on the NPV (<5%) and that the relationship with NPV is linear. The activity speed has a larger negative than positive effect on the NPV.

7.2.1.3.3 <u>Closure of traffic lanes</u>

Closure of traffic lanes determines how many traffic lanes are closed during construction and structural maintenance activities. The closure of traffic lanes determines the activity speed and the detours to pass from A to B during activity execution.

In the base case, one traffic lane is closed during activity execution. This analysis gives insights in the influence to the NPV when more or less traffic lanes have to be closed or will be closed during activity execution. What stands out in Figure 7-7 is that the relation between NPV and closure of traffic lanes during activity execution is nonlinear and the dropdown in NPV when 4 traffic lanes are closed compared to 3 traffic lanes. It can be seen that the amount of closed traffic lanes has an enormous effect on the NPV, because an increase of 80 % is shown when three traffic lanes are closed.

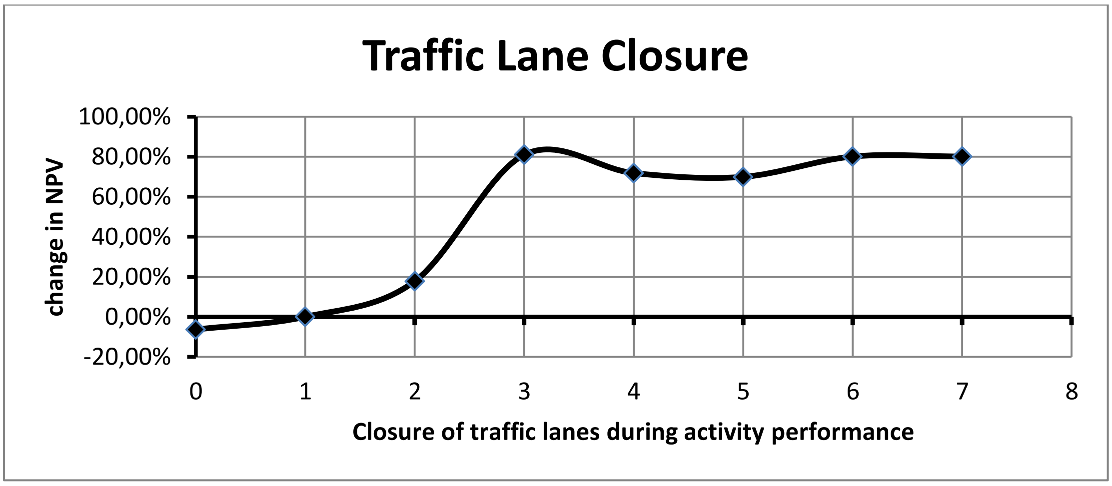


Figure 7-7 Spider plot Traffic lane closure

The decrease in influence on the NPV when more than 3 traffic lanes are closed can be explained by the configuration of the DSS and its relation to UDC. The decision to close traffic lanes influences the activity execution duration and UDC due to rerouting.

The activity execution duration is an factor influencing UDC. The activity execution duration per road section is the sum of all activity durations per trace sections and is estimated using Equation 11:

$$d_{ts} = \frac{l_{ts}}{S} + (ts_{tl} - CL_{tl}) * (\frac{l_{ts}}{S})$$ **Equation 11**

Where:

d_{ts} duration to perform trace section (h)
l_{ts} length of trace section (m)
S speed to perform activity (m/h)
ts_{tl} amount of traffic lanes for the trace section (-)
CL_{tl} Closure of traffic lanes during activity execution (-)

The duration to execute the trace section is dependent on the traffic lanes within the trace section (ts_{tl}) and the closure of traffic lanes (CL_{tl}). A theoretical example of how the DSS determines the activity sequencing is stated in Figure 7-8 and Figure 7-9.

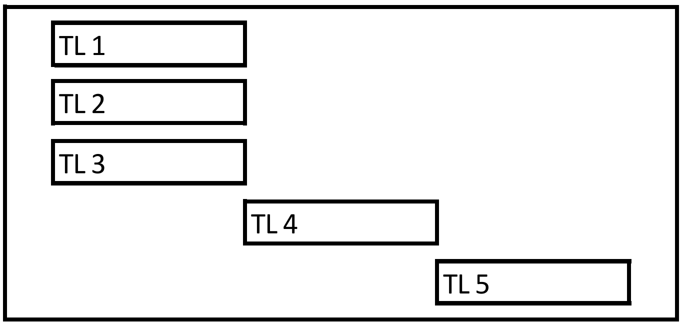


Figure 7-8 closure of three traffic lanes within one trace section

In this theoretical example, there is one trace section with 5 traffic lanes. In Figure 7-8, the decision maker decides to close a maximum of 3 traffic lanes at the same time. This makes it possible to execute traffic lanes 1, 2 and 3 parallel to each other, using 3 crews. The DSS plans the other two trace sections in a sequential way.

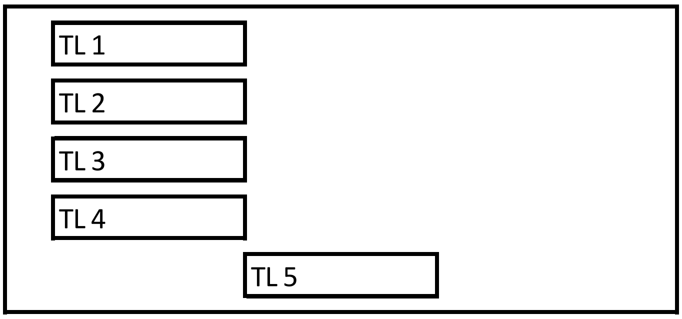


Figure 7-9 closure of 4 traffic lanes within one trace section

Within Figure 7-9 the same trace section is represented. The decision maker decides to close four traffic lanes at the same time, making it possible to execute the activity on traffic lane 1-4 parallel, using 4 crews. The DSS plans to execute traffic lane 5 sequential after the first 4 traffic lanes are performed. This theoretical example shows that in this case, the speed to perform the activity on the trace section will be shortened by a third when it is decided to close four instead of three traffic lanes.

Based on the decision to close a certain amount of traffic lanes, the DSS determines the two trace sections with the highest traffic intensity that are closed. In the base case, the trace sections with the highest traffic intensity are the same for a closure of three traffic lanes, as for a closure of four traffic lanes. Together with the explanation about how the duration is estimated, makes it possible that there will be a decrease to the NPV when there will be a decision to close one more traffic lane. This analysis makes clear that the effect of closure of traffic lanes is highly related to UDC.

7.2.1.3.4 Traffic speed during activity execution

Traffic speed during activity execution is the maximum speed allowed for regular traffic during activity execution. To execute maintenance and construction activities, regulations indicate that a safe working environment is prohibited and accomplished by traffic speed reduction. This influences the availability of the road, because the duration for the road users to move from point A to point B becomes longer. This additional time is one of the factors influencing UDC and therefore this parameter is analysed.

Within the analysis, traffic speed is changed in steps of 10 km/h ranging from 30 km/h to 110km/h. This represents a maximum increase or decrease of 40km/h to the base case traffic speed value of 70km/h.

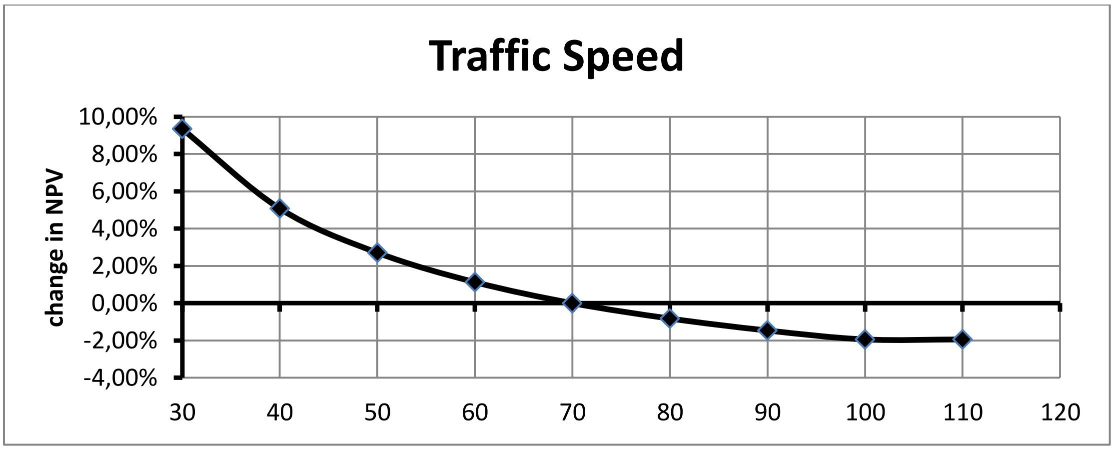


Figure 7-10 Spider plot traffic speed

Figure 7-10 presents the change in speed in relation to the change in NPV. A decrease of the traffic speed during activity execution has more influence on the NPV than an increase. Next to that, at a traffic speed of 100 km/h the parameter does not influence to the NPV anymore. The relationship between NPV and traffic speed during activity execution is nonlinear. What stands out is that there is no difference in influence between 100 km/h and 110 km/h. Reason for this can be found within the configuration of the road and the way the model is set up. In the analysed case, the maximum speed is 100 km/h and the equation to estimate UDC based on speed regulation is presented in Equation 17.

$$\Delta UDsr_n = \sum_{ts=1}^{TS} \left(\frac{l_{ts}}{V_a} - \frac{l_{ts}}{V_n} \right) * Tint_{ts} \qquad \textbf{Equation 17}$$

Where:

$\Delta UDsr_n$	average user delay per hour due to speed regulation in year n (cars/h)
TS	trace section
l_{ts}	length of trace section (km)
V_a	traffic speed during activity execution (km/h)
V_n	traffic speed during normal conditions (km/h)
$Tint_{rs}$	traffic intensity (cars/h)

Equation 17 indicates that user delay due to change in maximum speed is dependent on the difference between regular speed and during activity execution. In this case, at a traffic speed of 100 km/h there is no change in traffic speed which results in no change to the NPV, explaining the decrease in influence on the NPV.

7.2.1.3.5 Discount Factor

The discount factor is related to the value of money in the future. Within LCC estimations, one of the driving principles is that one euro is worth more today than tomorrow. This principles allows comparing different long term investment alternatives by discounting the costs over the analysing period back to a fixed moment in time, like the NPV. The difference in value is dependent of many factors, but is expressed in terms of the discount factor. It is a percentage value indicating how the value of money changes over time. The tornado diagram in Figure 7-5 indicates that the discount factor has a relatively large influence on the NPV (<10%) at a change of 20%. An increase in discount factor results in a lower NPV and vice versa. The spider plot indicates a linear relation between the discount factor and the NPV, and that there is a larger negative than positive effect to the NPV.

7.3 Two-way sensitivity analysis

The one-way analysis indicates the effect that one input parameter has on the NPV. This methodology does not provide insight in a possible interaction between input parameters. The two-way sensitivity analysis changes two input parameters at once to see the effect it has on the output parameter. The analysis helps the decision maker to better understand the combined impact of changes of two variables on the expected outcome of the decision (Khoramshahi, 2012).Presenting this in a scatter plot visualizes the relationship between the input parameters to the NPV. The input parameters under investigation are represented on the axes and the effect on the NPV is visualized in the scatter plot. Different parameter relationships are identified as surrogates damping and excitation. Setting a trend line through the scatter plot visualizes a linear or non-linear relation between the input parameters. A linear trend line indicates a linear relation between the two parameters, meaning that the parameters do not influence each other. The distribution around the trend line indicates which parameter has more effect on the NPV and if there is a damping or surrogate effect. A non-linear trend line indicates that the relation is nonlinear, and that there is either an excitation or damping effect between the parameters. Within Figure 7-11 the scatter plots are represented for the two-way sensitivity analysis. The axes indicate the parameters and the scale of each of the input parameters. Per scatter plot, the change in NPV is displayed in intervals of 10% when a certain change in value is made for the input parameters under investigation. In the next sections, the analysis is presented where the results are categorized in linear and nonlinear relations. Within the figure, the scatter plots are numbered and correspond to the analysis.

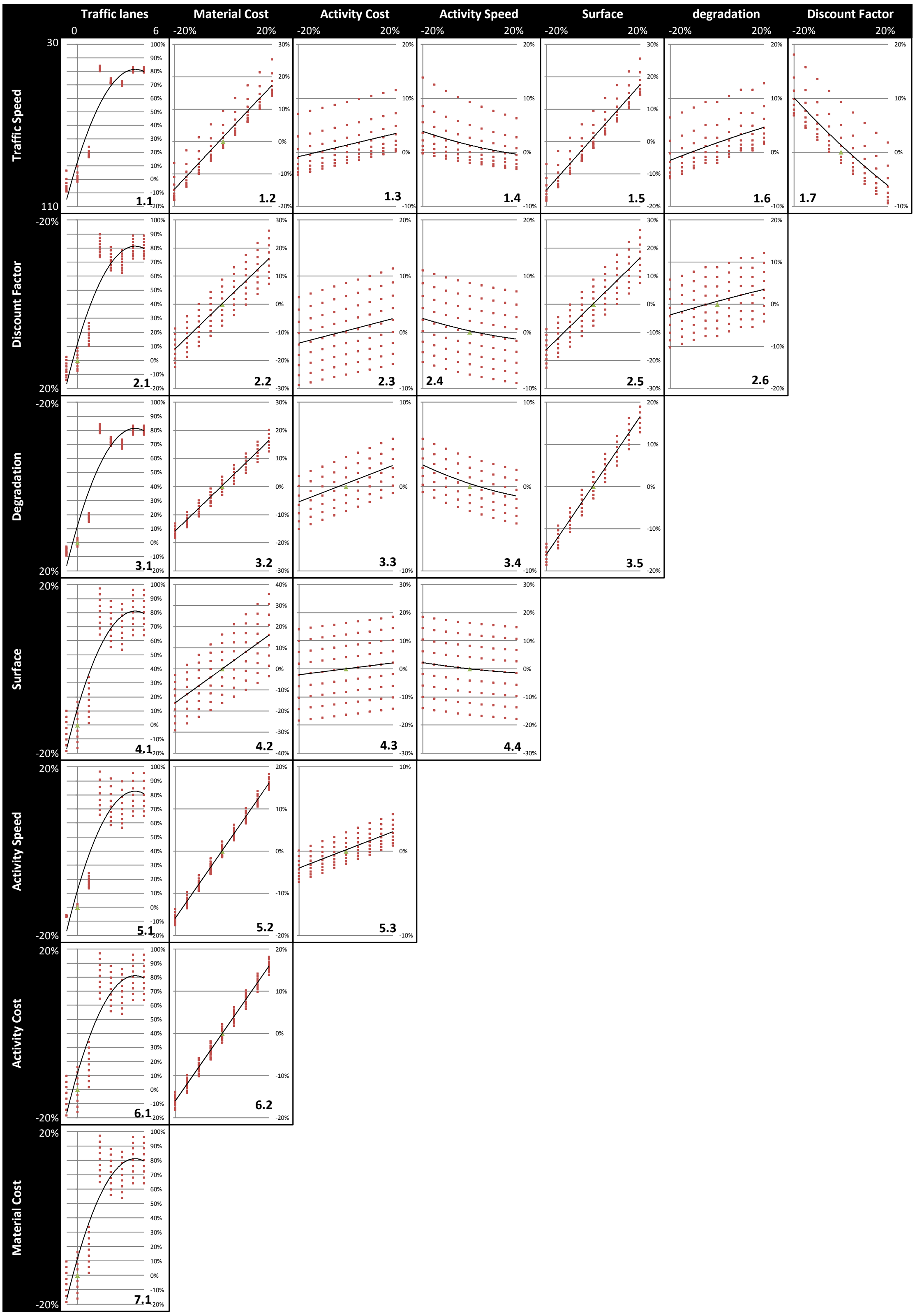


Figure 7-11 box plot of two-way sensitivity analysis

7.3.1.1 Linear relations

The trend line indicates if the relation between the input parameters is linear in relation to the NPV. The distribution indicates if there is a damping or excitation effect between the parameters. If there is no change in distribution in the x-axe or y-axe direction then the parameters are considered surrogates in the base case. This section discusses the linear relations and divides it into surrogates and non-surrogates. What can be seen within these relations is which of the parameters has the most influence on the NPV. This allows validating the one-way sensitivity analysis.

7.3.1.1.1 <u>Surrogates</u>

Material cost seems to have more influence on the NPV than degradation (3.2), activity speed (5.2) and activity cost (6.2). This is underpinned by the tornado diagram represented in Figure 7-5, where it is shown that material cost has the most influence on the NPV of the ratio scale parameters. Activity cost has less effect on the NPV than discount factor (2.3), degradation (3.3) and asphalt surface (4.3), but more influence than activity speed (5.3). Comparing the relation between discount factor and degradation (2.6) visualizes that the discount factor has more influence on NPV than degradation.

7.3.1.1.2 <u>Non surrogates</u>

Figure 7-10 indicates that traffic speed has less influence on the NPV than material cost (1.2), activity cost (1.3), asphalt surface (1.5), degradation (1.6) and discount (1.7) when the traffic speed is higher than the base value. It seems that traffic speed has more influence on the NPV then those parameters when the traffic speed is lower than the base value. This is also shown in the spider plot in Figure 7-10, which represents the one-way analysis for the traffic speed during activity execution. This plot indicates that a lower traffic speed has a higher negative influence on the NPV than a positive influence in the opposing direction when a same change is made. The analysis of the base case indicates a small damping and excitation effect between material cost and discount (2.2). An increase in discount in relation with a decrease in material cost to their base values results in a positive damping effect in comparison to the base case. In opposing direction a negative excitation effect can be seen. When material is more expensive and the discount is less than the base value, the NPV will increase in an excitation manner. A same relation can be seen between surface and material cost (4.2).

When the values of these parameters are smaller than their base values, a positive damping effect is shown to the NPV. In opposing direction a negative excitation effect is shown. This implies that surface has more influence on the NPV than material cost. In addition, asphalt surface has an excitation or damping relation with discount (2.5) and degradation (3.5). When either the input value of degradation or discount is bigger than the base value and surface smaller than the base value, then this has a positive damping effect on the NPV. In opposing direction a negative excitation effect to the NPV is found.

7.3.1.2 Nonlinear relation

The scatter plots resulted from the base case indicate a nonlinear relation between input parameters when one of the parameter is closure of traffic lanes (1.1, 2.1, 3.1, 4.1, 5.1, 6.1, and 7.1) during activity execution. In each of the relations closure of traffic lanes has more influence on the NPV than the other parameter. This is shown in the fact that the distribution in the y direction of the plots is relatively small. Within these relations there is a negative damping effect when more than three traffic lanes will be closed. When less than three traffic lanes are closed there is an excitation effect to the NPV. The damping effect can also be seen within the spider plot of Figure 7-4. In this figure, the effect to the NPV reduces when more than 3 traffic lanes are closed. This is in accordance with the scatter plots of Figure 7-10.

Another parameter that often shows a nonlinear relation with other parameters is that of activity speed. This applies for the relation with traffic speed (1.4), discount factor (2.4), degradation (3.4) and surface area (4.4). Each of these relations shows a negative excitation effect to the NPV when activity speed is slower than the base case. The analysis of the base case also indicates a positive damping effect when the activity speed is faster than the base value. Within Table 7-3 an overview can be seen of the relationships can be found.

ID	Parameters		Relationship		most influence
1.1	Traffic speed	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed
1.2	Traffic speed	Material cost	Linear	Non surrogate	
1.3	Traffic speed	Activity cost	Linear	Non surrogate	
1.4	Traffic speed	Activity speed	Nonlinear	Surrogate	Traffic speed
1.5	Traffic speed	Asphalt surface	Linear	Non surrogate	
1.6	Traffic speed	Degradation	Linear	Non surrogate	
1.7	Traffic speed	Discount factor	Linear	Non surrogate	
2.1	Discount factor	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed
2.2	Discount factor	Material cost	Linear	Non surrogate	
2.3	Discount factor	Activity cost	Linear	Surrogate	Discount factor
2.4	Discount factor	Activity speed	Nonlinear	Surrogate	Discount factor
2.5	Discount factor	Asphalt surface	Linear	Non surrogate	
2.6	Discount factor	Degradation	Linear	Surrogate	Discount factor
3.1	Degradation	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed
3.2	Degradation	Material cost	Linear	Surrogate	Material cost
3.3	Degradation	Activity cost	Linear	Surrogate	Degradation
3.4	Degradation	Activity speed	Nonlinear	Surrogate	Degradation
3.5	Degradation	Asphalt surface	Linear	Non surrogate	
4.1	Asphalt surface	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed
4.2	Asphalt surface	Material cost	Linear	Non surrogate	
4.3	Asphalt surface	Activity cost	Linear	Surrogate	Asphalt surface
4.4	Asphalt surface	Activity speed	Nonlinear	Surrogate	Asphalt surface
5.1	Activity speed	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed
5.2	Activity speed	Material cost	Linear	Surrogate	Material cost
5.3	Activity speed	Activity cost	Linear	Surrogate	Activity cost
6.1	Activity cost	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed
6.2	Activity cost	Material cost	Linear	Surrogate	Material cost
7.1	Material cost	Traffic lanes closed	Nonlinear	Surrogate	Traffic lanes closed

Table 7-3 Two-way sensitivity analysis: parameter relationships

8 Discussion

This research described the Decision Support System (DSS) to conduct Life Cycle Cost Analysis (LCCA) for Service Life Planning Assessment (SLPA) in the field of road pavement design. The DSS uses an object oriented model to capture and structure to conduct SLPA and evaluate alternatives based on Life Cycle Cost (LCC). The research focussed on the identification of an LCCA algorithm that incorporates Used Delay Costs (UDC) in the analysis. Besides that the research identified what information is needed to perform LCCA and how this information concerning must be captured and represented within the object oriented model. The DSS relates SLPA decisions to LCCA to automate the impact that a decision has on the LCC. The DSS is developed and tested in collaboration with practitioners' external experts. It is proven that the model supports the decision maker in the field of SLPA. Within the next paragraphs a discussion is presented per sub question as stated within chapter 2.7.

1. *What information is needed to perform road pavement LCCA?*

This research clarified that different sources of information are needed to perform LCCA in road pavement design. Information concerning material degradation and minimum performance level is needed to determine the service life of a layer. Information concerning construction period and design life is needed to perform the SLPA. Other information relates to the LCC of the alternative. These are related to road geometry (width and length), project unspecific information (labour equipment and material costs) and project specific information (value of time, traffic intensity, detour times and regular traffic speed). The model divides costs into time related and non-time related cost elements. UDC is incorporated in the LCCA in this way. Walls and Smith (1998) and Salem (2013) indicated that it was hard to take UDC into account within life cycle cost analysis. The research indicates that UDC influences the life cycle cost of a road infrastructure project significantly. Incorporation of UDC within the life cycle cost analysis of a road infrastructure project, should be an integral part of each decision making process. Within this case the model of Rijkswaterstaat was used to determine the UDC, but within other countries, the way UDC is determined can be different. Future research could identify how other counties estimate user delay cost to see if this part of the model can also be applied in other countries than within the Netherlands. This research identified that to perform LCCA for service life road pavement design, information is needed concerning the project, material properties, costs, execution method and activities.

2. *What are important decisions that should be integrated within the DSS according to the decision maker to come to reliable decisions?*

The DSS automates decisions concerning SLPA to see how it affects the LCC. The researcher became part of the project team giving him insights in the most important decisions in road pavement SLPA. These were incorporated in the mathematical model. , insights were gained concerning the SLPA process and which decisions were important, allows incorporating them within the algorithm. The decisions were categorized into material use, execution strategy, service life, value of money and performed activities.

It became clear that all these decisions influence the LCC of the alternative under investigation and that the decisions concerning material use, execution strategy and service life, influence the SLPA of the upper layer. More factors influence the service life of the road pavement, since the variation in SLP alternatives could mostly be found other layers than that of the upper layer. Further research concerning the relation between the road pavement composition to the service life of the road pavement is seen as a good direction, since it is expected that this will give a more realistic view on the SLP of the road pavement.

3. *How should the object oriented model be structured to perform the LCCA?*

The purpose of this research was to relate SLPA and LCCA to each other using a mathematical algorithm to automate the process to support the decision maker. Information is related to the different decisions so that the right information is used for the decision that will be taken

Within this research, nine objects were created and related to the hierarchical object breakdown and activity breakdown structure of the organization under investigation. The different objects have different attributes that are either used for data storage or information creation. The decision maker utilizes the information to underpin his decisions. The hierarchical breakdown structures are integrated so that the information in the model can be reused within other projects, but also to allocate historical data that becomes available over time. This study demonstrated the strength of object oriented modelling to capture and reuse data. This is shown within the case study where the same captured data was reused for each alternative generation. This research gained additional knowledge concerning the possibility of reuse of information using an object oriented model to simulate alternatives. Besides that, this research identified possibilities of using an object oriented model within the areas of service life planning assessment, but also in the field of road infrastructure. Till this moment, not much research was performed concerning the applicability of this type of model in these fields.

4. *How can this information be used to create a parametric decision support model?*

The parametric model is created by relating service life decisions to the LCC. Such an approach was already found within the rail infrastructure, but was not found within the road infrastructure. This research indicated possibilities to determine SLP alternative for road pavement using a mathematical algorithm, information and decisions. Information concerning costs is related to the information needed to conduct SLPA, the effect of a certain decision is directly presented in the form of LCC. This gives the decision maker information concerning pavement performance over time and LCC. The DSS also incorporates other decisions which are related to activity execution. This study clarified possibilities to relate material properties to LCCA in another field as that of rail infrastructure and to automate the decision making process. This is done by incorporation of existing modified and new equations. One of the main derivatives is the integration of previous performed construction and maintenance activities in the determination of the performance of the upper layer resulting in a visualization of the performance over the design life.

5. *What are the strengths and limitations of the model?*

The case study indicates that the model gives the decision maker objective information that can be used to perform LCCA. The possibility to relate the performance of the upper layer to the LCC of the alternative is one of the important features of the DSS, because it clarifies if a design alternative meets the performance requirements. The most important feature of the model is that it allows decision makers to incorporate UDC within the LCCA. UDC is investigated an important cost category when availability of the road is a project requirement. The DSS incorporates the cost category giving the decision maker a holistic view to the NPV of the alternative. When availability of the road is not one of the project steering mechanisms, the DSS gives the decision maker the possibility to exclude this from the analysis making the DSS applicable for all types of projects which focuses on a life cycle approach.

Downside of the model is that it does not create a risk profile. In current industry, many decisions are made based on a combination of costs and expected risks. A possibility for further research would be to integrate risk analysis to the model. A relative easy first step would be to give the decision maker the possibility to add a percentage to either to outcome of the model prediction or to the input parameters. After time, when the model is used more often within different cases, distribution of the input values of the parameters can be used to create probability based simulations. Another limitation is that the model does not support the distribution of an activity over more than one year. Within the alternatives of the tender team, different activities were spread over two years. On the one hand this is done because expectations could be different than reality, but on the other hand it was related to the way the project is pre financed. Integrating this within the model would be a good addition to the model.

6. *Which parameters influence the life cycle costs the most?*

The one-way analysis indicates that closure of traffic lanes influence the NPV the most in the base case. This effect is directly related to UDC. Looking at the equations stated, it can be seen that the value of time has a high influence on the estimated UDC. Since the outcome of the NPV is highly related to the UDC, it can be said that for this case, the client attaches great value to the availability of the road. In other project the influence of closure of traffic lanes could be different based on the road configuration and VoT. Another strategic parameter that has high influence on the NPV is the discount factor. This is an important outcome of the analysis, because this can be set for each project independently of suppliers etc.

Material cost is the parameter that influences the NPV the most from the parameters that are not strategy related. Based on this outcome, the contractor should invest resources to increase the knowledge base concerning material costs. One of the possibilities is to collect historical data. Another is creating sustainable relationships with suppliers to gain certainty concerning future material costs. The influence of material could be lower than found in this research, due to the fact that lump sum cost are used for material cost.

7. *What is the interaction between the input parameters?*

This research indicated that the closure of traffic lanes interacts in a non-linear way with all the other parameters that are investigated. Closure of traffic lanes is a parameter that is project specific and influences the other parameters the most. Performing sensitivity analysis for each project is advised to investigate what is important in the project. Activity speed is another parameter that has a nonlinear relation with other parameters.

Looking at the performed sensitivity analysis, the outcomes of the influence of degradation to the NPV should be discussed. In this case degradation does not have enormous influence on the NPV. One of the reasons for this could be found in the way that the analysis is performed. Within the analysis fines due to non-functioning and additional UDC due to unplanned maintenance of the road are not taken into account, but only the influence of the steepness of degradation curve is investigated. This way, the year that structural maintenance is needed is changed based on the minimum performance level and the steepness of the curve. A possibility for further research would be to integrate risk analysis to the model.

Another thing that must be discussed is the data that formed the input within the DSS. As already indicated, the sensitivity analysis performed using data from one case study. This implies that only data of one project is used as input within the DSS. The values of these data are mostly based on expert opinions. The outcome of the research and the conclusions that are drawn should therefore be seen as an indication of the possibilities of this DSS and a focus for further research. Especially in the case of the two-way sensitivity analysis, there is uncertainty about the two input parameters as well as the automated trend line within the plot. One of the derivatives of this is the analysis of activity speed. Activity costs in the case study is not related to the duration of the activity, but related to the length of the section. Within the case study, material, labour and equipment costs are integrated. Therefore the outcomes of the analysis could be different when more data from different cases would be integrated within the model. Additional research using a multiple case study where data from multiple projects are integrated within the object oriented to see if the outcomes of this research correspond to those, could give interesting additional certainty about the outcomes. It is expected that the outcome of the results would not change significantly, because practitioners indicate that within material cost, the price of the raw material is the main part.

Looking at the applicability of the DSS, it can be seen that the model supports the decision making in a Dutch DBFM tender for the contractor. In the researchers opinion, the model can also be used by Dutch road authorities, because they have to objectively underpin why certain decisions for, for instance the design life are taken. This will make it possible to use the model in a different way, budget allocation to the project. The applicability of the complete model in other countries is harder to define, because other ways of UDC estimation might be applicable. Therefore, further research on how UDC is estimated in other countries can determine the applicability of the model in other countries. The component that relates service life planning assessment to life cycle cost can be applied in other countries, because the service life is determined using degradation curves and the minimum performance of a certain degradation mode. It is therefore very important when willing to use the model, to start collecting historical data, starting with that of material costs, since this is the parameter with the most influence to the life cycle costs.

9 Conclusion

Decisions concerning service life road pavement design and maintenance strategies are important components in current road infrastructure projects, since they influence the life cycle costs of the alternative. Creating a road pavement design strategy for a longer period of time is a decision making problem wherein different trade-offs have to be made concerning construction cost, maintenance cost and user delay cost. Due to the long time span and the different processes within the design process, the decision making is considered a complex task.

To support decision makers with this complex task, a model is developed that gives insights on how different decisions affect the service life of road pavements by relating it the life cycle cost. The model visualizes the performance of the upper layer of the road over the design life and estimates the life cycle cost of the design alternative. The model uses an object oriented model to capture and structure required information to perform life cycle cost analysis. The model framed the decision making process into a parametric estimation, allowing the decision maker to perform ‘what if’ analysis where the object oriented model forms the input for the analysis. Using the object oriented model to capture and structure historical information gives the decision maker the time to focus on creation and evaluation of alternatives rather than capturing information before. The formalized structure of the life cycle cost estimation makes transparent what cost elements are incorporated in the model and what is not.

This research identified the decision making process concerning road pavement service life assessment and relates it to the life cycle cost estimation in a mathematical model. It identified the current process in the field of road pavement evaluation based on life cycle cost. it is now known what information is needed like cost information concerning materials, labour and equipment, activity speed, degradation curves of the material and project specific information like value of time, minimum performance level and road user information like traffic intensity, detour times and road configuration. Besides that, the decisions that have to be taken are captured and structured within the model to determine the service life planning of a design alternative like winter or summer construction, degradation curves and the use of prolonging maintenance and related to the cost items and categories which were identified before using the described algorithm. Next to that, a hierarchical structure is made to store information in so that reuse in other projects is possible. This can be used to streamline the design process during early development stages so that more alternatives can be created due to reuse of information, more transparency in the decision making process which is expected to lead to better decisions.

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Appendix I. Equations

Equation	Symbol	Description
Duration		
$d_{ts} = l_{ts} / S$	d_{ts}	duration to perform activity on trace section (h)
	l_{ts}	length of trace section (m)
	S	speed to perform activity (m/h/traffic lane)
$d_{ts} = \frac{l_{ts}}{S} + (ts_{tl} - CL_{tl}) * (\frac{l_{ts}}{S})$	d_{ts}	duration to perform activity on trace section (h)
	l_{ts}	length of trace section (m)
	S	speed to perform activity (m/h/traffic lane)
	ts_{tl}	amount of traffic lanes that the trace section has ()
	CL_{tl}	closure of traffic lanes ()
$d_a = \sum d_{ts}$	d_a	duration to perform the activity on the complete road section (h)
	d_{ts}	duration to perform activity on trace section (h)
$d_n = \frac{\sum_n d_a}{a_n}$	d_n	duration to perform all activities in year n (h)
	n	year under investigation ()
	d_a	duration to perform the activity on the complete road section (h)
	a_n	activities in year n ()
User Delay Costs		
$UDc_n = (\Delta UDsr_n + \Delta UDd_n) * VoT * \sum d_n$	UDc_n	User delay cost in year n (€)
	$\Delta UDsr_n$	average user delay per hour due to speed regulation in year n (delay/h)
	ΔUDd_n	average user delay due to detour in year n (delay/h)
	VoT	Value of time (€)
	d_n	duration to perform all activities in year n (h)
$\Delta UDd_n = Tint_{tsdt\,1} * f_1 * DT_1 + Tint_{tsdt\,2} * f_2 * DT_2$	ΔUDd_n	average user delay due to detour in year n (delay/h)
	$Tint_{tsdt1}$	completely closed trace section with the highest traffic intensity (cars/h)
	f_1	traffic intensity factor (%)
	DT1	detour time of trace section with highest traffic intensity (h)
	$Tint_{tsdt2}$	completely closed trace section with the second highest traffic intensity (cars/h)
	f_2	traffic intensity factor (%)
	DT_2	detour time of trace section with second highest traffic intensity (h)
$ts_{dt} = \sum^{TS} tl_{ts} \leq CL_{tl}$	ts_{dt}	trace sections which are going to be closed during activity execution ()
	TS	trace sections ()
	tl_{ts}	traffic lanes per trace section ()
	CL_{tl}	closure of traffic lanes ()
$\Delta UDsr_n = \sum_{ts=1}^{TS} \left(\frac{l_{ts}}{V_a} - \frac{l_{ts}}{V_n}\right) * Tint_{ts}$	$\Delta UDsr_n$	average user delay per hour due to speed regulation in year n (cars/h)
	TS	trace section ()
	l_{ts}	length of trace section (m)
	V_a	traffic speed during activity execution (km/h)
	V_n	traffic speed during normal conditions (km/h)
	$Tint_{rs}$	traffic intensity (cars/h)
Construction and structural maintenance costs		
$SM_n = n > c_{finish}$ $C_n = n \leq c_{finish}$	C_n	construction in year n ()
	SM_n	structural maintenance in year n ()
	n	year under investigation ()
	nc_{finish}	year when construction should be finished ()
$Ac_n = \sum_n d_a * (c_{lab} + c_{equip})$	Ac_n	Activity cost in year n (€/year)
	d_a	duration to perform the activity on the complete road section (h)
	c_{lab}	labour cost in to perform activity a (€/h)
	c_{equip}	equipment cost to perform activity a (€/h)

Equation	Symbol	Description
$mc_n = \sum_l L_w * l_{rs} * mc_l$	mc_n	material cost in year n (€/year)
	l	layer ()
	L_w	layer width (m)
	l_{rs}	length of road section (m)
	mcl	material cost of layer (€/m^2)
$Cc_n = mc_n + Ac_n$	Cc_n	Construction cost in year n (€/year)
	mc_n	material cost in year n (€/year)
	Ac_n	Activity cost in year n (€/year)
$SMc_n = mc_n + Ac_n$	SMc_n	Structural maintenance cost in year n (€/year)
	mc_n	material cost in year n (€/year)
	Ac_n	Activity cost in year n (€/year)
Maintenance costs		
$FMc_n = \sum_n FMa_n * fr * FMa_c$	FMc_n	Functional maintenance cost in year n (€/y)
	n	year under investigation ()
	FMa_n	functional maintenance activities that are performed in year n ()
	fr	frequency per year (€)
	FMa_c	cost to perform the functional maintenance activity a (€/unit)
$Mc_n = SMc_n + FMc_n$	Mc_n	maintenance cost in year n (€/y)
	SMc_n	structural maintenance cost in year n (€/y)
	FMc_n	Functional maintenance cost in year n(€/y)
Service life planning		
$SLP < DL$=new structural maintenance activity	SLP	Service life planning (Y)
	DL	Design Life (y)
$SLP = SL + n_{last}$	SLP	Service Life Planning ()
	SL	Service Life ()
	n_{last}	year where latest activity will be executed ()
$SL = \frac{P - P_{\min}}{DC}$	SL	Service life (Y)
	P	upper layer performance (%)
	P_{min}	minimum performance level (%)
	DC	Degradation curve (%/year)
$P = P_n + P_{inc}$	P	upper layer performance (%)
	P_n	layer performance in year n (%)
	P_{inc}	performance increase (%)
$P_n = (((SLP - (SLP - n)) * DC) + P_{\min}$	P_n	layer performance in year n (%)
	n	year were activity will be performed (y)
	SLP	Service life Planning (y)
	DC	degradation curve (%/y)
	P_{min}	minimum performance level (%)
Net Present Value		
$NPV = \sum_{n=1}^{N} \frac{Cc_n}{(1+i_{con})^n} + \sum_{n=1}^{N} \frac{Mc_n}{(1+i_{main})^n} + \sum_{n=1}^{N} \frac{UDc_n}{(1+i_{UDc})^n}$	NPV	Net Present Value (€)
	N	period under investigation ()
	Cc_n	Construction cost in year n (€/year)
	i_{con}	discount rate for construction cost (%)
	Mc_n	maintenance cost in year n (€)
	i_{main}	discount rate for maintenance cost (%)
	UDc_n	User delay cost in year n (€)
	i_{UDc}	discount rate for user delay cost (%)

Appendix II. Model parameter overview

Parameter	Explanation and unit
Ac_n	Activity cost in year n (€/year)
a_n	activities in year n ()
Cc_n	Construction cost in year n (€/year)
c_{equip}	equipment cost to perform activity a (€/h)
c_{lab}	labour cost in to perform activity a (€/h)
CL_{tl}	closure of traffic lanes ()
C_n	construction in year n ()
d_a	duration to perform the activity on the complete road section (h)
DC	degradation curve (%/year)
DL	Design Life (y)
d_n	duration to perform all activities in year n (h)
DT1	detour time of trace section with highest traffic intensity (h)
DT_2	detour time of trace section with second highest traffic intensity (h)
d_{ts}	duration to perform activity on trace section (h)
f_1	traffic intensity factor (%)
f_2	traffic intensity factor (%)
FMa_c	cost to perform the functional maintenance activity a (€)
FMa_n	functional maintenance activities that are performed in year n ()
FMc_n	Functional maintenance cost in year n (€/y)
fr	frequency per year (€)
i_{con}	discount rate for construction cost (%)
i_{main}	discount rate for maintenance cost (%)
i_{UDc}	discount rate for user delay cost (%)
l	layer ()
l_{rs}	length of road section (m)
l_{ts}	length of trace section (m)
L_w	layer width (m)
mcl	material cost of layer (€/m^2)
mc_n	material cost in year n (€/year)
Mc_n	maintenance cost in year n (€)
n	year were activity will be performed (year)
N	period under investigation ()
nc_{finish}	year when construction should be finished ()
n_{last}	year where latest activity will be executed (year)
NPV	Net Present Value (€)
P	upper layer performance (%)
P_{inc}	performance increase (%)

P_{min}	minimum performance level (%)
P_n	layer performance in year n (%)
S	speed to perform activity (m/h/traffic lane)
SL	Service life (Y)
SLP	Service life planning (Y)
SMc_n	structural maintenance cost in year n (€/y)
SM_n	structural maintenance in year n ()
$Tint_{rs}$	traffic intensity (cars/h)
$Tint_{tsdt1}$	completely closed trace section with the highest traffic intensity (cars/h)
$Tint_{tsdt2}$	completely closed trace section with the second highest traffic intensity (cars/h)
tl_{ts}	traffic lanes per trace section ()
TS	trace section ()
ts_{dt}	trace sections which are going to be closed during activity execution ()
ts_{tl}	amount of traffic lanes that the trace section has ()
UDc_n	User delay cost in year n (€)
V_a	traffic speed during activity execution (km/h)
V_n	traffic speed during normal conditions (km/h)
VoT	Value of time (€)
ΔUDd_n	average user delay due to detour in year n (delay/h)
$\Delta UDsr_n$	average user delay per hour due to speed regulation in year n (cars/h)

Appendix III. Overview change of equations

Equations from literature	Model equations	reasoning
Duration		
$S_{y,a} = roundup\left(\frac{RQ_{y,a}/PS_a}{TPP_y - L_a}\right)$	$d_{ts} = l_{ts} / S$	Also uses speed crew, but not the amount of shifts, since it should be known how long the road will be closed for the determination of UDC and activity costs
	$d_{ts} = \frac{l_{ts}}{S} + (ts_{tl} - CL_{tl}) * (\frac{l_{ts}}{S})$	This equation makes it possible to close the road partial instead with rail infrastructure to close the entire track
	$d_a = \sum d_{ts}$	Makes it possible to incorporate partial road closure and complete road closure Used for activity costs
	$d_n = \frac{\sum_n d_a}{a_n}$	Makes it possible to model activities that will be performed parallel
User Delay Costs		
$UDC = \left(VoT_o * \Delta ATT + \frac{1}{2} * (VoT_1 - VoT_0) * \Delta ATT\right) * ADT$	$UDc_n = (\Delta UDsr_n + \Delta UDd_n) * VoT * \sum d_n$	New equation incorporates both speed change and detour times for the estimation of UDC
	$\Delta UDd_n = Tint_{tsdt\,1} * f_1 * DT_1 + Tint_{tsdt\,2} * f_2 * DT_2$	Completely new, based on Rijkswaterstaat model and experts opinions
$\Delta ATT = \left(\frac{L}{V_m} - \frac{L}{V_N}\right) * n * upv$	$\Delta UDsr_n = \sum_{ts=1}^{TS} \left(\frac{l_{ts}}{V_a} - \frac{l_{ts}}{V_n}\right) * Tint_{ts}$	Duration component is taken out of the equation, because this is also used for the estimation of UDC due to detour times
Construction and maintenance activities		
	$Ac_n = \sum_n d_a * (c_{lab} + c_{equip})$	Makes it possible to relate cost to time needed to perform activities

	$mc_n = \sum_l L_w * l_{rs} * mc_l$	Keeps complete asphalt pavement in mind Makes it possible to relate cost to object
Construction and maintenance activities		
	$Cc_n = mc_n + Ac_n$ $SMc_n = mc_n + Ac_n$	Makes it possible to take both time as material related cost elements into account
Maintenance costs		
	$FMc_n = \sum_n FMa_n * fr * FMa_c$	Not much information known about it at the moment, taken into account as a possibility for further model development and since it is an important cost element in life cycle costing
	$Mc_n = SMc_n + FMc_n$	Makes it possible to divide in different cost elements
Service life planning		
$RQ_{y,a} = Q_a * P_{y,a}(T_f \geq TH_a)$	$SLP = SL + n_{last}$	Makes it possible to determine if there is a need for additional maintenance based on the design life
$\Delta C = (C_0 - C_w)/L_1$	$SL = \frac{P - P_{\min}}{DC}$	Same, only different naming
$C_t = C_{t-1} - \Delta C$	$P = P_n + P_{inc}$	Same, only different naming
	$P_n = (((SLP - (SLP - n)) * DC) + P_{\min}$	Makes it possible to relate new maintenance activities to previous performed activities
Net Present Value		
$NPV = Initial\ cost + \sum_{k=1}^{N} Rehab\ Cost_k [\frac{1}{(1+i)^{n_k}}$ $NPV = C_{inv} + C_{res} + \sum [PV(C_{o\&m}) + PV(C_{risk})]$	$NPV = \sum_{n=1}^{N} \frac{Cc_n}{(1+i_{con})^n} + \sum_{n=1}^{N} \frac{Mc_n}{(1+i_{main})^n}$	Allows taking the value of money over time into account Is able to split cost into cost categories needed to present to the clients Is able to set different rates of interest for

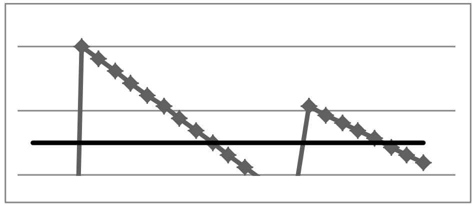
$E[C_{tot}(X,T)] = C_{ini}(X,t) + \sum_{t=1}^{T} \frac{1}{(1+q)^t} \{E[C_{mai}(X,t)] + E(C_{dis}(X,t)]\}$	$+ \sum_{n=1}^{N} \frac{UDc_n}{(1+i_{UDc})^n}$	maintenance and construction period

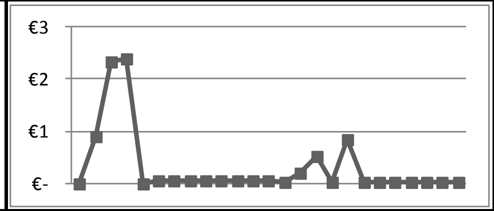
Appendix IV. Overview design alternatives of case study

Service Life Planning | Life Cycle Cost (x1.000.000)

Option 1

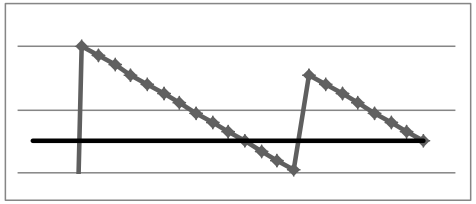
Year	Phase	Activity	Object	Material	Thickness	lane
2018	**Construction**	**laying**	**upper layer**	**ZOAB_2L**	**70**	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2032	**Maintenance**	**laying**	**upper layer**	**ZOABplus**	**50**	
2029	Maintenance	milling	upper layer	ZOAB_2L	50	
2030	Maintenance	laying	inner layer	AC_bin_30_45	60	

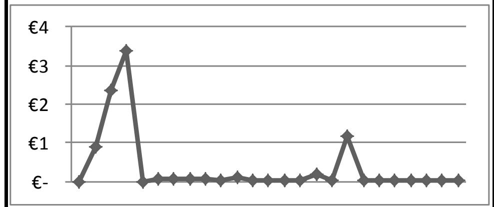




Option 2

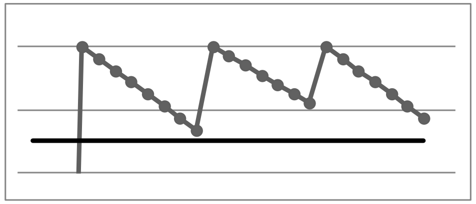
Year	Phase	Activity	Object	Material	Thickness	lane
2018	**Construction**	**laying**	**upper layer**	**ZOAB_2L**	**70**	
2018	Construction	laying	inner layer	AC_bin_30_45	60	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2025	Maintenance	laying	upper layer	Modiseal_ZX		Right
2032	**Maintenance**	**laying**	**upper layer**	**ZOAB_2L**	**70**	
2032	Maintenance	milling	upper layer	ZOAB_2L	70	
2030	Maintenance	laying	upper layer	Modiseal_ZX		All

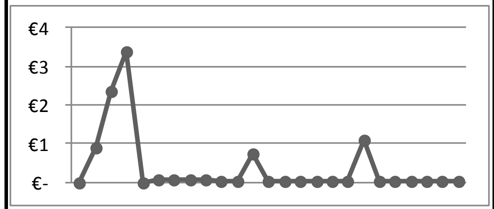




Option 3

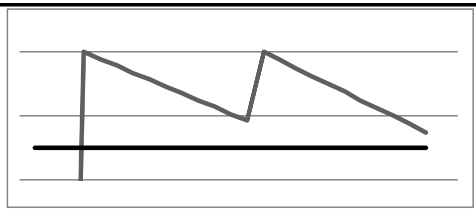
Year	Phase	Activity	Object	Material	Thickness	lane
2018	**Construction**	**laying**	**upper layer**	**ZOAB_2L**	**70**	
2018	Construction	laying	inner layer	AC_bin_30_45	60	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2026	**Maintenance**	**laying**	**upper layer**	**ZOAB**	**25**	
2026	Maintenance	milling	upper layer	ZOAB_2L	25	
2033	**Maintenance**	**laying**	**upper layer**	**ZOAB_2L**	**70**	
2033	Maintenance	milling	upper layer	ZOAB_2L	70	

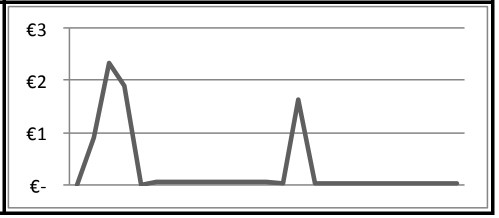




Option 4

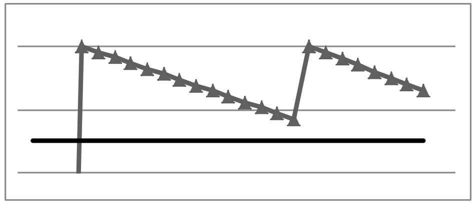
Year	Phase	Activity	Object	Material	Thickness	lane
2018	**Construction**	**laying**	**upper layer**	**ZOABplus**	**50**	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2029	**Maintenance**	**laying**	**upper layer**	**ZOABplus**	**50**	
2029	Maintenance	milling	upper layer	ZOABplus	50	
2029	Maintenance	laying	inner layer	AC_bin_30_45	60	



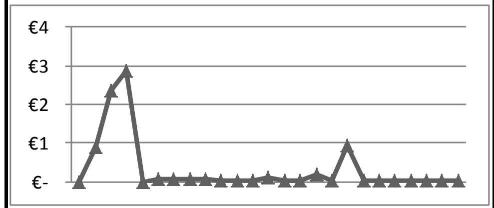


Year	Phase	Activity	Object	Material	Thickness	lane
Option 5						
2018	**Construction**	**laying**	**upper layer**	**ZOABplus**	**50**	
2018	Construction	laying	inner layer	AC_bin_30_45	60	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2027	Maintenance	laying	upper layer	Modiseal_ZX		Right
2032	**Maintenance**	**laying**	**upper layer**	**ZOABplus**	**50**	
2032	Maintenance	milling	upper layer	ZOABplus	50	
2030	Maintenance	laying	upper layer	Modiseal_ZX		All

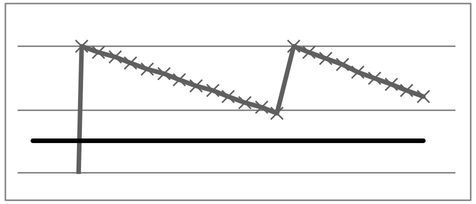
Service Life Planning

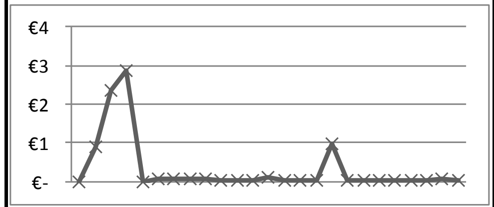


Life Cycle Cost (x1.000.000)



Year	Phase	Activity	Object	Material	Thickness	lane
Option 6						
2018	**Construction**	**laying**	**upper layer**	**ZOABplus**	**50**	
2018	Construction	laying	inner layer	AC_bin_30_45	60	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2027	Maintenance	laying	upper layer	Modiseal_ZX		Right
2031	**Maintenance**	**laying**	**upper layer**	**ZOABplus**	**50**	
2031	Maintenance	milling	upper layer	ZOABplus	50	
2038	Maintenance	laying	upper layer	Modiseal_ZX		Right





Year	Phase	Activity	Object	Material	Thickness	lane
Option 7						
2018	**Construction**	**laying**	**upper layer**	**ZOABplus**	**50**	
2018	Construction	laying	inner layer	AC_bin_30_45	60	
2017	Construction	laying	under layer	AC_22_base_30_45	65	
2017	Construction	laying	under layer	AC_22_base_30_45	70	
2016	Construction	laying	foundation	Menggranulaat_31_5	250	
2029	**Maintenance**	**laying**	**upper layer**	**ZOABplus**	**50**	
2029	Maintenance	milling	upper layer	ZOABplus	50