FRONT-END INCORPORATION OF MAINTENANCE IN THE DESIGN OF DBFM PROJECTS

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Colophon

Thesis Title

Front-end incorporation of maintenance in the design of DBFM projects

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Preface

The master programme Construction Management and Engineering focused on large-scale infrastructure projects. The courses and electives allowed me to study PPP projects and DBFM projects in an international and national context respectively. The payment mechanism, project performance and incentives to incorporate maintenance in projects were often discussed. However, these projects never parted with their theoretical character. Therefore, I aimed to investigate the incorporation of maintenance in DBFM projects in a company. Furthermore, such a topic appealed to me, as it is not solely a challenge from a technical point of view, people are at the centre it, as it touches upon many fields of expertise.

The result of this research would not have been possible without the outstanding supervision of my graduate committee. I would like to extend my gratitude towards them. Marian Bosch, thank you for making the time to see me regularly to discuss the research, and for structuring the ideas into this report. Ellen Sjoer, thank you for aiding me in incorporating knowledge management expertise in my research. Hans van Ooijen, thank you for your support and assisting me where possible at VolkerInfra Design. Rogier Wolfert, many thanks for taking over the position of chairman, for challenging me, and thank you for your critical contributions throughout this project.

A word of thanks goes to the interviewees who have made the time to answer my questions. Special thanks to the SAA-ONE maintenance staff; they had to put up with me asking the occasional critical question throughout my graduation research. All these people made it possible for me to graduate and they provided me with insight into the field of maintenance in construction projects. They made the research not only possible but also interesting.

I would like to thank the management team of Volker InfraDesign for providing me with the opportunity to embark upon this voyage called graduation and for facilitating it.

Last but not least, I would like to thank Trevor Wilson and Yoram Tap for proofreading my thesis and my parents for their everlasting support that enabled me to become an engineer.

Boy Tap, Rotterdam

Summary

Introduction

Construction projects are increasingly carried out under Design Build Finance and Maintain (DBFM) contracts in the Netherlands. Contractors finance projects and clients pay contractors based on availability throughout the contract. Therefore, contractors have to ensure that assets perform according to set performance levels. Maintenance considerations are to be comprehensively incorporated in the design of assets under DBFM contracts. This research is carried out in order to make recommendations as to how contractors can aim to integrate maintenance considerations in the design of assets. This can contribute to life-cycle cost reductions and the maximisation of availability payments throughout DBFM projects.

The aim of this research is to assess how maintenance considerations can be incorporated comprehensively in the design of assets and assessing how maintenance is currently incorporated the design of assets under DBFM contracts in the infrastructure industry. The results of the case study are compared to literature in order to draw practical conclusions.

This research is carried out in collaboration with Volker InfraDesign, part of Van Hattum and Blankevoort, which are VolkerWessels' companies.

Literature

A literature study was carried out to get an understanding of: the domains related to the design and maintenance of infrastructural works under DBFM contracts and the maintenance inclusion in various capital intensive industries with a long-lasting lifetimes of assets are assessed. The latter is assessed in order to be able to draw conclusions from the other industries as to how the infrastructure industry can incorporate maintenance in the design more comprehensively.

There is little literature available that covers the inclusion of maintenance considerations in the design of assets under DBFM contracts specifically. Therefore, there is no framework to research in projects. This research is a first attempt to bridge that gap in the literature. Therefore, the empirical study is exploratory in nature as elaborated on below.

Research Methodology

This research is carried out in an exploratory case study research, it utilises qualitative data from interviews and quantitative data through document analysis to assess how maintenance considerations are incorporated in the design of the projects. Three DBFM infrastructure construction projects are selected as cases for this study: SAA-ONE (A1/A6), SAA-GA (A9) and A-Lanes (A15), of which the main case is SAA-ONE and that is compared to the other cases. In total, 24 people are interviewed for this study in semi-structured interviews (18) and through informal conversations (6).

Findings

The main case (SAA-ONE) showed that maintenance is incorporated in the design through five elements (see Figure 1). These consist of: (1) contract requirements, (2) organisation, (3) collaboration, (4) activities, and (5) tools. These five main elements entail sub-elements, which are captured in paragraphs in this summary. These consists of: (1) the DBFM contract and additional contract requirements,

(2) the tender organisation, project organisation, the knowledge base of the maintenance department and the levels of maintenance, (3) interface design and maintain, incentive, BIM-sessions, the knowledge process of maintenance engineering and the focus of the departments over time, (4) activity such as maintenance input and design review and (5) tools such as the trade-of-matrixes and the management system respectively. These five elements are also researched in the other cases and are the basis for the comparison between SAA-ONE and SAA-GA, and SAA-ONE and A-Lanes.

Figure 1: Overview Maintenance Inclusion SAA-ONE

Contract Requirements

The three cases indicate that the basis for designing assets is the DBFM contract. There is a 'contract incentive' to incorporate maintenance considerations in the design of assets in order to maximise availability payments. In order to do so, all three projects produce additional contract requirements to translate contract requirements into internal design requirements. This document comprises a somewhat random collection of requirements of which the comprehensiveness and verifiability in the design is unclear. Furthermore, there is no clear distinction between functional (performance) requirements and specific requirements, which results in an ambiguous risk profile between the SPC and EPCm.

Organisation

Maintenance is mostly a separate entity in project companies, either in a separate team, department, or cross-functional unit. Hence, maintenance is physically detached from the design in the projects. The projects are divided into objects, which are assigned to different design teams with their separate design leader and budget. Such vertical splitting leads to fragmentation in the project. The composition of the maintenance staff is estimated to consist of 50-60% of external hires. This indicates the limited ability of the companies in the joint venture to supply maintenance staff for the incorporation of maintenance in the design assets in DBFM projects. When external hires leave the project, their knowledge leaves the project. Little knowledge is retained in the projects. Maintenance is generally managed on the operational and tactical level, and not on the strategic level.

Collaboration

The collaboration of designers and maintenance engineers is ad-hoc and bottom-up. The design and maintain interface is structured by 'interface meetings' such as BIM sessions. The input is dependent on individuals participating in those meetings. The lack of structure in the meetings could result in unclear results and unclear points of action. Most of the meetings are held based on 'expert view' and most knowledge is tacit. There is no overview as to what are reoccurring maintenance issues in the project. An opportunity to acquire full insight into such issues in designing projects is foregone. Due to the vertical splitting of the project into objects with separate budgets, there is little 'internal incentive' for the design teams to collaborate with maintenance engineers. The design teams are assessed on performance indicators such as designing assets according to contract specifications and within budget. Including maintenance entails spending more in the front-end to minimise costs throughout the project, which is contradictory to the focus of design teams. These teams are more focused on short-term optimisations and not on spending more to incorporate maintenance considerations to reduce life-cycle costs.

Activity

Maintenance input into design is generally provided through the additional contract requirements. The designs and design notes that are produced by the design department are reviewed for the inclusion of maintenance considerations by the maintenance department. The basis for these reviews are the additional contract requirements and expert views. However, the verifiability and comprehensiveness of these requirements is limited.

Tools

The tools that are assessed in the project company consist of the management system and Trade-Off Matrixes (TOMs). The management system guides the workflow and furthers the collaboration between designers and maintenance engineers, as the input and output of these teams are linked. However, staff indicate that they do not regularly use the system. A TOM is a tool that is utilised to support the decision-making between design options. The input of the TOMs is based on qualitative and quantitative information. However, the quantitative input and the skill to make life-cycle calculations is generally limited. Hence, the life-cycle cost calculations are mostly indicative.

Recommendations

The project organisations are recommended to have an integral life-cycle strategy that ensures that assets are designed for the long-term, based on life-cycle considerations including maintenance considerations. It should be clear to the entire organisation that best for life-cycle decisions (long term) prevail over best for 'design and construct' decisions (short term). The strategy should be formulated and managed from a high level in the organisation and translated into design and maintenance objectives.

Having an internal incentive for designers and maintenance engineers to collaborate is vital for incorporating maintenance considerations in DBFM projects. This is to be realised by replacing the function of the design leaders by the role of object leaders whereby their budget responsibility is extended to life-cycle budgets (including exploitation). This requires the decision-making to be based on best for project decisions over the life-cycle of assets. DBFM contracts span decades and object leaders will move on to other projects before the project is completed. However, object leaders are responsible for the life-cycle budgets and accountable for life-cycle decision-making. This is a strong 'internal incentive' to incorporate maintenance considerations in the design of assets and to make trade-offs in the design. Life-cycle calculations are to be supported by a dedicated life-cycle coordinator.

The incorporation of maintenance considerations in the design of assets depends on the sharing of knowledge between design and maintenance experts. Most knowledge is tacit and is difficult to share. Therefore, the sharing of knowledge needs to be facilitated by an integrator. Such a person understands both worlds and is able to connect them. Object leaders can fulfil the role of integrator and bring designers and maintenance engineers together.

In order to integrate maintenance more in the design of assets, the tactical maintenance engineers are to be placed in the design department. The split is then between operational and tactical maintenance, and not between design and maintenance.

The life-cycle decision-making should be based on data and knowledge of operational assets. Therefore, assets knowledge needs to be developed by monitoring assets throughout DBFM projects and maintenance projects under VolkerWessels' companies. Maximising asset knowledge can put into evidence what sort of design decisions result in life-cycle cost reductions and allows for more informed decision-making in future projects. Also, asset knowledge can make maintenance costs more visible. Hiring more in-house tactical maintenance personnel can further the knowledge development and retention within construction companies.

Samenvatting

Introductie

Constructie projecten worden in Nederland in toenemende mate uitgevoerd onder de contractvorm Design Build Finance en Maintain (DBFM). Door de integratie van de projectfasen in een contract, worden aannemers geprikkeld om te optimaliseren kijkende naar de totale kosten over de levensduur van projecten. In deze contractvorm is de aannemende partij verantwoordelijk voor de financiering van de projecten en is de betaling van de overheid aan deze partij gebaseerd op beschikbaarheid tijdens de exploitatie. De aannemende partij is verantwoordelijk voor het opleveren en beheren van het project om te blijven voldoen aan de beschikbaarheidseisen van de opdrachtgever. Onderhoudsoverwegingen moeten geborgd worden in het ontwerp van objecten binnen DBFM contracten. Dit onderzoek is uitgevoerd om aanbevelingen te kunnen doen aan aannemers over hoe onderhoud geborgd kan worden in het ontwerp binnen DBFM contracten. Deze aanbevelingen kunnen bijdragen aan lagere kosten over de levensduur van projecten en bijdragen aan het maximaliseren van beschikbaarheidsvergoedingen tijdens DBFM projecten.

Het doel van dit onderzoek is om te onderzoeken hoe onderhoudsoverwegingen geborgd kunnen worden in het ontwerp van DBFM projecten en hoe het op dit moment wordt geborgd in DBFM projecten in de infrasector. De resultaten van het casestudie onderzoek worden vergeleken met literatuur om praktische aanbevelingen te kunnen doen.

Dit onderzoek is uitgevoerd in samenwerking met Volker InfraDesign, onderdeel van: van Hattum en Blankevoort, een VolkerWessels onderneming. Het bedrijf van Hattum en Blankevoort werkt samen met KWS, Vialis en VolkerRail. Samen vormen zij VolkerInfra en richten zich op het aansturen en uitvoeren van integrale projecten en op kennisontwikkeling op dit gebied.

Literatuur

De literatuur is bestudeerd om een kader te scheppen bestaande uit: (1) kennisdomeinen rakende aan het ontwerp en onderhoud binnen integrale DBFM projecten (Asset Management, DBFM contracten, onderhoud en tools zoal life-cycle cost calculaties), (2) kennismanagement om te kunnen onderzoeken hoe de kennisprocessen lopen in projecten, en (3) literatuur over hoe verschillende kapitaal intensieve industrieën, met objecten met een lange levensduur, omgaan met het borgen van onderhoud in het ontwerp. Deze verschillende industrieën zijn onderzocht om aanbevelingen voor de infra op te kunnen baseren. Specifiek over het borgen van onderhoud in het ontwerp.

In de huidige literatuur is weinig specifiek onderzoek gedaan naar het borgen van onderhoud in het ontwerp van DBFM projecten. Daardoor levert de literatuurstudie geen kader op wat in de casestudie onderzocht kan worden. De casestudie is daardoor exploratief, wat wordt uitgelegd in de volgende paragraaf.

De literatuur geeft wel duidelijk aan dat asset management en onderhoud vanuit een strategisch perspectief benaderd en gemanaged moet worden binnen alle lagen van de organisatie (operationeel, tactisch en strategisch). De potentie om totale projectkosten te reduceren ligt in de vroege

fases van het project. De beslissingsvrijheid is dan groot en de kosten om veranderingen te implementeren zijn laag.

Methodologie

Het onderzoek naar het borgen van onderhoud in het ontwerp van DBFM projecten is uitgevoerd in een exploratieve casestudie. Het maakt gebruik van kwalitatieve data uit interviews wat wordt ondersteund door kwantitatieve data uit documentanalyse.

Drie DBFM projecten in de infrasector zijn geselecteerd voor de casestudie gebaseerd op beschikbaarheid, een van deze cases dient als hoofdcase (SAA-ONE). Er zijn in totaal 24 mensen geënterviewd voor dit onderzoek, waarvan 18 personen door middel van semigestructureerde interviews en 6 personen in informele besprekingen. De respondenten zijn bevraagd naar het borgen van onderhoud in het ontwerp tijdens het project. De rollen van de respondenten bestaan uit: onderhoudsmanagers, onderhoudsingenieurs, ontwerpcoördinator, ontwerpleiders en directieleden op het project. De uitgewerkte interviews zijn verstrekt in Appendix E.

Vier criteria zijn van belang voor het beoordelen van een casestudie. Deze bestaan uit constructvaliditeit, interne validiteit, externe validiteit en betrouwbaarheid. Constructvaliditeit is geborgd door het gebruiken van meerdere bronnen (interviews, documentanalyse en observaties). Interne validiteit is niet toepasbaar op exploratieve casestudies. Externe validiteit is gesterkt door het feit dat meerder projecten zijn onderzocht, waaronder een project van vergelijkbare schaal, in een vergelijkbare projectfase met een joint venture bestaande uit andere bedrijven.

Bevindingen

De bevindingen van de hoofdcase (SAA-ONE) laten zien dat onderhoud geborgd is op vijf manieren. Dit zijn: (1) contracteisen, (2) de organisatie, (3) samenwerking, (4) activiteiten, en (5) tools. Deze vijf hoofdelementen zijn onderzocht voor het borgen van onderhoud in het ontwerp in de projecten. Onder deze hoofdelementen is een verdeling gemaakt in sub-elementen (zie Figure 2), welke worden behandeld in dit hoofdstuk. Deze bestaan uit: (1) DBFM contracteisen en aanvullende contracteisen, (2) de tenderorganisatie, projectorganisatie, de kennisbasis binnen de onderhoudsafdeling, en de levels van onderhoud in de organisatie, (3) het raakvlak tussen ontwerp en onderhoud, prikkels om samen te werken, BIM-sessies, het kennisproces van onderhoudsengineering, de focus van ontwerpers en onderhoudsengineers over de tijd heen, (4) activiteiten bestaande uit onderhoudsinput leveren aan ontwerp en ontwerpreviews, en (5) tools zoals de trade-off matrixes en het management systeem.

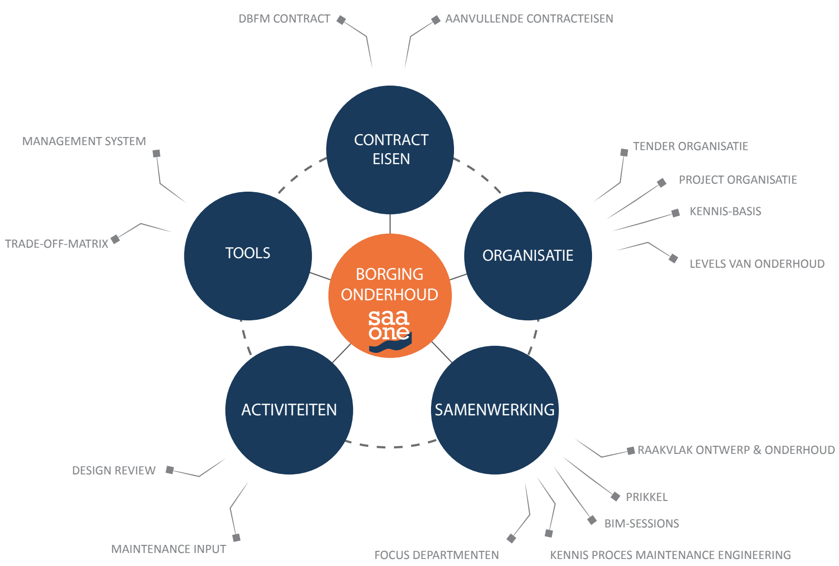

Figure 2: Overzicht Borging van Onderhoud in SAA-ONE

Deze vijf elementen zijn onderzocht in de hoofdcase (SAA-ONE), waarna deze bevindingen zijn vergeleken met SAA-GA en met het A-Lanes project.

Contracteisen

De drie projecten laten zien dat de het DBFM contract het uitganspunt is voor het ontwerp. Bepaalde contracteisen zijn gekoppeld aan boetepunten die resulteren in beschikbaarheidskortingen. Er is een prikkel vanuit het contract om onderhoud te borgen in het contract om de beschikbaarheidsvergoedingen te maximaliseren. Om het onderhoud te borgen in het ontwerp zijn er intern aanvullende contracteisen opgesteld. Deze worden binnen SAA-ONE Special Design Requirements (SDRs) genoemd en worden opgesteld door onderhoudsingenieurs. Nader onderzoek naar de SDRs laat zien dat deze lijst van aanvullende eisen bestaat uit een willekeurige lijst met eisen waarvan de begrijpelijkheid, de compleetheid en verifieerbaarheid in het ontwerp onduidelijk is. Daarbij is er geen duidelijk onderscheid tussen prestatie-eisen en specifieke 'voorgeschreven' eisen, wat resulteert in een willekeurig risicoprofiel tussen de SPC en de EPCm.

Organisatie

De onderzochte projecten hebben verschillende projectorganisaties over de fasen van het project. Met als overeenkomst dat onderhoud is ondergebracht in een apart team of departement, of als horizontale functiegroep in een matrixorganisatie. Het nadeel van het plaatsen van onderhoudsingenieurs is dat het team ten alle tijden is losgekoppeld van de ontwerpers, waaraan zij input moeten leveren om zo het onderhoud in het ontwerp te kunnen borgen. De projecten zijn gesplitst in objecten die worden toegewezen aan verschillende teams met aparte budgetten. Deze verticale splitsing in het project leidt tot fragmentatie.

Een inschatting is gemaakt naar de achtergrond van de onderhoudswerknemers, 50-60% van de staf op het gebied van onderhoud wordt extern ingehuurd. Dit geeft het beperkte vermogen aan van de bedrijven in de consortia om onderhoudspersoneel aan te leveren om onderhoud te borgen in het project. De levels waarop onderhoud herkent, en gemanaged wordt in de projectorganisaties is op een operationeel en tactisch niveau.

Samenwerking

De samenwerking tussen ontwerpers en ouderhoudsingenieurs wordt gekarakteriseerd door ad-hoc en bottom-up samenwerking. Het raakvlak tussen ontwerpers en ouderhoudsingenieurs wordt in toenemende mate gestructureerd door vaste vergaderingen zoals 'BIM sessies' te organiseren. De input en output van deze vergaderingen is afhankelijk van het deelnemend personeel, er is weinig structuur wat de samenwerking faciliteert. Het ontbreken van structuur kan resulteren in onduidelijke uitkomsten met onduidelijke actiepunten. De basis voor deze vergaderingen is de 'expert view' van de deelnemers en de meeste kennis die wordt gebruikt is impliciet. Van enkele vergaderingen zijn notulen gemaakt en opgeslagen op de gebruiksonvriendelijk project database 'Thinkproject'. Nader onderzoek naar deze notulen laat zien dat de input op het gebied van onderhoud in zeer beperkte mate besproken wordt in deze vergaderingen. Er wordt geen gebruik gemaakt van deze vergaderingen om bij te houden welke issues op het gebied van onderhoud besproken worden om 'key issues' te identificeren. Het inzicht door overzicht op het gebied van onderhoud in het ontwerp tijdens door deze besprekingen wordt niet verkregen.

Door de verticale splitsing van objecten is er weinig 'interne prikkel' voor ontwerpteams om samen te werken met onderhoudsingenieurs. Ontwerpteams worden beoordeeld op het afleveren van een ontwerp wat voldoet aan de gestelde eisen binnen de gestelde budgetten. Het borgen van onderhoudsoverwegingen in het ontwerp resulteert over het algemeen in een duurdere constructie om kosten te kunnen besparen tijdens exploitatie. Daarentegen heeft het ontwerpteam een eigen budget en focust op korte termijn optimalisaties waarin weinig prikkel is om trade-offs te maken om onderhoud te borgen over de levensduur van het project om zo de projectkosten over de levensduur te verminderen.

Activiteiten

Door middel van de aanvullende interne eisen levert onderhoud input aan ontwerp. De door de ontwerpteams geproduceerde tekeningen en ontwerpdocumenten worden door de afdeling onderhoud beoordeeld voor het borgen van het onderhoud. Dit gebeurt op basis van de gestelde interne eisen en op basis van 'expert views'.

Tools

De tools die worden gebruikt om de samenwerking tussen ontwerp en onderhoud bevorderen en te managen, en om ontwerpbeslissingen te ondersteunen bestaat respectievelijk uit het management systeem en Trade-Off Matrixes. Het management systeem geeft begeleiding aan de werkzaamheden van de ontwerpers en de onderhoudsingenieurs. Input en output van de teams zijn aan elkaar gekoppeld wat de samenwerking bevordert. Daarentegen zijn de stappen in het systeem niet uitgewerkt en mensen geven aan weinig met het systeem te werken. De input in de Trade-Off Matrixes bestaat uit kwalitatieve en kwantitatieve informatie. De kwantitatieve input is gelimiteerd en de life-cycle costs als uitkomst van deze modellen is sterk indicatief. De kennis en kunde om deze life-cycle kosten calculaties te maken zijn gelimiteerd.

Aanbevelingen

De projectorganisaties wordt aanbevolen om te werken met een integrale life-cycle strategie die zeker stelt dat het project wordt ontworpen voor de lange termijn, gebaseerd op projectkosten over de totale levensduur, waarin onderhoudsoverwegingen worden geborgd. De focus van ontwerpteams moet gericht zijn op de levensduur van het project en niet alleen op de constructie. De hele organisatie moet zich bewust zijn van het feit dat keuzes gebaseerd op totale projectkosten over de complete levensduur (lange termijn) belangrijker zijn 'ontwerp voor constructie' beslissingen (korte termijn). Deze life-cycle strategie moet geformuleerd en gemanaged worden vanuit de hogere niveaus in de organisatie en vertaald worden naar werkdoelen op de lagere niveaus in de organisatie. Dit moet bevorderen dat keuzes gemaakt worden op basis van de levensduur van het project en moet de toepassing van life-cycle cost calculaties bevorderen.

Het introduceren van een interne prikkel voor ontwerpers en onderhoudsingenieurs om samen te werken is belangrijk voor het borgen van onderhoud in het ontwerp in DBFM projecten. De functie van ontwerpleider wordt vervangen door de rol van objectleider. De budgetverantwoordelijkheid van de objectleider is voor de totale levensduur van het object, tot en met de exploitatie. Dit maakt het baseren van beslissingen op de levensduur van het object noodzakelijk. DBFM contracten hebben een looptijd tot 30 jaar, langer dan de werkzaamheden van de objectleider op een dergelijk project. Daarentegen heeft de objectleider wel de verantwoordelijkheid om ontwerpbeslissingen te baseren op de projectkosten over de totale levensduur. Dit is een sterk 'interne prikkel' om de samenwerking tussen ontwerp en onderhoud te bevorderen en trade-offs te maken in het ontwerp. Deze life-cyce calculaties moeten worden ondersteund door een life-cycle coördinator.

Het borgen van onderhoud is afhankelijk van de kennisdeling tussen ontwerpers en onderhoudsingenieurs. De meeste kennis is impliciet en moeilijk deelbaar. Daarom zal de kennisdeling gefaciliteerd moeten worden door een 'integrator', een persoon die beide werelden met elkaar in verbinding kan brengen. De objectleiders zullen deze rol moeten vervullen.

Om het onderhoud meer te borgen in het ontwerp wordt het tactisch onderhoudspersoneel bij het ontwerpend personeel geplaats. De split zit dan tussen operationeel en tactisch onderhoud en niet tussen ontwerp en onderhoud.

De besluitvorming over de levensduur van projecten moet gebaseerd zijn op kennis van operationele projecten. Daarom moet project- en objectkennis ontwikkeld worden door DBFM projecten en onderhoudsprojecten te monitoren. Het maximaliseren van project- en objectkennis kan dienen als bewijsvoering welke ontwerpbeslissingen resulteren in lagere life-cycle costs en kan bijdragen aan meer geïnformeerde besluitvorming. Het inhuren van meer eigen personeel op het gebied van tactisch onderhoud bevordert het borgen van onderhoud in het ontwerp, en bevordert de kennisontwikkeling en het behoud van kennis in constructiebedrijven.

Table of Contents

Research Background

This research is carried out for the Master programme Construction Management and Engineering at the Delft University of Technology in collaboration with Van Hattum & Blankevoort.

Delft University of Technology

This thesis finalises the master programme CME studied at the Delft University of Technology. This is a two-year programme, which consists of three faculties: Architecture, Civil Engineering, and Technology Policy and Management. CME focuses on the rising need for reform in the construction industry and addresses topics such as project management, risk management, PPP, Infrastructure projects, collaborative design and the like. This research project is supervised by the design and construction processes department of Civil Engineering in Delft.

Van Hattum & Blankevoort

Van Hattum and Blankevoort is a contractor that is part of Volkerwessels. Together with KWS, Vialis and VolkerRail, they form VolkerInfra. These decentralised companies are focused on infrastructural works and represent VolkerWessels when collaborating in consortia. The research is carried out for Volker InfraDesign, which is part of Van Hattum and Blankevoort.

List of Figures

List of Acronyms

Acronym	Definition
AM	Asset Management
BIM	Building Information Modelling
CM	Corrective Maintenance
D&C	Design and Construct
DBFM	Design Build Finance and Maintain
DBFMO	Design Build Finance Maintain and Operate
DIKW	Data-Information-Knowledge-Wisdom
E&C	Engineering and Construct
EPC	Engineering, Procurement and Construction
EPCm	Engineering, Procurement, Construction and Maintenance
FHWA	Federal Highway Administration (USA)
KM	Knowledge Management
LCC	Life-Cycle Costing
M-Co	Maintenance Company
ME	Maintenance Engineering
MEAT	Most Economically Advantageous Tender
PDCA	Plan Do Check Act
PM	Predictive Maintenance
PPC	Public Private Comparator
PPP	Public Private Partnership
ProMaSys	Project Management System
RAMS	Reliability Availability Maintainability Safety
RE	Reliability Engineering
RWS	Rijkswaterstaat
SDR	Special Design Requirement
SE	Systems Engineering

Acronym	Definition
SPC	Special Purpose Company
STEM	Serviceability Task Evaluation Matrix
SWR	Special Work Requirement
TCO	Total Cost of Owenership
TOM	Trade-Off Matrix
VDM	Value Driven Maintenance
VFM	Value For Money
VISE	VolkerInfra Systems Engineering
VVU	Voertuig Verlies Uren (in Dutch)

Acronyms used in formulas*

AC	Availability Correction
AD	Availability Discount
AD_{cr}	AD-corrective
AD_{pr}	AD-preventive
BP	Bonus Percentage
DP	Discount Percentage
NAP	Net Availability Payment
PD	Performance Discount
GAP	Gross Availability Payment

Projects

(1) SAA-ONE	Project: Schiphol-Amsterdam-Almere (A1-A6)
(2) SAA-GA	Project: Schiphol-Amsterdam-Almere (A9) (Gaasperdammerweg)
(3) A-Lanes	Maasvlakte-Vaanplein (A-15)

*Freely translated from Dutch terms, see footnotes in chapter 4.2.1

INTRODUCTION

1 Introduction

The contract form Design, Build, Finance and Maintain (DBFM) is relatively new (Koster and Hoge 2008). Construction projects are increasingly carried out under such contracts (V&W 2007). Most construction companies and personnel have built up their experience under more traditional forms such as Engineering and Construct (E&C) or Design and Construct (D&C) contracts. DBFM contracts require the inclusion of financing and maintaining assets for the long-term project duration (25 years or more) (Garsse, Muyter et al. 2009). Maintenance is becoming increasingly important in infrastructural projects. Therefore, companies are seeking possibilities to research how to adapt their modus operandi. They aim to integrate maintenance in the design in order to be able to design and operate assets more efficiently and effectively (Lenferink, Tillema et al. 2013). Hence, this master research is carried out. The incorporation of maintenance considerations in the design of companies is the focal point of this thesis.

1.1 Problem Formulation

In many DBFM projects contractors, generally known as Special Purpose Companies (SPCs) (Garsse, Muyter et al. 2009), tender for such contracts. Such joint ventures consist of the contract holder and various other companies, including Engineering Procurement and Construction companies (EPCs) and Maintenance companies. Parts of the contract are distributed over the various companies in the joint venture. As a result one company is responsible for design and construction works, while the company is responsible for carrying out maintenance. Maintenance is carried out on the existing infrastructure or the execution of maintenance commences after asset completion. As a result, the maintenance company is on the background in the front-end of projects.

Currently, maintenance expertise is not fully incorporated in the early stages of projects. The focus is more on the design process for construction and not on maintainability in order to be able to manage assets effectively and efficiently. Attempts are made to incorporate maintenance considerations in projects. Part of the challenge stems from the fact that designers are used to; 'designing for construction' and maintenance engineers are used to; 'maintaining existing assets'.

Since contracts are awarded on life-cycle costs and payments to SPC are dependent on availability, it is vital to design assets that are maintained efficiently and effectively. In order to win tenders, and during projects to minimise life-cycle costs and maximise availability payments over the complete contract duration.

Ideally, companies that form joint ventures that are working under DBFM contracts focus the complete life-cycle costs. Therefore, the designs should be based on considerations from a design, construction and maintenance point of view.

As can be seen in Figure 3 the front-end of the process provides the greatest potential of reducing life-cycle costs at minimum investment. Later on in the process, the reduction potential decreases while the cost of implementing changes increases. The upper line in Figure 3 indicates the potential for cost redcution and the lower line indicates the cost of change (Flanagan, Norman et al. 1989).

Therefore, it is vital to incorporate maintenance expertise in the front-end design process in order for life-cycle cost reduction to be effective. In some cases, additional money spent on construction can lead to savings in the maintenance phase (Flanagan, Norman et al. 1989). However, companies investing in for instance durable solutions and the company benefitting are not necessarily the same. A fragmented perception of the life-cycle cost throughout joint ventures can hamper the advancement of such contracts and limit its affiliated life-cycle benefits. Companies and experts in joint ventures are possibly working towards individually defined goals and success is defined within each organisation or department.

Knowledge and expertise built up over the duration of the project is restricted to the company executing independent phases, or to individuals working on the project. Feedback, positive or negative, from partners in joint ventures is limited and is therefore not implemented in future projects (Maylor 2010). In addition, most knowledge is tacit and is not made explicit (Jashapara 2011). Therefore, the sharing of knowledge and the learning of projects is limited (Hertog and Huizenga 2005; Geisler and Wickramasinghe 2009).

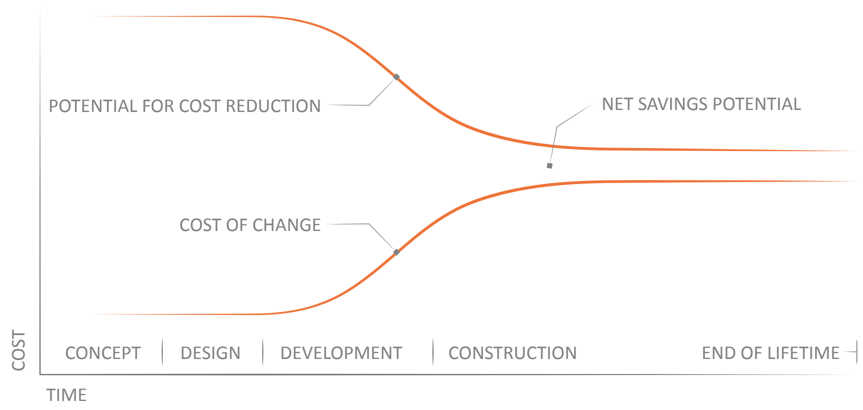

Figure 3: Relationship between life-cycle cost savings over time, adapted from Flanagan, Norman et al. (1989)

1.2 Research Objective and Research Questions

The aim of this study is to find a way to incorporate maintenance in the early phases of the development of infrastructural road projects under DBFM contracts to contribute to life-cycle costs reduction. Which focuses on people, process, contracts, knowledge and the organisation of project companies. By analysing how maintenance is currently incorporated in the design processes in the DBFM projects; SAA-ONE, SAA-GA and A-LANES.

The research draws from related literature to come up with practical recommendations (managerial implications) as to how to incorporate maintenance considerations efficiently and effectively in a DBFM context. This research adds to the body of knowledge of the inclusion of maintenance in the design of assets under a DBFM contract, as there is currently little literature available that specifically researches this topic.

Main research question

How can maintenance considerations be incorporated comprehensively in design projects under a DBFM contract?

Sub questions

- How is the design process currently organised within project companies?
- How is maintenance incorporated in projects?
- How is the collaboration between designers and maintenance engineers facilitated in projects?
- How are design decisions made?

1.3 Reading Guide

Chapter one, introduction, entails the problem formulation, the research objectives, the research questions and the reading guide.

Chapter two, literature study, the literature study that is carried out in order to get an understanding of related fields to the inclusion of maintenance in the design of assets under DBFM contracts.

Chapter three, methodology, discusses the basis of this research through explaining the general characteristics of this research, its strategy and quality, case design, case introduction and the selected respondents for interviews.

Chapter four, empirical research, entails the actual case study wherein the results of the research of the main case are provided.

Chapter five, cross case analysis, discusses the results that are found in the main cases, which are compared to the second and third case.

Chapter six, discussion, links the result of chapter four and five to literature on maintenance inclusion in other capital-intensive industries. It comprises the managerial implications of the improvements that can be made in the incorporation of maintenance considerations in DBFM projects. Also, the limitations of this research are discussed.

Chapter seven, conclusions and recommendations entail the overall conclusions of this study and the research implications are provided.

LITERATURE STUDY

2 Literature Study

The focus of this research is on the design process and the inclusion of maintenance considerations in the design phase of DBFM projects. The literature study for this master research is carried out to get an understanding of the domains related to the design and maintenance of infrastructural works and its context. Knowledge management is assessed in order to be able to research knowledge processes in the design process of such infrastructural projects.

This literature study covers five main themes, which consist of Asset Management, DBFM contracts, Maintenance, Knowledge Management, and Maintenance Inclusion in Various Industries. Every theme and related topics are assessed in more detail in the following sections.

2.1 Asset Management

2.1.1 Introduction

Infrastructure is vital to the functioning of economies as it contributes positively to people's quality of life and drives economic growth (Haughwout 2001). A holistic view of construction and the upkeep of infrastructure at minimum costs is therefore of the utmost importance (Too, Betts et al. 2006).

Assets are a means to provide value to people and road users (Verlaan and Ridder 2010). Infrastructure assets are defined as something long-term and stationary, generally maintained for a great number of years. Examples include: roads, highways, bridges, tunnels, dams, etc. (OFM 2012).

Asset Management (AM) is a term that is widely used in literature. The term is broad and offers various perspectives. Hence, it is still unclear to many what is meant by AM (Too 2010). Asset management is defined by Sarfi and Tao (2004) as "the process of optimising return by scrutinising performance and making key strategic decisions throughout all phases of an assets life-cycle". This definition is clear-cut and captures the essence of asset management as it is based on: management: optimising return, scrutinising performance, making key strategic decisions, all phases of an assets life-cycle. Therefore, this definition is used as a reference in this report. In order to provide a more detailed insight into the meaning of Asset Management, several other definitions are provided in Appendix A (paragraph 1.1).

Woodhouse (2007) describes AM as being the 'core role' of infrastructure owners and operators. Assets are to be 'cared for' and 'exploited' cost-effectively. AM consist of 'pre-acquisition' strategies concerning: planning, initiating assets, operation and maintenance, and monitoring performance. Therefore, a life-cycle approach is identified as an inherent part of infrastructural asset management. It aims at providing quality, availability and reliability while complying with contracts (Amadi-Echendu, Willett et al. 2010). Asset management is becoming an integral part of construction projects and construction companies.

To date, asset management is often associated with the practical side of AM (Too, Betts et al. 2006) and is focussed on operational maintenance, inventory management and affiliated services. Focusing solely on the operational and not on strategic levels of AM hampers the advancement of it (Too 2010).

Furthering asset management relies on companies and organisations focusing on the strategic level of AM (Australian National Audit Office 1995).

The major components of an asset management system are displayed in Figure 4. An asset management system is a framework in order to make informed decisions concerning resources, capital and maintenance strategies, which in turn must lead to community benefits (OECD 2001).

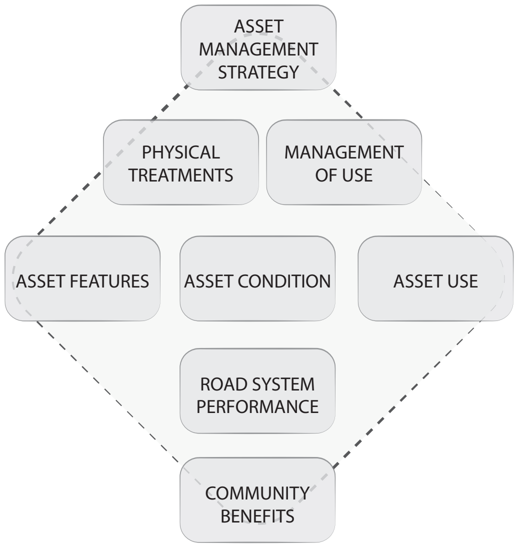

Figure 4: Elements of Asset Management System, adapted from OECD (2001)[2]

[2] Original source Austroads, strategy for Improving Asset Management Practice (1997)

2.1.2 Section Summary

The definition of asset management is provided, specifically that it centres on optimising return, scrutinising performance, and making key strategic decisions over all the phases of assets' life-cycles (Sarfi and Tao 2004). The most important notion is that AM is to be strategic, however, to date AM is often associated with operational maintenance (Too, Betts et al. 2006). The major elements of an asset management system are provided, to give insight into the interrelation of the AM strategy, the use of assets, physical treatments, road performance, etc.

Next Section

The following section discusses the themes related to DBFM and its PPP context. It addresses the progression from more traditional contracts to PPPs, contract integration, the changing role of RWS, the life-cycle cost reduction potential, PPP payment mechanism and the DBFM organisation

2.2 Design, Build, Finance & Maintain (DBFM)

2.2.1 Introduction

DBFM contracts are becoming the norm in the Netherlands for complex projects that exceed the threshold of €112.5 million (Eversdijk, Beek et al. 2008). The Dutch government aim to increase the deal flow of DBFM contracts. These contracts are applied if, through a Public Private Comparator (PPC)[3], DBFM contracts prove to provide better Value For Money (VFM)[4] (V&W 2007; Eversdijk, Beek et al. 2008). As a result, contractors are keen on investigating how to adapt to this type of contracts.

2.2.2 DBFM Context (PPP)

DBFM contracts are solely one type of Public Private Partnerships (PPP). "A PPP is a partnership between the public sector and the private sector for the purpose of delivering a project or a service traditionally provided by the public sector" (European Commission 2003). There exist many different types of contracts within PPPs (HM Treasury 2006), a number of commonly used structures are provided in Appendix A (paragraph 1.2). The development of the contract integration into DBFM contracts is discussed in the following paragraph.

[3] PPC is a tool to assess the 'added value' of different project, which aids decision-making prior to procurement. Its goal is to determine whether PPPs offer VFM over other procurement types. The Dutch Ministry of Finance developed the PPC (Eversdijk, Beek et al. 2008).

[3] VFM measures the benefits of a procurement method by assessing whole-life costs, quality and fitness for purpose of assets and services to users. VFM is a relative concept (HM Treasury 2006)

2.2.3 Contract Integration

Until the 90's, RWS was responsible for planning, technical design and maintaining road infrastructure. In the late 1990's, tasks and responsibilities were transferred to the private sector, as private sector parties are expected to be able to deliver innovative solutions, deliver more cost and time effectively and operate efficiently (Arts 2007). Figure 5 displays the development of contracts over time. The first step to move away from the traditional approach is the introduction of Engineering and Construct (E&C) contracts. Second, Design and Construct (D&C) contracts were introduced. These contracts integrated several phases of the life-cycle of projects, however, maintenance was still a stand-alone phase. Next, DBFM contracts were introduced in which all stages except operations are the responsibility of the private sector (Lenferink, Tillema et al. 2013). The phases: design, build, finance and maintain are elaborated on in Appendix A (paragraph 1.3). DBFMO is the most integral contract in this regard. The 'O' of operations refers to 'traffic management', which is a core role of the Dutch Ministry of Transport. Therefore, they are generally not applied in infrastructure project in the Netherlands (Eversdijk, Beek et al.).

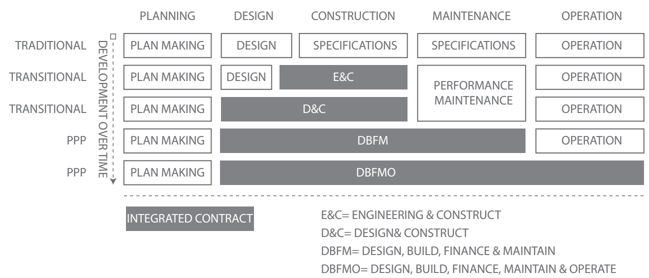

Figure 5: Development of contracts over time, adapted from Lenferink, Tillema et al. (2013)

Integrating contracts into DBFM contracts lead to increased efficiency, better governance, improved transparency, reduced lifecycle costs, provides incentives for performance, accountability, and reduced up-front government investment (Davies and Eustice 2005; Delmon 2011; Herrala, Pakkala et al. 2011). However, there are also drawbacks to the utilisation of DBFM contracts. Clients are faced with the challenge to define functional and service specifications. Responsibilities and risks are transferred to the private sector, which diminishes the Governments' ability to make changes. PPP procurements generally take longer than traditional procurements that result in higher project costs. Contractors have to commit to long-term debts (Herrala, Pakkala et al. 2011). The risk pricing and the private financing schemes potentially result in higher cost. Furthermore, the PPP payments scheme involves large fixed payments in the long-term, which limits the budget flexibility of future governments (Grimsey and Lewis 2007).

The benefit of DBFMs is that PPPs maximise the use of private sector skills, as the private sector is responsible for delivering assets that perform at satisfactory levels set by RWS. According to Grimsey and Lewis (2007), there are three elements that render PPPs productive and efficient in comparison to traditional procurement: ownership, bundling of tasks and risk transfer. In PPP contracts the public sector transfers control rights of infrastructure assets to the private sector. Ownership or control rights of assets are a strong incentive for cost efficient investments. The construction and operations of assets is bundled into one contract, which diminishes transaction costs. Bundling creates opportunities for companies to make larger upfront investment to reduce maintenance costs. Risks are transferred to the private party and they need to treat those risks explicitly and price them cost effectively. The company is only remunerated when the assets perform at satisfactory levels. Therefore, companies need to build assets correctly, limit costs without giving in on quality (Grimsey and Lewis 2007).

2.2.4 RWS Client Organisation

Since 2006, RWS has been the executive agency for the Ministry of Infrastructure and the Environment[5]. RWS is the largest infrastructure client of the Netherlands and is responsible for the construction, management and maintenance of the main road network, the main water network and the main water system (Rijkswaterstaat 2008). According to RWS; projects should be realised by private sector parties if they can deliver better quality. This statement became their motto: "The Private Sector, Unless…"[6]. RWS is becoming a public oriented network director, which also acts as project and crisis manager in projects (Rijkswaterstaat 2012). Their executing role diminishes (Rijkswaterstaat 2008).

2.2.5 DBFM Organisation

As displayed in Figure 6; key figures in DBFM contract are the procuring agency (public sector client), the contractor holder known as Special Purpose Company (SPC). Construction and maintenance work is divided into two contracts between

[5] The Ministry of Infrastructure and the Environment is formerly known as Ministry of Transport, public Works and Water management ("Misterie van Verkeer en Waterstaat" abbreviated as V&W in Dutch)

[6] Freely translated from "Markt, Tenzij…"

the Engineering Procurement and Construction (EPC) company and the Maintenance Company (M-Co) respectively.

The public sector client has a direct agreement with the SPC (DBFM contract). SPCs are financed through shareholders (equity) and external financers (debt). These consist of shareholders' agreements and financing agreements respectively (Koster and Hoge 2008).

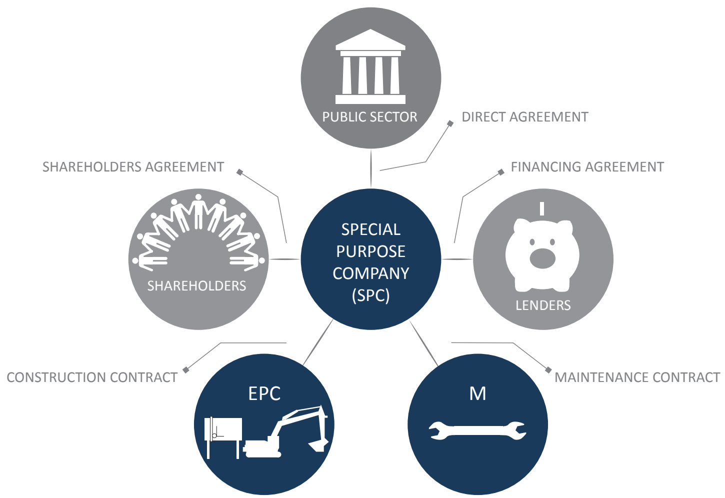

Figure 6: DBFM contract structure, adapted from Koster and Hoge (2008)

2.2.6 Payment Mechanism

This paragraph discusses the payment mechanism of DBFM contracts. Private parties are responsible for the upfront investment (for designing and constructing assets) as well as the costs related to the upkeep of the agreed levels of performance (small and heavy maintenance) (see Figure 7). During construction, the contractor receives performance-payments for the maintenance carried out on existing road infrastructure up to replacement. Governments generally pay the private company a one-off agreed amount after commissioning. This payment limits the cost of financing for SPCs and reduces availability payments for governments. Moreover, the one-off payment is fixed to a date, which restrict time overruns (Koster and Hoge 2008).

For the remainder of the contract, payments are related to availability and quality of assets. The link between payments and quality (performance requirements) is regarded a key instrument for governments to steer and guarantee contractor performance. If contractors fail to meet these requirements, governments generally pay a discounted availability payment to the contractor (Garsse, Muyter et al. 2009).

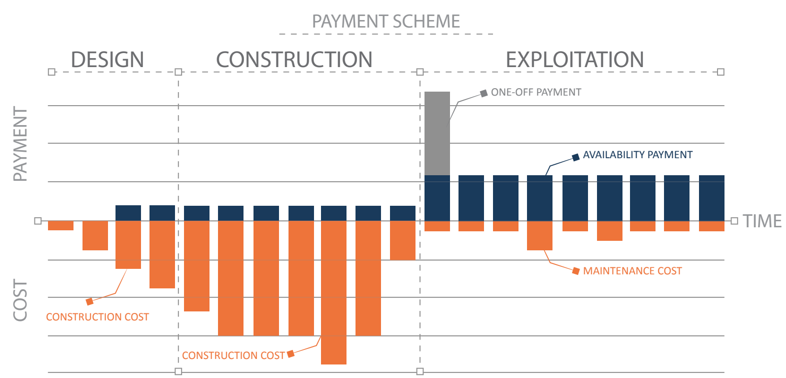

Figure 7: PPP Payment Scheme, adapted from (PWC 2012)

2.2.7 Life-Cycle Optimisation Potential in Projects

As the private sector is responsible for the delivery and performance of assets over the duration of the contract as a whole, it is vital to take the life-cycle and the affiliated costs into account. Life-Cycle Cost (LCC) is defined as "a method of economic analysis for all costs related to building, operating, and maintaining a project over a defined period of time" (Harvard 2010).

As can be seen in Figure 8, in the front-end of the process, one has the greatest potential of reducing life-cycle costs at minimum investment. Later on in the process, the reduction potential decreases while the cost of implementing changes increases The upper line in Figure 8 indicates the potential for cost redcution and the lower line indicates the cost of change (Flanagan, Norman et al. 1989).

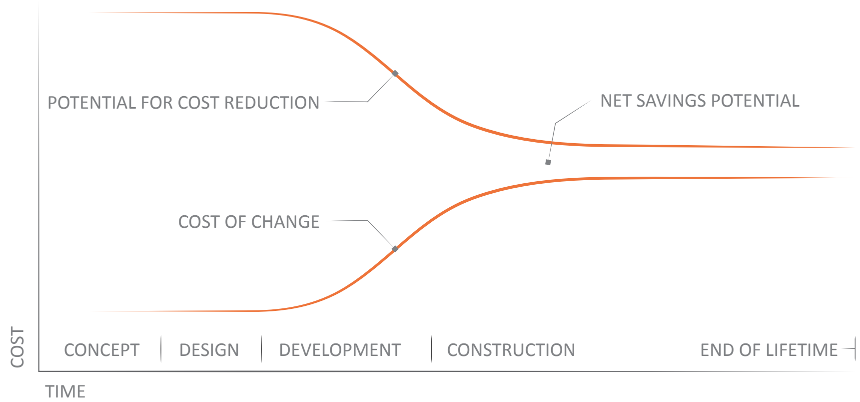

Figure 8: Relationship between life-cycle cost savings over time, adapted from Flanagan, Norman et al. (1989)

More specifically, (Woodward 1997). Korpi and Ala-Risku (2006) underline the importance of LCC incorporation in the design phase, as 70-90% of all costs are determined in the front-end of projects. As can be seen in Figure 9, the commitment to costs increases, as time progresses, i.e. in the beginning of development stage costs accumulated to 20% of the total, then 80% of the total LCC are determined (INCOSE 2006).

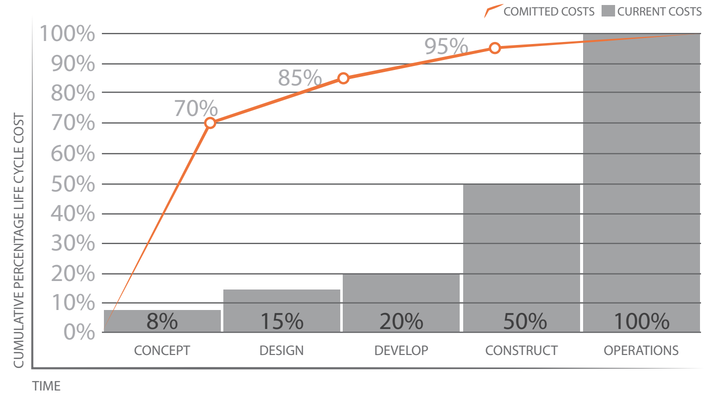

Figure 9: Committed Life-Cycle Cost Against Time, adapted from INCOSE (2006)

Therefore, it is vital to incorporate back-end and thus maintenance expertise in the design process in order for life-cycle cost reduction to be effective (Flanagan, Norman et al. 1989).

2.2.8 Section Summary

This section assessed the DBFM contract and its context. It discussed how contracts progressed from fragmented traditional contracts to inclusive DBFM contracts. It provides insight in the role of RWS as client organisation, the DBFM organisation, and the payment mechanism. Payments are generally based on availability (Herrala, Pakkala et al. 2011), which renders it important to incorporate maintenance considerations in the design of assets to ensure that performance requirements are met over the duration of the contract. Furthermore, the front-end of projects have the greatest potential of life-cycle cost optimisation (Flanagan, Norman et al. 1989), which demands maintenance considerations to be incorporated in the front-end of designing assets. Important is the notion that when 20% of projects costs are made, that 80% of project costs are determined and dedicated to (INCOSE 2006).

Next Section

The next section will zoom in on maintenance, levels of maintenance, maintenance engineering, monitoring maintenance performance, types of maintenance tasks, maintenance strategies and tools that are utilised in the design of assets such as RAMS, systems engineering (SE), and life-cycle costing (LCC).

2.3 Maintenance

2.3.1 Introduction

Maintenance is increasingly becoming a vital functional area in many types of organisations such as transportation, manufacturing, construction, etc. It affects multiple functional areas within organisations such as production, availability, inventory and quality. The increase in maintenance is estimated to represent up to 30% of all operating costs of modern construction and manufacturing companies (Al-Turki 2009). "Proper maintenance helps to keep life-cycle cost down and ensures proper operations" (Waeyenbergh and Pintelon 2002).

Mobley (2008) places maintenance in its context by stating that maintenance is a science, an art and a philosophy. It is science because carrying out maintenance depends on nearly all forms of science. Maintenance is art because similar problems are solved in varying approaches and ultimately it is a philosophy because maintenance can be applied "intensively, modestly, or not at all".

In this chapter; maintenance is defined and related fields are discussed in order to get an understanding of what maintenance entails. This consists of levels of maintenance (in organisations), Maintenance and Reliability Engineering (ME and RE), maintenance performance, types of maintenance tasks, maintenance strategies, and the value of maintenance. Subsequently, tools that are used in the planning and design phase of infrastructure projects are discussed. These consist of: RAMS, Systems Engineering (SE) and Life-Cycle Costing (LCC).

2.3.2 Maintenance

In a broad sense, maintenance consists of all decisions related to maintaining a high level of availability and reliability of assets (Al-Turki 2009). According to Parida (2006) maintenance is defined as "the combination of all the technical and administrative actions, including supervision, intended to retain an item in, or restore it to a state in which it can perform a required function". Maintenance tasks can consist of repair, replacement, modification or check-ups (Parida and Kumar 2009). Maintenance systems vary from organisation to organisation, however, two aspects are vital to take into consideration: the level on which maintenance is carried out and a structure that supports maintenance that include planning, day-to-day decisions and resources (Ahmed and Duffuaa 2009).

2.3.3 Levels of Maintenance

Maintenance is of the essence on three levels namely: strategic, tactical and operational. The maintenance strategy and objectives are to be derived from the corporate strategy, which have to be translated from the strategic level to the tactical and operational level. The tactical level assigns the correct resources in order to carry out maintenance work and the operational level entails the correct execution of maintenance work (Parida 2006). Aiming at optimal maintenance can be reached through setting the right maintenance objectives; "does a company strive towards lowest cost, maximal availability of equipment or maximal safety of the maintenance personnel?"(Van Horenbeek and Pintelon 2013).

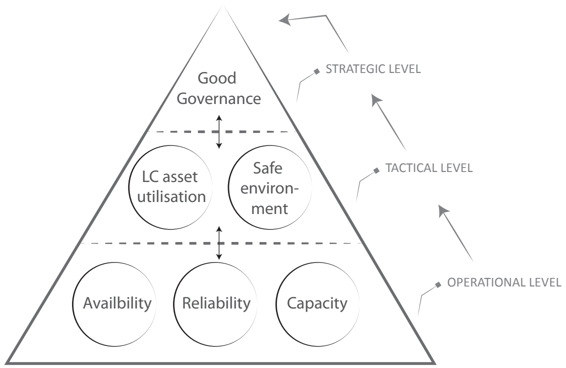

Figure 10: Levels of Maintenance, adapted from Parida (2006)

Van Horenbeek and Pintelon (2013) identified the definition of maintenance objectives in literature, the most clear cut definition is: "*The objective of the maintenance function is to support the production process with adequate levels of availability, reliability, operability, and safety at an acceptable cost*" (Van Horenbeek and Pintelon 2013).

2.3.4 Maintenance Engineering and Reliability Engineering

Maintenance Engineering (ME) is generally defined as a responsibility that entails ensuring that maintenance techniques are effective, that assets are designed and modified to increase maintainability, monitor and investigate technical maintenance issues, and make sure that corrective actions are taken to ensure asset improvement. ME is generally on a tactical level (Mobley 2008). Reliability Engineering (RE) is responsible for life-cycle assessments. It is strategic and covers long-term strategies to ensure capacity, quality, reliability, maintainability and best life-cycle cost. The focal point is maintaining assets in order to prevent: repetition of failure, reduce and improve maintenance work to reduce downtime, and prolong the economic life of assets (Mobley 2008).

2.3.5 Maintenance Performance

In order for the asset to be controlled and corrected; it becomes vital to monitor maintenance performance. Such information is important for the planning and the decision-making process of maintenance in future projects (Parida and Kumar 2009). Performance measurement is a system that is used to quantify the effectiveness and efficiency of actions (Parida and Kumar 2009). According to Parida (2006) maintenance performance measurement is defined as "*the multi-disciplinary process of measuring and justifying the value created by maintenance investment, and taking care of the organisation's stakeholders' requirements viewed strategically from the overall business perspective.*"

2.3.6 Types of Maintenance tasks

There are two types of maintenance tasks: Preventive Maintenance (PM) and Corrective Maintenance (CM). The main difference is that PM is time-driven and in CM, a problem or failure must exist before maintenance work is carried out (Mobley 2008). Preventive Maintenance is a concept that consists of regular checks before failures materialise to prolong assets' lifetimes. This concept relies on the probability of time interval wherein assets are breaking down (Ahuja 2009) and aims at eliminating breakdown or eliminating the need for corrective maintenance. Corrective Maintenance aims at minimising further deterioration once a defect occurs. The purpose of CM is to increase asset reliability, safety and reliability (Ahuja 2009) and ultimately to prevent breakdowns (Mobley 2008). The public sector client in the Netherlands prefers contractors to carry out preventive maintenance, as corrective maintenance is linked to discounts in availability payments.

2.3.7 Maintenance Strategies

Maintenance strategies utilise a combination of the previously mentioned maintenance tasks. An overview of maintenance strategies is provided in Appendix A (paragraph 1.4). These strategies focus on the operations of assets. Increasing availability and reliability becomes a focal point, while limiting costs. Maintenance is increasingly incorporated in companies; however, this is mainly focused on short-term cost reductions. Focusing on the short term might have long-term implications, as effects of maintenance often surface later in time (Waeyenbergh and Pintelon 2002).

2.3.8 The Value of Maintenance

Maintenance is of importance to organisations. However, the value of maintenance is often not clear. Value Driven Maintenance (VDM) is an approach that proves the criticality and value of maintenance in terms of economic value. The approach aims at shifting from regarding maintenance as cost centre to regarding it as value potential (economic value). Value is defined as: "*the sum of all future free cash flows, discounted to today*". The value of maintenance is created through: "*delivering maximum availability at minimum cost*". VDM is a means to identify value potential of four value drivers and providing a tool to manage and control these drivers. These value drivers consist of asset utilisation, cost control, resource allocation, and safety, health and environment (Jonker and Haarman 2006).

Managing maintenance means balancing availability and maintenance costs. While taking into account the laws and regulations concerning safety, health and environment and utilising the right amount of resources. Through calculating the net present value of alternatives an informed decision can be made as to how to adapt the maintenance strategy to crate value for the organisation (Jonker and Haarman 2006).

2.3.9 Analysis and Design Tools in Infrastructure Projects

Various analytical tools and software for design are utilised in the planning and design phase of projects. These consist of RAMS, systems engineering (SE) and life-cycle costing (LCC). These are discussed in the following paragraphs. The paragraph on BIM is provided in Appendix A (paragraph 1.5).

2.3.10 RAMS

RWS and contractors are responsible for the main road network and utilise a tool related to design and maintenance that is founded on the pillars of: Reliability, Availability, Maintainability and Safety (RAMS) (Rijkswaterstaat 2010). Reliability is defined by RWS as the probability of non-occurrence of system failure. Availability refers to the probability that assets perform according to set requirement expressed in terms of a fraction (%) of time. Maintainability refers to the probability of being able to carry out maintenance tasks within pre-specified periods and in the context of the time and place of occurrence, either preventive or corrective maintenance. Safety refers to “the lack of” unacceptable risks in terms of people’s injuries (Rijkswaterstaat 2010).

2.3.11 Systems Engineering

Systems Engineering (SE) is defined by the Federal Highway Administration (2013) as “*an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem*”. The elements that constitute the complete problem consist of: operations, cost & scheduling, performance, training, testing, manufacturing, and disposal (FHWA 2013). According to (NASA 2007), a system is a collection of elements that produce results, which are not achievable by the elements on their own. The added value by the complete system is created by the connection and the relation between the elements in order to achieve a functional and operational system over its life-cycle (NASA 2007).

According to Rijkswaterstaat (2011), SE is about working from stakeholder wishes, through a specification process to output specifications. The iterative specification process is top-down, which is about defining systems in systems elements. The realisation process is bottom-up and is about integrating these elements into the main system. This is generally captured in the V-model. Verification and validation are essential in in this process as it entails making the system development explicit and checkable. The V-model and the definitions of verification and validation (systems engineering) are provided in Appendix A (paragraph 1.6). Verification and validation is applied in the design and realisation of construction projects.

2.3.12 Life-Cycle-Costing

Life-cycle-costing (LCC) is a “*forecasting tool used to compare or evaluate alternative planned capital expenditures with the aim of ensuring the optimum value from capital assets*” (Taylor 1981). The model aims at improving investment efficiency as it takes all costs of the complete life-cycles of assets into account and not solely costs related to initial investments (Woodward 1997; Navarro-Galera and Ortúzar Maturana 2011). Perrons and Richards (2013) indicate that decisions in various industries are not based on the long-term. Instead, the focus is on short-term budgets in order to minimise up front costs, which can have an adverse effect on the total life-cycle cost. In contrast, true life-cycle costs range from costs for design, operations, distribution, maintenance, disposal, testing, training, supplies, computer resources, as well as, acquisition and disposal costs. All these costs should be included in the life-cycle costs assessment. The life-cycle is generally defined as the duration of assets ownership by an organisation (Flanagan, Norman et al. 1989)

LCC assesses future costs and benefits and these are expressed in present values (Taylor 1981); costs and benefits have to be discounted and inflation needs to be accounted for (Korpi and Ala-Risku 2006). Investment decisions can then be based on the least utilization of resources, which leads to savings and efficiency (Navarro-Galera and Ortúzar Maturana 2011). However, the selection of the discount rate has profound effects on the outcome (Woodward 1997). Utilising the LCC technique enables companies to make trade-off decisions between costs over the life-cycle of assets, for example, higher initial investments reduce future maintenance costs (Taylor 1981). LCC is not a new concepts, it has been developed for the US Department of Defence in 1970s. However, the implementation of LCC across various industries is slow (Woodward 1997; Korpi and Ala-Risku 2006).

2.3.13 Section Summary

This section identified the definition of maintenance and discussed its context. The basis of maintenance is that it covers all actions to retain or restore the required function of assets (Parida 2006). And that proper maintenance reduces the life-cycle costs of assets (Waeyenbergh and Pintelon 2002).

The levels on which maintenance is applied are strategic (long term objectives), tactical (medium term objectives) and operational maintenance (carrying out maintenance). Maintenance and Reliability Engineering aim at designing and adapting assets to increase maintainability ultimately to increase asset performance (Mobley 2008). Therefore, monitoring maintenance performance is essential (Parida and Kumar 2009). Furthermore, types of maintenance tasks and maintenance strategies are discussed. Maintenance tasks consist preventive and corrective maintenance. Such tasks differ in the timing of execution: preventive maintenance is carried out to prevent failure and is time driven, corrective maintenance prevents further deterioration (Mobley 2008). The operational strategy should be deduced from the corporate strategy in order to be successful (Parida 2006). A returning element in the literature is the strategic character of asset management and maintenance.

Furthermore, this section assessed infrastructure maintenance and the tools that are utilised in infrastructural projects. These consist of RAMS, SE and LCC. Generally speaking, these tools are employed as design and analysis tools. Although the techniques such as LCC is not new and present clear advantages, the implementation into the industry is slow (Woodward 1997; Porwal and Hewage 2013).

Next section

In order to be able to understand the design processes and the knowledge that is required and transferred between experts and departments, Knowledge Management is assessed. In the next section, definitions on KM are provided. A distinction is made between data, information and knowledge. Also, the distinction between tacit and explicit knowledge is provided. Knowledge processes and the transition between tacit knowledge and explicit knowledge are elaborated on, which lead to conclusions as to how to share knowledge and how to extract knowledge from projects.

2.4 Knowledge Management

2.4.1 Introduction

Knowledge management (KM) is increasingly becoming an accepted and well-liked discipline among scholars and in the industry. According to the OECD (1996), knowledge, information and technology are drivers for economic growth. According to Jashapara (2011), knowledge is becoming a key asset to companies' success and KM activities aim at enhancing companies' performance. Knowledge development and knowledge sharing is vital in companies in the construction industry. Therefore, the basic constructs of KM are researched in this chapter.

This chapter provides a definition of Knowledge Management, discusses knowledge areas, which is followed by the description of tacit and explicit knowledge. This chapter concludes with knowledge processes, how organisational knowledge is created trough the interaction between tacit and explicit knowledge.

2.4.2 Knowledge Management

Jashapara (2011) defines KM is "*the effective learning processes associated with exploration, exploitation and sharing of human knowledge (tacit and explicit) that uses appropriate technology and cultural environment to enhance an organisation's intellectual capital and performance*". In order to provide insight into the meaning of knowledge management, several other definitions are provided in Appendix A (paragraph 1.7).

The definition of Jashapara (2011) provides a distinction between tacit and explicit knowledge that is an important notion in knowledge processes. Furthermore, Jashapara (2011) underlines that the goal of KM is to enhance organisations' performance that can be linked to the strategic role of asset management that also aims at increasing performance.

The definition of knowledge can be clarified when relating it to the concepts of data and information (Hertog and Huizenga 2005). These concepts are widely discussed throughout literature, however, R.L. Ackoff was the first to interrelate them hierarchically. The relation of the basic concepts of the Data-Information-Knowledge-Wisdom hierarchy (DIKW) can be found in Appendix A (paragraph 1.8)

2.4.3 Knowledge Carriers and Areas

Knowledge needs a carrier; people are the most important carriers, either individually or collectively. Materials can also carry knowledge, which consists of: hardware, software and documents (Hertog and Huizenga 2005).

Within the concept of knowledge consist three types of knowledge areas; functional knowledge, operational knowledge and contextual knowledge. *Functional knowledge* is based on specific disciplines or functional areas in companies. Vital to functional knowledge is *know what* and *know why* and is often anchored in functional departments of companies. *Operational knowledge* is based on physical action, and built upon experience. Learning by doing is essential in operational knowledge, which results in *know how*. *Contextual knowledge* stems from operating in specific domains. For instance, specialised companies are familiar in their market. Such knowledge is linked to its environment, its context. It focuses on *know where* and *know when* (Hertog and Huizenga 2005).

2.4.4 Explicit & Tacit knowledge

Explicit knowledge is concrete, formalised, transferrable, and can be stored. When people are knowledge carriers, that knowledge is referred to as tacit knowledge (Hertog and Huizenga 2005). Tacit knowledge is generally defined as conceptual thinking, abilities and expertise, it is the knowledge that is not exchanged yet or is impossible to exchange (Geisler and Wickramasinghe 2009).

People generally possess both tacit knowledge and explicit knowledge. These are generally referred to as know-how and know-what respectively. Converting tacit knowledge into explicit knowledge is a great challenge to organisations (Jashapara 2011). Creating, sharing and transferring knowledge is discussed in the following paragraphs.

2.4.5 Creating Knowledge in Organisations

The increasing importance of knowledge in this so-called 'knowledge society' poses challenges to organisations as to how to process and create knowledge. Nonaka (1994) developed 'A Dynamic Theory of Organisational Knowledge Creation'. According to Nonaka (1994), there are two dimensions to knowledge creation, which are the 'ontological' and the 'epistemological' dimension. The ontological dimension refers to the social interaction between people that develop and share knowledge. Although ideas are created within people's minds, the interaction between people plays an important role in developing ideas. Such interaction might be between departments or organisations. Epistemological organisational knowledge creation relies upon the continual dialogue between explicit and tacit knowledge (Nonaka 1994).

2.4.6 Ontological Knowledge Creation

People create knowledge; organisations can support creativity and provide specific contexts for such knowledge creation. Organisations should 'amplify' the knowledge creation process and 'crystallise' knowledge in order to integrate it in the knowledge base of the company.

Key to the success of knowledge creation is commitment, which is linked to factors that drive it such as 'autonomy' and 'fluctuation'.

Autonomy is a principle that can be applied on: the individual, group and organisational level. Personal autonomy increases the possibility that people will motivate themselves to create new knowledge; the opportunity of people introducing unanticipated opportunities is then increased.

Fluctuation refers to discontinuity and chaos. Knowledge creation is dependent on the interaction with the context. Breakdowns or periodic interruptions lead to a situation in which people have the opportunity to rethink: the value of their habits, routines and their alignment of commitment (Nonaka 1994).

2.4.7 Epistemological Knowledge Creation

The transformation of explicit and tacit knowledge is bidirectional and allows for the proposition of four modes of conversion (see Figure 11); tacit to tacit, explicit to explicit, tacit to explicit, explicit to tacit.

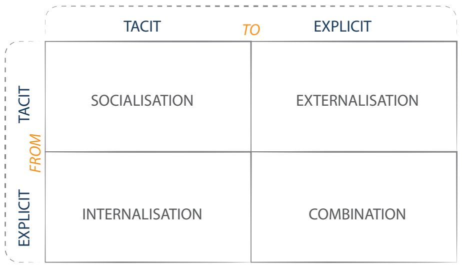

Figure 11: Modes of Knowledge Creation, adapted from Nonaka (1994)

The conversion of tacit knowledge can be achieved through interaction between people, which is called 'socialisation'. Individuals can acquire tacit knowledge without language through working with mentors, observing, imitating and practising (on the job training). The key to acquiring tacit knowledge is experience.

Converting explicit knowledge into new knowledge requires social processes to combine various bodies of knowledge held by individuals. Combining and exchanging knowledge is possible through exchanging, rearranging, adding, sorting, reconfiguring explicit information. The process of creating explicit knowledge is referred to as 'combination'.

The conversion from tacit to explicit (know how to know what) is called 'externalisation', generally through finding metaphors to describe certain elements. The conversion from explicit to tacit (know what to know how) is traditionally called is called 'internalisation' and is dependent on action such as learning (Nonaka 1994).

2.4.8 Dynamic Knowledge Creation

The aforementioned modes of knowledge creation above are able to create knowledge independently. However, organisational knowledge creation depends entirely on a dynamic interaction between the four modes. It centres on the creation of both tacit and explicit knowledge. Pure interpretation of the modes of knowledge creation can become artificial and unrelated to its context. The 'share-ability' of knowledge created through pure socialisation might be limited to the context in which it was created. True organisational knowledge creation hinges on a dynamic application of all four modes of knowledge conversion when it is managed continually by organisations (Nonaka 1994).

2.4.9 Section Summary

This section assesses a definition of knowledge management, of which the main propose is to enhance organisations' performance and intellectual capital through processes such as creating, gathering, exploiting, and sharing of knowledge. Important is the notion that this knowledge can either be tacit and explicit (Jashapara 2011). Tacit knowledge is rooted in action and generally difficult to communicate; explicit knowledge is concrete, formalised and shareable. Furthermore, a dynamic knowledge creation process is presented, which is based on socialisation, externalisation, internalisation and combination. All modes can create knowledge, however, true knowledge creation that has meaning outside the context in which it was created and hinges on a dynamic approach to knowledge creation (Nonaka 1994).

2.5 Maintenance Inclusion in Various Industries

2.5.1 Introduction

This section assesses how various capital-intensive industries that have long-lasting lifetimes, similar to the infrastructure industry, handle the incorporation of maintenance is the design of assets. These findings are the basis for the drawing of conclusions and recommendations as to how maintenance considerations can be incorporated in the design of infrastructural road projects.

The assessed industries consist of the petrochemical, satellite and space, oil and gas, production, renewable energy and manufacturing industries. The findings are presented in the following section (in no particular order) and are followed by a key success factor checklist, which is utilised to compare to the findings of the case study.

2.5.2 Maintenance Strategies From space onto the Oil and Gas industry

According to Perrons and Richards (2013), the upstream oil and gas industry could improve asset maintenance by applying certain maintenance strategies from the space sector. The experience of 50 years of servicing satellites in orbit results in best practices that are grouped in four categories: maximising knowledge of target satellite, managing the scale of servicing activities, minimising the precision of servicing activities and minimising temporal constraints (Perrons and Richards 2013).

Maximise knowledge of target satellite

Maximising knowledge reduces uncertainty in servicing operations. The less information is available, the more operations are needed to be adaptable, which adds to the complexity of the operations. Asset information can be obtained through having fault detection equipment and equipment with diagnostic capabilities. Early signs of weakness are easily detected and the reliance on inspections is reduced (Perrons and Richards 2013).

Manage scale of servicing activities

Managing the scale of servicing activities is vital to controlling the complexity of servicing operations. Three main recommendations are applicable to the servicing of satellites: limiting fuel consumption (through the concentration of parts and areas that need service), minimising the number of unique tasks, and component commonality (Perrons and Richards 2013).

Minimise precision of servicing activities (modularity)

Systems that generally consist of tailored solutions and custom components that are integrated in one system do not offer a service tolerance that modular systems offer. Therefore, modular systems should be developed and implemented (Perrons and Richards 2013).

Minimise temporal constraints

There are several temporal determinants of success in the space and satellite industry, of which 'access-timing' is applicable to the oil and gas industry. It entails the time of transporting tools to the area that needs maintenance. In both industries, uptime is essential; significant planning and resources are to be allocated to carrying out preventive maintenance to prevent downtime (Perrons and Richards 2013).

2.5.3 Maintenance Performance Measurement of Manufacturing Companies

Maintenance management is vital in production companies due to decreasing inventory buffers and due to automation. It becomes increasingly important for maintenance managers to be informed about the performance of assets. This is done through a maintenance performance measurement and identifying maintenance performance indicators. Such a system needs to be aligned with the corporate strategy. Van Horenbeek and Pintelon (2013) set up several steps to develop a business specific maintenance performance measurement system.

1. Prioritise maintenance objectives on all organisational levels (top-down)
2. Translate specific maintenance objectives into relevant MPI on all organisational levels (bottom-up)
3. Measure, monitor and control maintenance performance based on MPI
4. Continuous improvement by redefining maintenance targets within specific business environment.

2.5.4 Design of easily maintained rolling stock

According to a research that is currently carried out by the University of Twente (work in progress), the design of vehicles and the design of the maintenance service influence the maintenance process. Especially the early phases of the development of the design have great influence. Through redesigning trains the need for specific maintenance equipment was eliminated, which resulted in substantial savings over the life-cycle of each train (Mulder, Basten et al. 2013).

2.5.5 Green maintenance initiatives in design and development of mechanical systems

Maintenance is vital to retain and restore assets to perform their function. Due to increasing concerns on global environmental degradation, many industries are considering to service, restore, and dispose assets environmentally friendly. This requires integrating product design and maintenance activities, as incorporating maintainability in the design phase leads to a reduction of maintenance requirements during operation. Therefore, having a full understanding of operational maintenance requirements is vital in order to be able to 'map' that onto the design characteristics in the design phase. As a result, accessibility, modularity, standardisation, simplicity, assemblability and disassemblability become increasingly important (Ajukumar and Gandhi 2013).

Ajukumar and Gandhi (2013) propose important steps to arrive at design alternatives that take maintenance considerations into account. It includes:

- Identifying maintenance requirements
- Establishing a relation between maintenance requirements and design characteristics
- Identifying design characteristics that facilitate maintenance
- Calculating the impact of design alternatives
- Ranking design alternatives

2.5.6 Designing and developing services for manufacturing firms

Manufacturing companies traditionally focussed on design and development of products. Service was regarded to be supplementary and mainly provided in aftermarket activities. However, value is derived from enhancing the use of assets or products over its life-cycle. Tan, Matzen et al. (2010) identified that, to date, there is little literature available on how to systematically design products that takes production and service into account. Therefore, they propose Product/Service Systems for developing integrated products and services to support customer activities.

Tan, Matzen et al. (2010) describe various design methods ranging from product-centred approaches to service-centred design approaches. The range of design methods consists of: design for serviceability, design for supportability, design for service, and service design.

Design for Serviceability

Design for serviceability or maintainability takes design simplicity, part characteristics, operating environment, etc. into account. By employing a Serviceability Task Evaluation Matrix (STEM), decision-making is supported. STEM consists of estimations of cost and time durations of maintenance tasks, parts costs, diagnosis time, technician requirements (training) and part availability.

In doing so, the plan-do-check-action (PDCA) cycle is vital, which serves as a 'bridge' between operational maintenance and design. First, data is obtained from operational assets through: monitoring, inspections and failure diagnosis. Second, maintenance engineers on the tactical level carry out a deterioration evaluation, failure effect evaluation and a maintenance effectiveness evaluation. The findings are compared to the original maintenance strategy for accurateness and appropriateness. If discrepancies materialise, strategies can be adapted based on actual data. Third, this information is fed to the design department in order for tactical maintenance considerations to be effectively and efficiently incorporated in the design.

Design for supportability

Design for supportability consists includes: "*reliability, availability, serviceability, usability and installability*". The paper identified factors that currently limit the application of design for supportability. Prioritising the following factors allows companies to further the development of products or assets while taking supportability into account.

1. Support requirements are incorporated too late in the product development cycle
2. Field engineers and managers do not have the possibility to influence the product designs
3. Decisions taken to lower production costs makes has a negative effect on support
4. Product features prevail over product support considerations

Design for service

One example of a company that moved away from offering service around products to 'Designing a Service and the product that supports it' is Rolls Royce (power systems manufacturer). This requires an organisational and cultural change; designers and service providers needed to start collaborating towards a mutual goal. Key requirements are: translation of cost of ownership to engineering and organisational deliverables, effective service knowledge management, life-cycle cost analysis tools and skills, and effective identification of potential deterioration of the product over time.

Service Design

A requirement in the design of Product/Service Systems is the capacity to collect, store and analyse data about products and consumers that can be provided to improve the quality consumer value. Monitoring is essential to garner a full understanding of operational products. Hence, data analysis and fault detection are important and monitoring provides insight into costs and allows for identifying savings. The technical capability of the system allows for system optimisation, solution design and ensures that the predetermined levels of performance are reached. Service departments internally share information to research and development concerning the needs for servicing, which are to be implemented in future designs (Tan, Matzen et al. 2010).

2.5.7 Executive Information System

In order for maintenance management in petrochemical plants to be efficient, an executive information system is vital. Such a platform aims at enhancing plant reliability while being competitive. The system provides plant managers and engineers a complete overview of the plant status and the effects of their maintenance work (Hwang, Tien et al. 2007).

Every plant has to be equipped with a management system to manage: "*facility recordings, maintenance records, maintenance job orders, maintenance resources and spaces"*. The obtained data are transformed to calculable documents that are used for better management and allows for quicker and improved decision-making (Hwang, Tien et al. 2007).

2.5.8 Key Factors Checklist

The important factors that are indicated in the publications by authors in the various industries are listed in a key success factor in below.

- Maximising assets knowledge
    - Provide input to design by collecting, storing and analysing data of asset performance through monitoring asset and fault detection
    - Storing of relevant information through the monitoring of assets in an executive information system (cause of failure, job orders, work history, resources, maintenance costs, etc) and transforming data into calculable files for analysis
- Deducing maintenance objectives from corporate objective
- Translate TCO to engineering deliverables, effective knowledge management, LCC tools and skills, and the identification of potential deterioration of assets over time
- Considering reliability, availability, serviceability, usability and installability in the design. Through:
    - (1) Incorporating maintenance requirements in an early stage in the design
    - (2) Providing maintenance engineers and managers with power to influence the design

- (3) Focus on life-cycle cost and not on initial investments
- (4) Focusing on maintenance considerations as opposed to asset features

- Adapt the organisation to work towards a mutual goal

Section Summary

This section discussed how various other industries handle the incorporation of maintenance. Elements such as implementing an Executive Information System are highlighted as being important It entails mapping resources, maintenance costs, etc. that can be transformed into calculable data for better decision-making (Hwang, Tien et al. 2007). Also, maximising asset knowledge, managing the scale of activities, minimising precision of activities (modularity), and minimising temporal constraints is vital for maintenance to be integrated effectively and efficiently. Maximising knowledge can be achieved through maintenance performance measurement, fault detections, diagnostic capabilities and inspections (Perrons and Richards 2013). Maintenance strategies are to be derived from corporate strategies and translated into tactical and operational objectives. Maintenance has to be fully comprehended before it can be mapped onto the design of assets. This includes garnering an understanding of: accessibility, modularity, standardisation, simplicity, assemblability, and disassemblability (Ajukumar and Gandhi 2013). Furthermore, tools such as serviceability task evaluation matrix can be employed to improve products and its maintenance design (Takata, Kirnura et al. 2004). Various design strategies can be considered depending on the level of service that is provided; design for supportability, design for service and service design (Tan, Matzen et al. 2010).

Next Section

The following section comprises the conclusions of the literature study and identifies the elements from literature that are the basis for the empirical study.

2.6 Summary Literature Study

The literature study provides definitions of Asset management and insight into the asset management system, the public sector client (RWS) and their role as asset manager and network manager. Due to decreasing funding possibilities by the government, which results in infrastructure budget cutbacks (Schultz van Haegen and Mansveld 2013), the private sector gets more responsibilities in the provision of infrastructure. Not only are contractors responsible for the construction of assets, they are also responsible for financing and long-term maintenance of projects (Lenferink, Tillema et al. 2013). These projects are carried out in the form of DBFM contracts. Moreover, projects as a whole, including maintenance, are to be executed efficiently and cost effectively (V&W 2007). Which underlines the relevance of asset management (Sarfi and Tao 2004) and the incorporation of maintenance in the design phase of projects. Especially the strategic role of maintenance is identified as key to the successful implementation of AM (Australian National Audit Office 1995).

Furthermore, a background of PPP schemes and particularly the context of DBFM contracts are provided, since that is the norm in the Netherlands for contracts other than traditional contracts (Eversdijk, Beek et al. 2008). Every contract with project costs exceeding 112.5 million is assessed for Value for Money in order to opt for either a traditional or DBFM contract (Rijkswaterstaat 2012). DBFM contracts cover all phases of project development: *Design, Build, Finance and Maintain (Koster and Hoge 2008)*. The efficiency of PPPs stems from ownership or control rights that are regarded to be an incentive for performance, bundling of contracts limit transaction costs, and risk transfer motivates contractors to treat risks explicitly and price and produce effectively (Grimsey and Lewis 2007).

Front-end decisions have great impact on the outset of projects. The literature study shows that 80% of all costs are dedicated to when 20% of project costs are made (INCOSE 2006). In addition, project companies or SPVs finance projects; payments are generally based on availability (Herrala, Pakkala et al. 2011). Therefore, life-cycle integration is vital in projects (Flanagan, Norman et al. 1989). The incorporation of maintenance expertise in the design phase should result in maintainability, which reduces life-cycle costs (Waeyenbergh and Pintelon 2002) and ultimately result in effective and efficient maintenance strategies.

The maintenance chapter provides an overview of the context of maintenance, maintenance tasks and maintenance strategies. Most importantly, the role of maintenance is discussed. It is to be part of the corporate or project strategy, not solely a task that is to be carried out after project delivery (Parida 2006). Specifically, infrastructure maintenance is assessed and the design and analysis tools that are employed in the design process are discussed. Which consist of RAMS, SE, LCC. Although various tools present clear benefits, the incorporation of LCC in the industry is slow (Woodward 1997; Porwal and Hewage 2013).
Furthermore, knowledge management and the concepts that KM is based upon are discussed. Most important is the notion that knowledge can either be explicit or tacit. Both are present within people, and both are present in companies and organisations. Explicit knowledge is referred to as *know what* and is transferrable, tacit knowledge is *know how* and is not easily transferred (Jashapara 2011). A model of dynamic knowledge creation is presented, which consist of the conversion of knowledge from: tacit to tacit (socialisation), explicit to explicit (combination), tacit to explicit (externalisation), explicit to tacit (internalisation). Socialisation is generally operationalized through 'on the job learning', combination can be through sharing documents and having meetings, externalisation can be reached through rounds of dialogue when making an effort to articulate knowledge and internalisations is generally referred to as learning. Key to the success of knowledge creation is commitment (Nonaka 1994).

The great infrastructure demand (increasing deal-flow), the inclusive DBFM contracts that entail long-term maintenance of assets, payments based on availability (Garsse, Muyter et al. 2009), and the potential to reduce life-cycle cost in the front-end of projects (Flanagan, Norman et al. 1989) underline the relevance and necessity of the inclusion of maintenance in the design phase of projects. Integral contracts have to be managed integrally, not sequentially, as most project costs are fixed from an early stage in projects (INCOSE 2006). Designers in the front-end and maintenance engineers have to be able to share and incorporate the necessary knowledge to reduce life-cycle costs of projects (Morieux 2011). Therefore, maintenance expertise should be on a *know what* level (Hertog and Huizenga 2005). Maintenance should not solely be on an operational level (Too, Betts et al. 2006), it should be strategic. The empirical study will research how maintenance can be incorporated comprehensively in the design of infrastructural road projects under DBFM contracts.

The literature on maintenance inclusion in various industries highlighted several elements that are regarded important for incorporating maintenance efficiently and effectively in the design of assets. Elements such as implementing an Executive Information System are highlighted as vital, It entails mapping resources, maintenance costs, etc. that can be transformed into calculable data for better decision-making (Hwang, Tien et al. 2007). Also, maximising asset knowledge, managing the scale of activities, minimising precision of activities (modularity), and minimising temporal constraints is vital for maintenance to be integrated integrally. Maximising knowledge can be achieved through maintenance performance measurement, fault detections, diagnostic capabilities and inspections (Perrons and Richards 2013). Maintenance strategies are to be derived from corporate strategies and translated into tactical and operational objectives (Parida 2006). Maintenance has to be fully comprehended before it can be mapped onto the design of assets. This includes garnering an understanding of: accessibility, modularity, standardisation, simplicity, assemblability, and disassemblability (Ajukumar and Gandhi 2013). Furthermore, tools such as serviceability task evaluation matrix can be employed to improve products and its maintenance design (Takata, Kirnura et al. 2004). Various design strategies can be considered depending on the level of service that is provided; design for supportability, design for service and service design (Tan, Matzen et al. 2010).

2.7 Literature study implications for Empirical Research

The literature study on the topic of the inclusion of maintenance in the design of assets provides no frameworks to assess in the empirical research. Little research is carried out that specifically researched the inclusion of maintenance in the design of DBFM projects in the infrastructure industry. The framework that is built and utilised is centred on the main and most important elements found in literature. These are based on two bases of literature. On one hand on: Asset Management, DBFM, Maintenance, knowledge management, and on the other on the maintenance inclusion in the various capital-intensive industries. The research protocol that is employed in interviews in the empirical study is based upon these findings.

Elements from the literature study of previous chapter that are covered in the empirical study consist of the contract requirements and how the DBFM characteristics influence the design and decision-making are assessed. The corporate or project strategy is assessed and how it relates to the design and maintenance strategy. The levels of maintenance (strategic, tactical, operational) that are important to the project companies are analysed. The ways in which the value of maintenance are incorporated in the design and how design decisions are made. The roles of tools such life-cycle costing are analysed and how they are incorporated in design decisions. The role of knowledge management is researched. More specifically, how knowledge is developed, shared and stored in projects.

The aforementioned elements are captured in five levels of maintenance inclusion that consist of: contract requirements, organisation, collaboration, activity and tools (see Figure 12)

Figure 12: Levels of Maintenance Inclusion

METHODOLOGY

3 Methodology

3.1 Introduction

The general introduction of this thesis focused on the importance of incorporating maintenance consideration in early stages of the project. In order to be able to research the incorporation of maintenance in the design of assets in the context of DBFM context, a research design is vital.

This chapter covers the research plan that was employed to carry out this research to meet objectives and subsequently to answer the main research question. This chapter consists of general characteristics of the research design and its implications. These characteristics lead to a strategy, which is linked to the quality of the research and how that is ensured.

3.2 General Characteristics

Since the topic of maintenance inclusion in the front-end of projects is relatively new, there is little research carried out as to how to implement that in projects. Existing literature provides little guidance or frameworks as to what to research or how to research previous findings. As a result, the character of this study is explorative.

The aim of this thesis is to draw practical conclusions (managerial implications) that are of added value to the company, as well as to contribute to existing theory. Due to increasing numbers of DBFM projects, this area is increasingly interesting to contractors.

3.3 Research Strategy and Quality

According to Yin (2003) different research methods can be used for different research purposes. They all have their specific advantages and disadvantages. The question as to when to use which strategy depends on three conditions: (1) the type of research question, (2) the level of control of the researcher over the researched events, (3) the extent of focus on contemporary as opposed to past or historical events. Research questions consist both of 'form' and 'substance', the 'form' of research question influences the type of research that is to be used. For instance, 'how' or 'why' questions are more probable to lead to the use of research strategies such as experiments, histories and case studies. This research, for VHB and the TU Delft, requires no control over the researched events; it focuses on contemporary events and 'how' or 'why' questions are posed. Therefore, a case study strategy is most relevant as opposed to experiments and histories (Yin 2003). There are three types of case studies: explanatory or causal case studies, descriptive case studies and exploratory case studies. These are based on diverse types of evidence: documents, observations and interviews. The technical definition of the scope of case studies is defined by Yin (2003) as: *"A case study is an empirical inquiry that investigates a temporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."(Yin 2003)*

This study aims at exploring what the current situation is like in joint ventures working under a DBFM contract, and investigating how maintenance can be incorporated effectively and efficiently by taking maintenance considerations into account form an early stage. Therefore, an exploratory case study strategy is most suitable.

Four criteria are vital in order to judge the successfulness of case studies. These consist of: construct validity, internal validity, external validity and reliability (Yin 2003).

Construct validity refers to using correct operational measures. *Internal validity* means finding causal relationships, which is applicable to explanatory or causal studies and not to exploratory case studies. *External validity* refers to the possibility to generalise findings. *Reliability* refers to repeatability of operations (data collection) and to possibility of arriving at the same results (Yin 2003).

Utilising multiple sources of evidence ensures construct validity. Different people throughout organisations and different methods are used to study the same phenomenon. This is referred to as data triangulation. The different methods consist of: interviews, observations, document analysis and management system analysis. As mentioned, internal validity is not applicable to exploratory case studies (Yin 2003). Three cases are studied in the empirical research allows for greater external validity. The second and third cases are studied to check the key findings of the first case. The reliability of the study will increase by using a case study protocol (interview protocol). Furthermore, case study descriptions, interview transcriptions and conclusions based on the research are shared or presented to the involved personnel for verification (Voss, Tsikriktsis et al. 2002).

3.4 Case Design

The research is conducted by studying three DBFM projects (multiple cases). Within these cases, there are three main units of analysis; the design department and the maintenance department, and the direct management of these departments. This leads to interviewing several individuals in the project; *designers design manager, maintenance engineers, maintenance manager, EPC manager and SPC manager.* As a result, this is research is an embedded multiple case study.

When a full understanding is garnered and a detailed case description is provided from the first case; a cross case-analysis is executed in order to assess similarities and differences between them. The findings of the cases are placed in the context of the literature of the 'various industries' in order to make cross-industry comparisons.

Primary instruments for data collection in this research consist of semi-structured interviews, interactions, attending meetings, informal conversations and document analysis.

The document analysis consists of contracts, internal contracts, project diagrams (organograms) and decision-making models in order to get an overview of the responsibilities, design requirements, lines of communication, maintenance input, and level of influence of maintenance experts on the decision-making in the design process. Furthermore, the management system is assessed in order to get an insight into how the maintenance incorporation in the design is facilitated.

The research will be conducted in an iterative cycle. First relevant literature is reviewed. Second, empirical data is gathered. Third, the data is analysed for the first case and compared across cases. Fourth, the analysis and the findings are placed within existing literature. Fifth, conclusions are drawn based upon the findings. Last, recommendations are made and shared with VHB.

3.5 Case Protocol

In order to be able to make sure that the validity of the research is enhanced; a research protocol is utilised that guides the interviews. The interviews are semi-structured in order to be able to follow up on answers that are provided. The interview protocol functions as a checklist. The protocol is not provided prior to the interview in order for the interviewees to provide their first reaction and honest perception (Voss, Tsikriktsis et al. 2002). The interview protocols are adapted to the individual roles of the interviewees, the basis for the protocol can be found in Appendix B.

The interviewees are selected based on getting a broad view on the inclusion of maintenance in de design in the project. Therefore, the design department, maintenance department, the EPCm directors, SPC staff and contract managers are interviewed.

All interviews were recorded with the approval of the interviewees and the key findings are transcription in tables and can be found in Appendix E.

3.6 Case Selection

Three infrastructural construction projects under DBFM contracts are selected for this research, based on availability. Two projects are researched are wherein VolkerWessels is involved and one project is researched outside VolkerWessels.

The following consortia carry out the projects that are selected for this research;

- SAA-ONE (VolkerWessels, Boskalis, Hochtief and DIF)
- SAA-GA (VolkerWessels, Boskalis, Hochtief and DIF)
- A-Lanes (Ballast Nedam, Strukton, John Laing and Strabag)

The progress of the projects varies; the timeline of the projects is displayed in Figure 13.

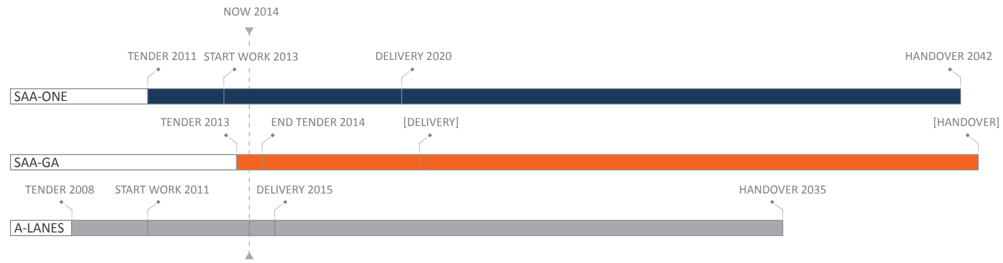

Figure 13: Project Timeline

In projects SAA-ONE and SAA-GA, VolkerWessels is part of the consortia. Of these cases, SAA-ONE commenced in 2011 and SAA-GA commenced in 2013. The A-Lanes project, which started in 2008 is outside VolkerWessels. This case is selected because it is of similar scale to the SAA-ONE project and carried out by another organisation. This case provides an outside view. SAA-ONE and SAA-GA are best accessible; of these cases SAA-ONE is furthest in progress. Therefore, most information is available form the SAA-ONE project. This case is studied most in depth and is regarded the main case. The other two cases are studied to check the findings of SAA-ONE. The checking of findings is discussed in the comparison chapter (see chapter 5).

3.6.1 SAA-ONE

SAA-ONE is the first DBFM SAA project of five SAA projects (Schiphol-Amsterdam-Almere). It is commissioned by RWS and is undertaken by the construction consortium consisting of VolkerWessles, Boskalis, HOCHTIEF and DIF. It entails the replacement and refurbishment of the A1 Diemen – A6 Almere Havendreef. The A1/A6 will be expanded over 20km. The construction is scheduled to commence in 2014 and is completed in 2020. As of the first of September 2013; the maintenance obligation of the existing infrastructure has begun. The joint venture is responsible for this road section for 30 years; the handover will be in 2042.

3.6.2 SAA-GA

SAA-GA is the second DBFM SAA project. This project consists of the road section on the A9, between the junction Holendrecht and Diemen (Gaasperdammerweg). The project is currently in the pre-qualification stage. The road section is currently 2 by 2 lanes plus a hard shoulder[7] on either side for "hard shoulder running"[8]. The project entails the construction of a 2 by 5 lanes plus one reversible lane[9]. This motorway is regarded the second bypass of Amsterdam. A section of the road is going to be built in a land tunnel, in order to minimise the physical impact of the road on the environment. The project also entails the construction of fly-overs to increase the traffic flow at the Holendrecht junction (Rijkswaterstaat 2013).

3.6.3 A-LANES

A-lanes is the consortium responsible for the broadening of the A-15 from the Maasvlakte 2 to Vaanplein (A29). The consortium consists of Ballast Nedam, Strukton, John Laing and Strabag. This road section is the most important road of the port of Rotterdam. It comprises 37 km of road, the replacement of the bridge over the 'Old Meuse' known as the Botlekbrug and the refurbishment of the Botlektunnel and the Thomassentunnel. The consortium is responsible for the road section for 25 years. On the 26th of September 2011, the maintenance obligation of the existing infrastructure has begun. The delivery of the asset is planned for the end of 2015; the handover will be in 2035 (A-lanes 2014)

3.7 Respondents

The role of maintenance in the design of assets in the SAA-ONE case is researched by carrying out interviews (and document analysis). The roles of the respondents are: Senior Maintenance Manager, Maintenance Manager, Maintenance Engineers, Design Reviewer, Integral Design Coordinator, Contract Coordinator, Quality Manager, EPCm Director and Design Leaders.

In order to make the comparison of maintenance inclusion in the design with the SAA-ONE case various interviews are held in the SAA-GA and A-Lanes project. The roles of the respondents in the SAA-GA project consist of: Senior Maintenance

[7] Translation of vluchtstrook

[8] Translation of spitsstrook gebruik

[9] Translation of wisselstrook

Manager, Maintenance Manager, and two maintenance engineers (roads and systems). The roles of the respondents in the A-Lanes project consist of: Maintenance Manager, Maintenance Engineer and Design Leader (roads). An overview of the respondents is provided in a list in Appendix C.

EMPERICAL STUDY

4 Schiphol-Amsterdam-Almere A1-A6 (SAA-ONE)

Characteristics

The first case that is researched is the SAA-ONE project. It is commissioned by RWS and is carried out by the consortium consisting of VolkerWessles, Boskalis, HOCHTIEF and DIF. It entails the replacement and refurbishment of the A1 Diemen – A6 Almere Havendreef. The A1/A6, which is displayed on the map in Figure 14, will be expanded over 20km. The construction is scheduled to commence in 2014, after 4 years of construction there is an exploitation phase of 25 years. The joint venture is responsible for this road section for 29 years; the handover will be in 2042. As of the first of September 2013; the maintenance obligation of the existing infrastructure has begun.

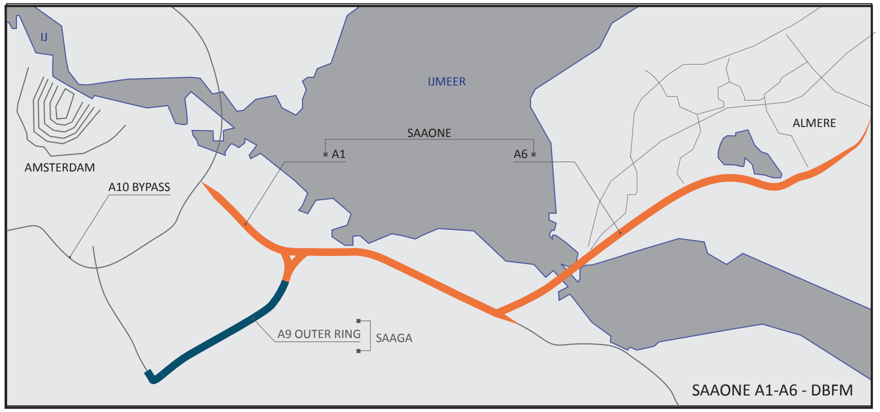

Figure 14: SAA-ONE Map

The chapter is divided in six sections. First, the contract structure is discussed. Second, the DBFM contract and the payment mechanism are explained. Third, a description of the tender organisation is provided. Fourth, the project organisation is discussed. Fifth, the maintenance department and its knowledge base are assessed. Sixth, the conclusions of this chapter are provided.

The A1-A6 project is carried out under a DBFM contract. In Figure 15 below, the general contract characteristics are displayed. The consortium is displayed as 'SAA-ONE' and Rijkswaterstaat is depicted as RWS.

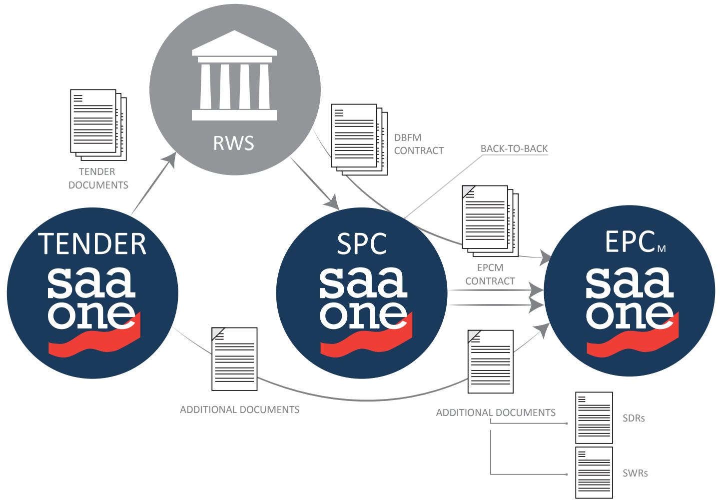

Figure 15: Contract structure SAAONE

As displayed in the scheme, the tender organisation provides tender documents to RWS. When the project is awarded to the SAA-ONE consortium, the DBFM contract is concluded between RWS and the SPC. Subsequently, the SPC forwards the DBFM contract back-to-back to the EPCm (Garsse, Muyter et al. 2009). This contract is referred to as the EPCm contract.

The EPCm contract contains all minimum requirements the contractor has to meet up to the handover in 2042. In order to ensure the long-term maintainability of assets internally (between the SPC and EPCm); the SPC incorporated additional contractually binding documents to the EPCm contract, namely: Special Design Requirements (SDRs) and Special Work Requirements (SWRs). SWRs are discussed in more detail in the 'additional contract requirements' paragraph (4.2.2).

4.1 Introduction

The case study assesses the overall set-up of the project for the inclusion of maintenance in the design. This is researched on five main elements and is captured in sections in this chapter. These consist of: (1) contract requirements, (2) organisation, (3) collaboration, (4) activities, and (5) tools. These five main elements are researched for the role of maintenance in the design of assets in the project. This is executed through carrying out interviews within the project and doing document analysis.

The five main elements as displayed in Figure 16 below entail sub-elements, which are captured in paragraphs in this chapter. These consists of: (1) the DBFM contract and additional contract requirements, (2) the tender organisation, project organisation, the knowledge base of the maintenance department and the levels of maintenance, (3) interface design and maintain, incentive, BIM-sessions, the knowledge process of maintenance engineering and the focus of the departments over time, (4) activity such as maintenance input and design review and (5) tools such as the trade-of-matrixes and the management system respectively.

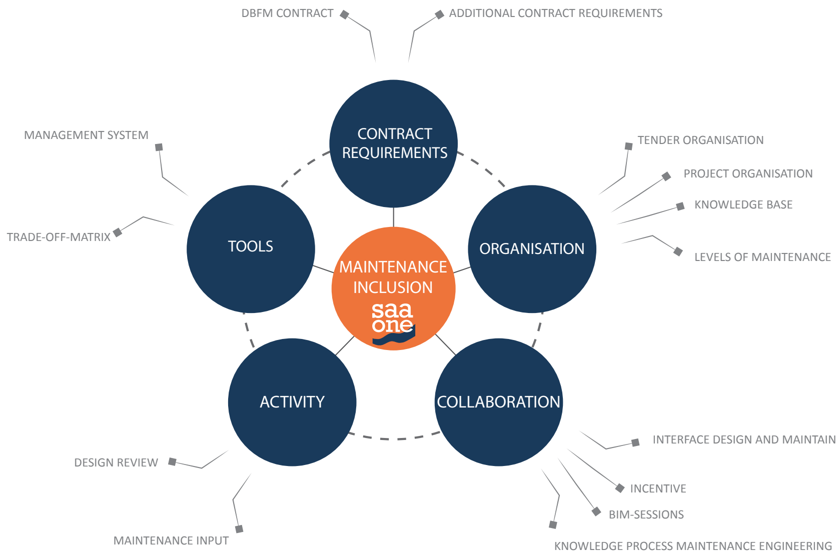

Figure 16: Overview Maintenance Inclusion SAA-ONE

4.2 Contract Requirements

4.2.1 DBFM Contract

The DBFM contract between RWS and the SPC entails (among other elements): key obligations, financing, RWS infrastructure (e.g. design, construct and maintain), transfer, quality assurance, liability and indemnity, changes, insurance, intellectual property rights, indexation, and final provisions (Rijkswaterstaat 2012). Specific information concerning asset specifications, contract requirements, financial specifications, calculation models for VVUs[10], response times, etc. are provided in appendices and annexes to the DBFM contract (Rijkswaterstaat 2012). Interesting for this thesis is the payment mechanism, as it regulates the payments to the contractor throughout the exploitation.

Payment Mechanism

The payment mechanism is linked to so-called VVUs, there is a set amount of VVUs that can be used throughout the contract, namely; 2.725.245 VVUs during construction (55%) and 2.274.955VVUs during exploitation (45%) (see Figure 17). VVUs are an indication for the loss of vehicle hours, which is discussed in more detail in the VVUs paragraph below. The number of VVUs that are to be utilised are divided over the payment periods according to projected requirements and are laid down in appendix 2 annex 5. Payment periods are equal to calendar quarters. There are 116 payments periods in the SAA-ONE contract, 16 of which in the construction phase (4 years) and 100 payment periods in the exploitation phase (25 years) (DBFM Appendix 2 Annex 5 2012).

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[10] VVU stands for Voertuig Verlies Uren in Dutch

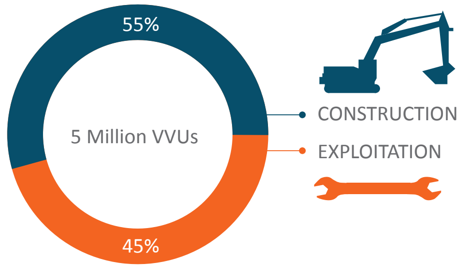

Figure 17:VVUs for Construction and Exploitation phase

The payment mechanism linked to VVUs and performance standards is regarded to be a steering mechanism for quality (Koster and Hoge 2008). Contractors were rewarded if they were able to carry out the construction and maintenance operations throughout the contract. Offering a bid with under 5 million VVUs discount maximally in the Most Economically Advantageous Tender (MEAT[11]) (Contract Coordinator 2013). Bidding under 5 million VVUs limits hindrance to road users and is regarded to be an incentive to include maintenance in the design and an incentive to carry out maintenance efficiently and effectively.

VVUs

The VVUs are an indication for the loss of vehicle hours. It is a unit that measures how much time is lost for vehicles utilising the infrastructure. It encompasses regular and reduced: road capacity, traffic intensity, speed, in relation to section

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[11] Most Economically Advantageous Tender is known as Economisch Meest Voordelige Inschrijving (EMVI) in Dutch

length that causes hindrance, time of day, and the time required to take a detour. The calculation of VVUs can be found in DBFM Appendix 2 Annex 4 (2012). The specific calculations are outside the scope of this thesis, the general formula for calculating the VVUs is captured in the following formula: $VVU=VVU_{queue}+VVU_{measure}+VVU_{detour}$

Payment Scheme

Since this contract is a DBFM contract, the contractor finances the construction of the assets. After the completion certificate is issued, RWS pays a one-time payment (Koster and Hoge 2008) of €200.000.000 (two hundred million) to the contractor. Throughout the contract, pays the contractor based on availability (Garsse, Muyter et al. 2009). This is called 'Gross Availability Payments' (GAP) and are to the value of €12.167.250 per payment period (DBFM Appendix 2 2012).

Calculating Net Availability Payments

In order to calculate the Net Availability payments (NAP[12]) in the exploitation phase, the Availability Correction (AC[13]) and a Performance Discount (PD[14]) have to be subtracted from the gross availability payments. This is captured in the following formula: $NAP=GAP-AC-PD$

Calculating the AC is explained below, the calculation of PD is provided in Appendix D (paragraph 1.1). If the availability correction and the performance discount together are worth more than the period's gross availability payment, the total correction is spread out over several payment periods. As a result, the client has a claim on all calculated corrections (DBFM Appendix 2 2012).

Availability Correction (AC)

The availability correction is calculated by adding Availability Discount (AD) for preventive measures and AD for corrective measures. This is captured in the following formula: $AC=AD_{pr}+AD_{cr}$.

Availability Discount for Preventive Measures

This availability discount is calculated (see formula below) by multiplying the amount of VVUs required for finishing the work by a set value. After which the predetermined maximum VVUs for that payment period times the set value are subtracted from that amount. Preventive measures have a value of 15€/VVU. The value per preventive VVU and the maximum amount of VVUs per payment period are laid down in the contract. The minimum value of AD_{pr} is by definition zero ($AD_{pr}>0$) (DBFM Appendix 2 2012).

$$AD_{pr}=(€15*VVU)-(€15*VVU_{max})$$

Availability Discount for Corrective Measures

This availability discount is calculated (see formula below) by multiplying the amount of VVUs required for finishing the work by a set value. Corrective

[12] Net Availability Payment is freely translated from Netto Beschikbaarheidsvergoeding

[13] Availability Correction is freely translated from Beschikbaarheidscorrectie

[14] Performance Discount is freely translated from Prestatiekorting

measures have a value of 25€/VVU. The availability discount for corrective measures is captured in the following formula: AD_{cr}=(€25*VVU)

As a result, the Availability Correction is zero if and only if less preventive maintenance is carried out than the agreed amount of maintenance VVUs ($VVUs_{pr}$<VVU_{max}), and if no corrective maintenance is carried out (VVU_{cr} is zero). Otherwise, a correction is calculated, which is subtracted from the gross availability payments (DBFM Appendix 2 2012).

4.2.2 Additional Contract Requirements

As mentioned before, the EPCm contract is extended by the incorporation of additional contract requirements. They consist of: Special Design Requirements and Special Work Requirements. The SDRs are incorporated to ensure the maintainability of assets in the long term in the design (Mobley 2008). Also, they aim at ensuring that the design ensures that future maintenance interventions limit the effect on the VVUs and that maintenance actions are carried out within the limits of the VVUs. In addition, the SDRs are regarded to be a document that governs the interface between the design and maintenance department (Interview 1)

The SWRs are added to ensure that the assets are constructed according to the set specifications for the long-term maintainability (Mobley 2008). The SDRs are the focus of the additional contract requirements in this thesis, as these consist of design requirements.

The maintenance department produced the SDRs through surveying the maintenance experts. SDRs generally consist of elements concerning the quality, controllability and maintainability of elements (Mobley 2008). It covers geotechnical elements, pavement requirements, properties for quality control, drainage requirements, system requirements and routine maintenance requirements.

When assessing the SDRs in more detail (see Appendix D, paragraph 1.2), it becomes clear that the SDRs entail a wide variety of requirements. From an overall perspective, there does not seem to be a guiding principle as to how these requirements are set up. Some are specific and detailed requirements as to how thick the top layer of the asphalt needs to be. Others indicate the importance of existing contract requirements, some prescribe performance standards for new and existing systems, resulting in some ambiguous, superfluous and some clear and measureable SDRs (either specific or functional). Measuring how to comply or verify these requirements is not specified in the SDR document.

The aim of the SDRs is not part of the document and they are not linked to the maintenance strategy. As a result, the aim of certain SDRs is unclear (Interview 5, 8).

However, there is no structure as to how to produce a comprehensive list. Nor is there a structure as to how to extract these requirements from operational assets (Interview 6). Hence, the comprehensiveness of these requirements is dependent on the experience of maintenance engineers and on readily available knowledge of important issues. Since there is no form of maintenance requirements database or no manner in which these requirements can be complemented with new insights when the project progresses, there is little certainty as to how comprehensive these requirements are. There are no verification plans incorporated in these documents, which leads to discussion as to how to verify (Interview 6, 10). There has not been a decision as to produce these requirements specifically or functionally. This strongly influences the risk distribution between the SPC and the EPCm. The more functional (specifying performance) the requirements are, the less risk to the SPC. The more specific the requirement, the more risk to the SPC (see Figure 18) (Interview 6).

Therefore, it is essential to decide whether performance or specific requirements are laid down in the contract. Specifying functional or performance requirements offers more flexibility throughout the contract, as no contractual change is necessary when applying different methods or materials and there is room for optimisation throughout the contract (Interview 1, 6).

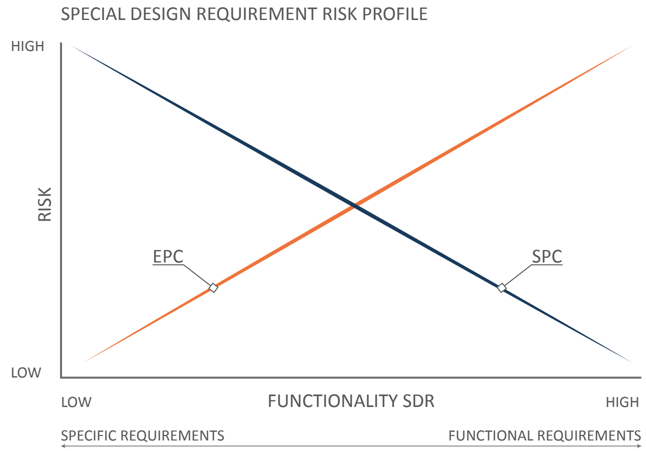

Figure 18:SDR risk Profile for SPC and EPCm

4.3 Organisation

4.3.1 Tender Organisation

The tender organisation consisted of several working groups, namely: design & construct, and maintenance engineering groups. The organisation of the design and maintenance team was set up non-hierarchically in a functional organisation. The working groups had the same 'power' to influence the decision-making in the design. Maintenance engineers were on the same hierarchical level as the design and construct engineers. However, the number of maintenance personnel is much smaller than the design staff, which tips the scale in favour of the design team in decision-making (see Figure 19) (Interview 1).

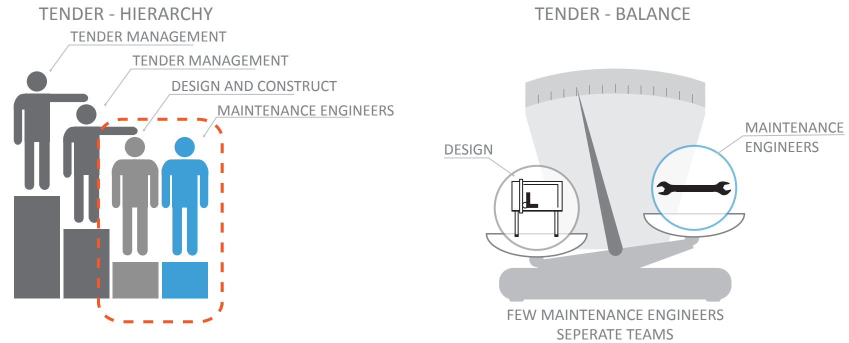

Figure 19: Tender Organisation

4.3.2 Project Organisation

The project organisation of SAAONE from contract closure to delivery is displayed in Figure 20. On the top is the SPC, under which the EPCm is placed. After completion of the construction, the maintenance company will take over the project from the EPCm.

The overview displays that the SPC has an agreement with the EPCm, which consists of three people that represent Boskalis, VolkerWessels and Hochtief. These companies form the consortium. There are two EPCm project directors (Boskalis and VolkerWessels) and one EPC manager (Hochtief). The project director from Boskalis is responsible for general management, the project director from VolkerWessels is responsible for the design, realisation and for the maintenance (upkeep) of the project up to delivery. The EPC manager (Hochtief) is responsible for staff functions such as contract management, stakeholder management, calculations, finance & control and safety.

What can be seen from the organisation chart is that the organisation is functional in nature. There is a relation between design and maintenance through the role design review in the maintenance department. Maintenance expertise is fed back to the design department through design reviews, which is discussed in more detail in the second section.

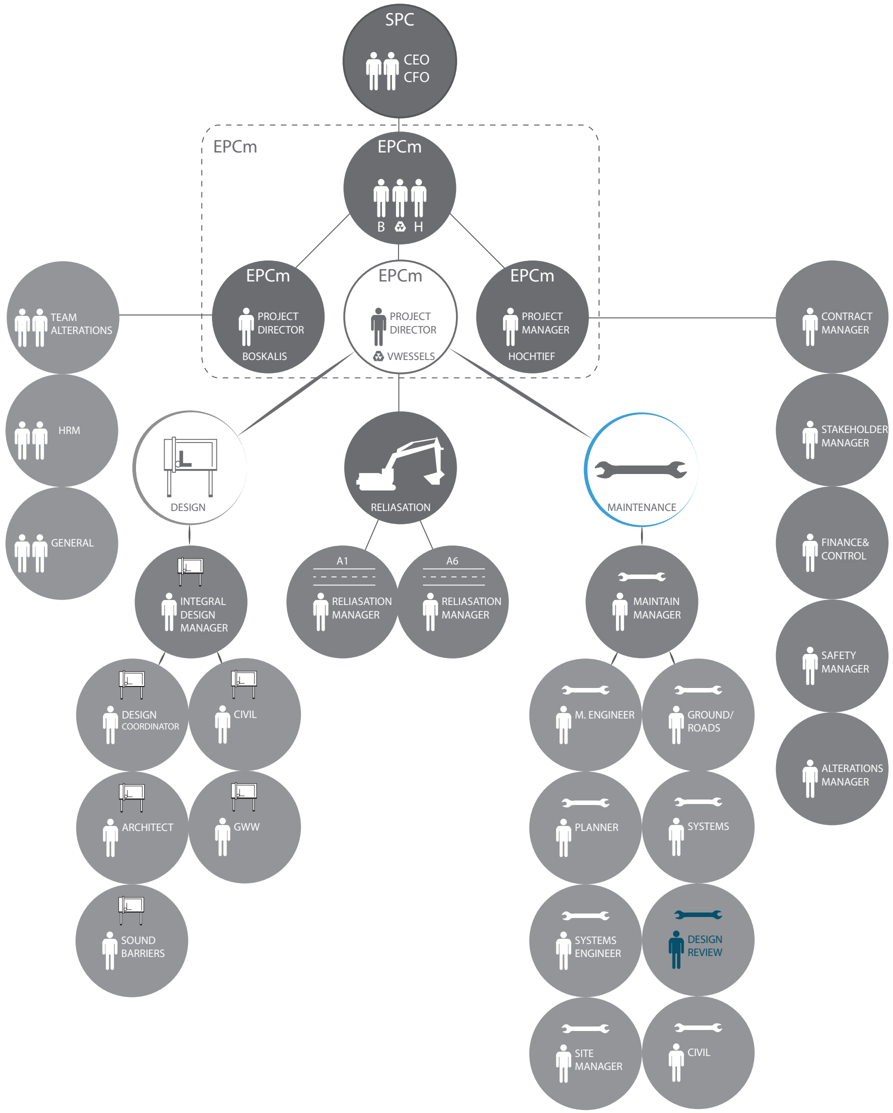

Figure 20: Project Organisation SAAONE, adapted from internal documentation SAA-ONE

4.3.3 Knowledge Base

This paragraph assesses the composition of the maintenance department during the conceptual design and detailed design phase. The maintenance department consist of 13 people; a maintenance manager, tactical employees, operational employees and support staff. The composition of the department is shown in Figure 21 below.

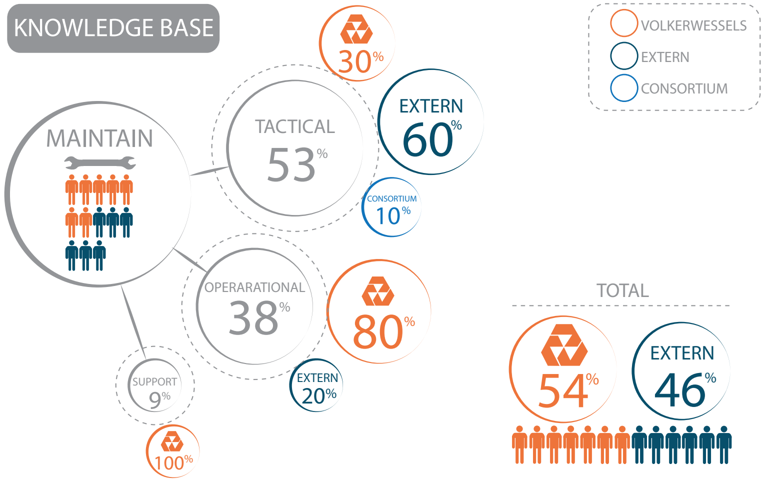

Figure 21: Composition Maintenance Department (observation)

As can be seen in the figure, the largest percentage of the maintenance staff (53%) is tactical maintenance personnel, 38% of the staff is operational and 9% is support. In total, VolkerWessels' companies employ 54% of the maintenance staff and 46% is extern. The planner (tactical staff) working for the consortium company Hochtief falls under 'extern' personnel in the 'total' overview.

The tactical staff comprises of 60% of externally hired personnel, only 30 % of the people are employed by VolkerWessels' companies and 10% is employed by Hochtief (consortium). Operational staff comprises of 80% of VolkerWessels' personnel, while only 20% is extern. The support staff (9%) is employed by VolkerWessels (Observation).

4.3.4 Levels of Maintenance

The level on which maintenance is recognised as important is on the operational and tactical level. However, it should be considered on the strategic level (Parida and Kumar 2009; Too 2010). Corporate strategies should be the basis for the maintenance strategy and have to be translated to tactical and operational objectives (Parida 2006).

4.4 Collaboration

4.4.1 Interface design and maintain

When observing the current modus operandi in the maintenance department, various people from the design department make enquiries into maintenance related matters. When such a situation occurs, it is unclear who from the maintenance department should handle the issue and who bears responsibility for it. It seems that issues that have arisen pose challenges and result in extra work. As a result, the issue is redirected to someone else. No structural action is taken to take note of such issues, identify the background of or the frequency of issues (Observation). The collaboration between the two departments mainly depends on individuals making an effort to find one another, which can be typified as bottom-up collaboration (Interview 3).

4.4.2 Incentive

The VVUs for preventive measures that are laid down in DBFM Appendix 2 Annex 5 (2012) are an incentive for the contractor to carry out all work preventively and within the set periods. Carrying out work correctively costs 25€ per VVU and carrying out preventive work outside the set amount of VVUs per payment period costs 15€ per VVU. As a result, executing more preventive work than planned or carrying out work correctively (because it fails to perform satisfactorily during exploitation) has a direct effect on the availability payments to the contractor. Therefore, there is a 'contract incentive' for maintenance to be carefully planned, incorporated into the design to minimise the effect on VVUs and penalties (Koster and Hoge 2008). Budgets need to be aligned accordingly and corrective maintenance needs to be prevented as much as possible. However, the departments have their own responsibility, focus and budgets (Interview 3, 5). They are responsible for the design and construction of assets according to the contract. However, the contract sets the minimum quality standards and does not involve maintenance considerations that could be beneficial in the long-term (Interview 3). There is little 'internal incentive' for these focus groups to spend additional money in the front-end, in order for the maintenance company to save money during exploitation.

4.4.3 BIM Sessions

The fourth method of controlling the maintenance requirements of assets is through so-called BIM session, which is one of the 'interface meetings' (Interview 5). Such meetings are categorised and are organised weekly in order for multiple disciplines to meet and to present their views on asset designs. Generally, someone within one of the groups of expertise presents their views on the state of affaires and the involved disciplines are provided with the possibility to discuss designs. The meeting minutes are produced and uploaded to the project database 'Thinkproject'. When issues are identified, a person is assigned to a task that is to be completed before the next meeting (Interview 10).

4.4.4 Knowledge Process Maintenance Engineering

This section assesses the knowledge process during the tender to get an understanding how maintenance issues are identified and handled. It provides insight into how experts collaborate, communicate and how knowledge is exchanged and retained. This is captured in the Figure 22 below.

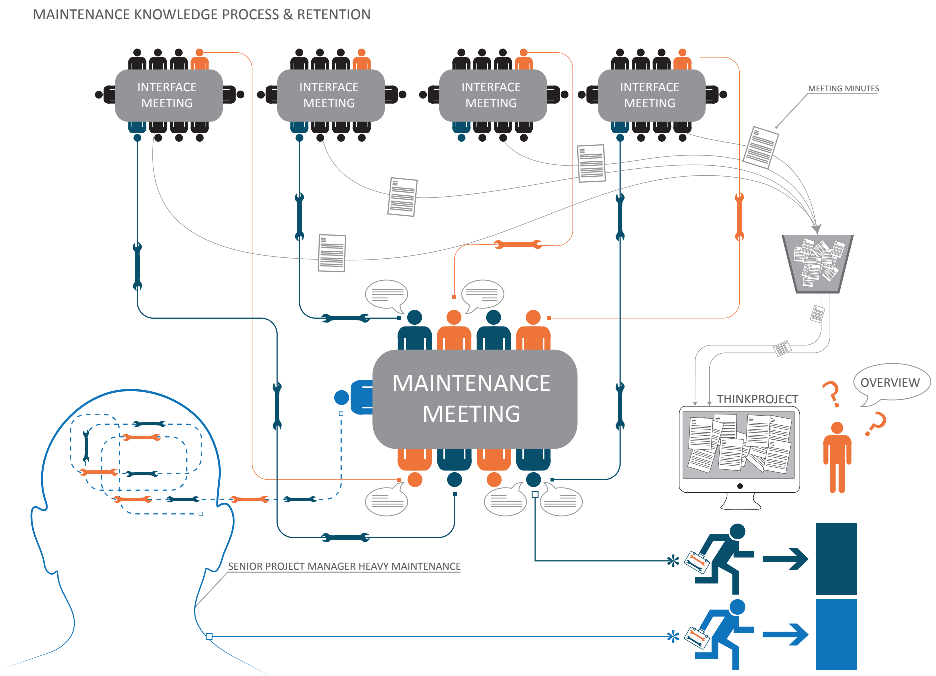

Figure 22: Knowledge Process Tender Phase

On the top of the figure can be seen that there are various meeting in which experts of various departments meet to discuss for instance design and maintenance related topics. The orange (VolkerWessels) and blue persons (extern) indicate that the maintenance staff consists for roughly 50% of external hires, as discussed in the maintenance department paragraph 4.3.3. After such meetings, minute meetings are produced, which are captured in the project database platform Thinkproject. Also, general maintenance meetings are organised in order for the maintenance team to be up to date on maintenance issues throughout the project.

The senior project manager heavy maintenance is up to date on all the maintenance issues (Interview 1). The minutes from these maintenance meetings are captured in the database. However, most staff members are not able to find documents in the database (Observation). So most information that is used in the project is tacit knowledge (Jashapara 2011). No effort is made to make that information explicit or to get insight into the discussed topics. There is no overview concerning all the information that is put onto the database. Only the senior project manager has the overview of returning maintenance issues, who is employed by Hochtief. If the project is finished (or even before), the project manager leaves for another project and the knowledge is not retained within VolkerWessels. Also, if the external maintenance experts leave for other projects, the knowledge is not retained within the project or within VolkerWessels.

4.5 Activity

4.5.1 Maintenance Input

This section assesses what the relation is of the ways in which maintenance is incorporated in the SAA-ONE project. Therefore, an overview is provided in Figure 23 (below). This figure interrelates the types of contract requirements (DBFM and SDRs) and links it to the activity of reviewing designs.

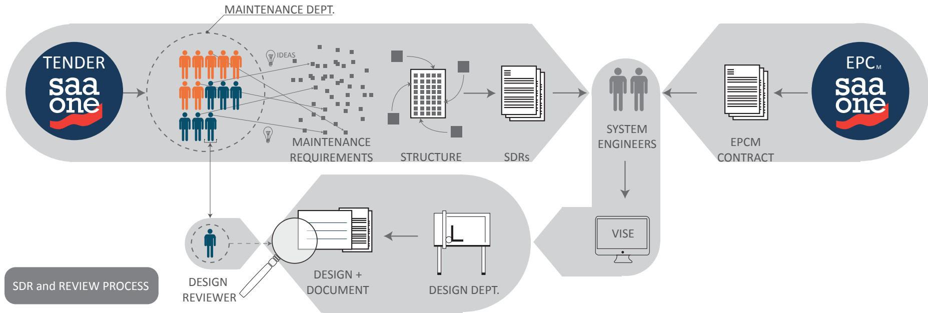

Figure 23: Relation EPCm & SDR/SWR requirements and design review

In the upper left hand corner can be seen that the maintenance department is part of the SAA-ONE consortium, as it falls under the SAA-ONE tender organisation. In order to ensure the long-term maintainability of assets; the maintenance department identified maintenance requirements for the design and construction of assets (Mobley 2008). These requirements are produced in the tender by surveying the maintenance engineers and are based on experience and expert judgement. Every 'discipline' produced their requirements without any specific framework or system. The somewhat 'random' collection of requirements is displayed as unevenly distributed dots in the figure. These requirements are put into a written document, after which they are structured into a matrix and several rounds of review are carried out and feedback is incorporated. That results in a structured matrix of 49 Special Design Requirements. This document is provided to the System Engineers (SEs).

In the upper right hand of the diagram, the EPCm is displayed that forwards the 'EPCm contract' to the System Engineers. Requirements are deduced from the contract, coupled to objects and incorporated in VISE.

From the left and the right in the figure, the System Engineers are provided with the SDRs and the EPCm contract respectively. SEs analyse all requirements and incorporate them into system requirements. These requirements are put into the software programme VolkerInfra SystemsEngineering (VISE).

The design department produces asset designs in compliance with all requirements in VISE (EPCm contract requirements and SDRs).

One of the staff members of the design department has the role of design reviewer. That person checks and coordinates checks for compliance with the SDRs in the design documents. SDRs are the starting point for maintenance input and the basis for the design reviews.

4.5.2 Design Reviews

The maintenance department appointed a design review coordinator. That person reviews designs based on the SDRs and SWRs and coordinates design reviews within the maintenance department. This review process is carried out within the online platform 'Thinkproject'. The platform facilitates the sharing of documents and drawings with multiple 'disciplines' for consideration and comments can be made. There are three review rounds before a concept drawing becomes final. This process is carried out in conceptual design, detailed design and final design. When the maintenance department reviews the design, files such as drawings, design reports and verification reports are sent to the review coordinator. The coordinator either carries out the review or that particular aspect is put forward to a specialist ME (Interview 4). The review process is displayed in Figure 24.

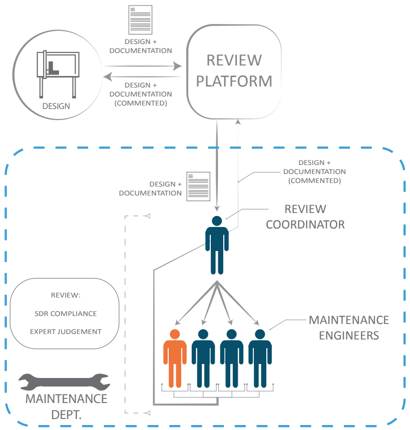

Figure 24: Review Process

The review coordinator comments on the documents and sends them back to the responsible design leader in 'Thinkproject'. When the design is reviewed by all disciplines, the design department can start to process the comments. The design department either makes design alterations or disagrees with the comments made by the maintenance department. No feedback is provided as to how comments are processed, unless the design leader does not regard the comments to be: 'best for project'. Then, the design leader is supposed to contact the maintenance department and find a solution (Interview 5). The handling of comments is based on trust (Interview 10). When vital aspects are to be taken under consideration or budget issues arise, the maintenance manager and the integral design manager are involved (Design Reviewer 2013)

4.6 Tools

4.6.1 Trade-Off-Matrixes

The fifth manner in which maintenance considerations are incorporated in the design is through the development of Trade-off-Matrixes. These are weighted models in excel in various design options are considered. Some models are mostly based on qualitative information and offer limited life-cycle calculations (observation). The aim of such a Trade-off-Matrix is to identify the cheapest solution over the lifetime of that asset (Takata, Kirnura et al. 2004).

Various TOMs are analysed for this thesis, which are different in nature. One of the models is quantitative in nature, while the other is mostly qualitative in nature with solely an indication of the operation costs. The quantitative model assesses the lighting systems for the aqueduct and is based on added numbers for acquisition and operation costs, which are not discounted to today's values. The time value of money is ignored, which results in ambiguous results (Korpi and Ala-Risku 2006).

The assessment of a son-t lighting system versus a led system is captured in a Total Cost of Ownership (TCO) model, which differs from an LCC calculation (Korpi and Ala-Risku 2006) and is based on added numbers. Interesting to note is that the overall cost of acquiring the system, operating it, and replacing necessary elements indicates that led is cheaper over the exploitation phase of

25 years. However, when utilising the same numbers to calculate a Net Present Value (Taylor 1981), the result is that son-t system is less costly. The exact opposite result is obtained (see Appendix D, paragraph 1.4). Hence, when following the outcome of the TCO model, that decision is based on oversimplified calculations. The awareness of the life-cycle of assets is present, however, the skills required to calculate an NPV correctly is absent.

4.6.2 SAA-ONE Management System

This section assesses how the management system works and how it guides the staff in their operations. The 'Project Management System' (ProMaSys), generally referred to as management system, of SAAONE is a dedicated version of the general VolkerInfra ProMaSys. For the purpose of this study, the relation between the design and maintenance department is assessed in the system. These departments fall under the EPCm; the design and maintain processes are captured and put under so-called EPCM primary processes. In total there are 12 main processes, which are numbered from PRO 1 to PRO 12. Design processes fall under PRO 10 and maintain processes fall under PRO 12. These are assessed in the following paragraphs. The aim is to what extent the system provides guidance in carrying out the steps that are defined in the system.

PRO 10 – Design Process

From an overall perspective, the design process consists of six main steps:

1. Design Management (PRO 10.1)
2. Functional Analysis (PRO 10.2)
3. System Analysis (PRO 10.3)
4. Concept Design (PRO 10.4)
5. Detailed Design (PRO 10.5)
6. Final Design (PRO 10.6)

In the first three processes, no apparent link with maintenance is incorporated in the process. These processes cover the work that is carried out prior to doing design work. PRO 10.4 and PRO 10.5 are discussed in the following paragraphs. PRO 10.6, which covers the final design stage for construction drawings falls outside the scope of this thesis.

The process figures display the process steps vertically. Boxes on the left side of process steps indicate inputs; boxes on the right side of process steps indicate outputs. Both the inputs and the outputs (on either side of the process steps) are related to elements on the side to; ISO norms, SAA-ONE results, KSF, documents, or VISE applications. These are displayed on the left and right hand side of the figures.

ISO is a norm that covers the process to manage projects, it consists of activities, results and goals; the project has to be carried out in compliance with these norms.

SAA-ONE results indicated in the management system are elements that were indicated as important by people from the company. These elements are translated into results and coupled to outputs in the management system. The client does not request these results, nor is the company audited on these aspects.

KSF's stands for Critical Success Factors[15], which is a translation of the projects vision and strategy into results that are coupled to output.

Documents consist of files that are coupled to the management system for ease of use. Staff can utilise these files to produce the required output. And VISE application is the software programme; Volker Wessels Systems Engineering. No templates are produced and coupled to the management system. It is up to the people working with the system to produce results they seem fit, or they coordinate that with their direct managers (Interview 9)

PRO 10.4 captures the conceptual design as partly displayed in Figure 25. It is a 7-step process that ranges from a-to-g. The following sub processes are highlighted due to their link with maintenance processes and cover the following elements:

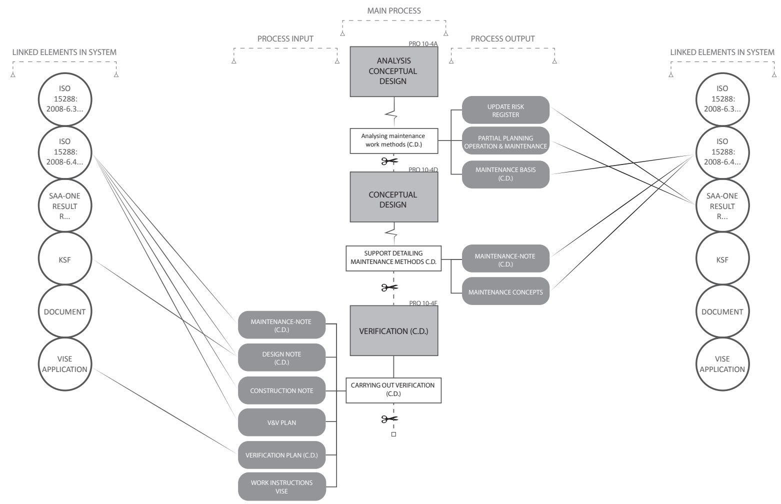

Figure 25: PRO 10.4, adapted from (SAA-ONE 2013)

Observations PRO 10.4

The linkages of the process steps are to ISO norms, to SAA-ONE Results, to KSF's and one link to VISE. Little instructions are provided as to how to carry out the tasks, some descriptions of the aim of the tasks are present. However, these are general in nature and open to interpretation.

In PRO 10.5, the detailed design is captured in the same 7-step process that ranges from a-to-g. The couplings with the varying elements in the management system are displayed in Figure 26 below. Coupling with maintenance can be found in the process steps a.3, b.1, d.2, d.4, 2.5, f.3, f.6, and g.2. Only a selection is displayed as these capture the unique couplings within the programme.

[15] Critical Success Factors is freely translated from Kritieke Succes Factoren (KSF)

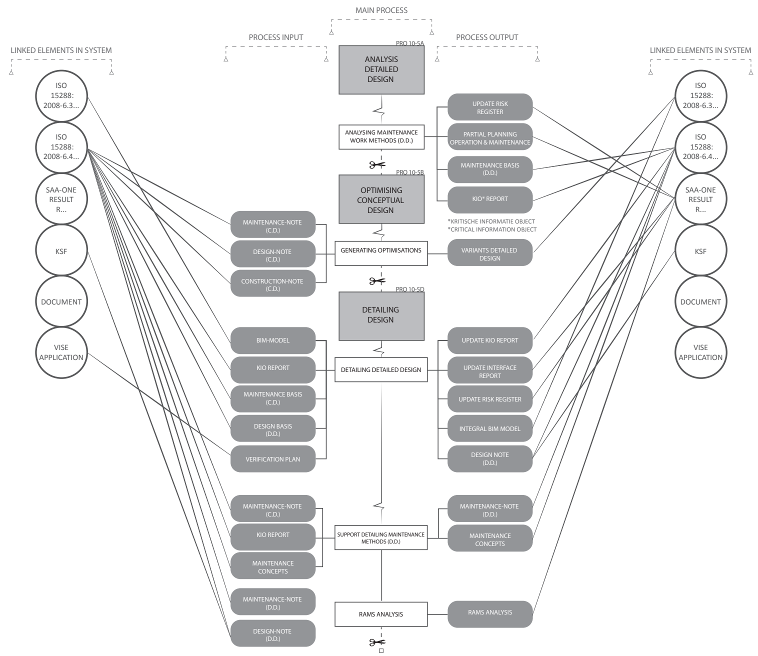

Figure 26: PRO 10.5, adapted from (SAA-ONE 2013)

Observations PRO 10.5

The linkages of the process steps are to ISO norms, to SAA-ONE Results, to KSF's and one link to VISE. Little instructions are provided as to how to carry out the tasks, some descriptions of the aim of the tasks are present. However, these are general in nature and open to interpretation.

PRO 12 – Maintenance processes

From an overall perspective, the process consists of six main steps:

1. Managing maintenance (PRO 12.1)
2. Mobilisation (PRO 12.2)
3. Maintenance Engineering (PRO 12.3)
4. Maintenance (GAO[16]&TAO[17]) (PRO 12.4)
5. Checking the state of the asset (PRO 12.5)
6. Failures, Damages and Incidents (SAO[18]) (PRO 12.6)

The first two processes cover starting up the project for the maintenance department. The third process (PRO 12.3) covers the input for the design of the asset, which is the focal point of this paragraph. The last three process cover the operational phase of maintaining the asset after the asset is handed to the contractor (between handover to contractor and delivery).

The third process is analysed with a focus on 12.3.A because it covers the incorporation of maintenance in the design phase. PRO 12.3 consists of three main processes:

a) Design Input
b) Maintenance Management
c) Evaluation Asset Performance

[16] GAO=Gebruiksafhankelijk Onderhoud

[17] TAO=Toestandsafhankelijk Onderhoud

[18] SAO=Storingsafhankelijk Onderhoud

The process of design input (PRO-12.3.a) is displayed in Figure 27 below.

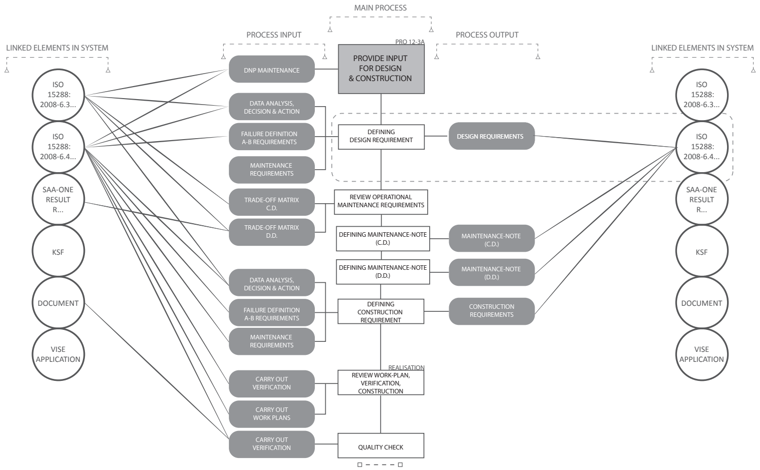

Figure 27: PRO 12.3.A, adapted from (SAA-ONE 2013)

Observations PRO 12.3.A

The linkages of the process steps are to ISO norms, to SAA-ONE Results, and one link to a document. Little to none instructions are provided as to how to carry out the tasks, some descriptions of the aim of the tasks are present. However, these are general in nature and open to interpretation.

4.7 Case Summary

When assessing the overall set-up of the project for the inclusion of maintenance in the design, various actions are taken to incorporate maintenance in the design of the project. These consist of: (1) contract requirements, (2) organisation, (3) collaboration, (4) activities, and (5) tools. These are displayed in Figure 28 below.

Figure 28: Overview Maintenance Inclusion SAA-ONE

From an overall perspective, maintenance is comprehensively incorporated through various channels and the workflow is guided by the SAA-ONE management system (ProMaSys).

However, when zooming in on the various aspects, it becomes apparent that some elements are in place but in a basic state. And that collaborating integrally proves to be challenging.

4.7.1 Contract requirements

The DBFM contract covers all elements that have to be realised by the contractor (Eversdijk, Beek et al. 2008). The contract entails specific requirements that aim at constructing assets of a certain quality, requirements that ensure the maintainability of the assets in the long term and requirements that specify that contractor shortcomings that lead to penalty points (Garsse, Muyter et al. 2009). This contract is forwarded to the EPCm (back-to-back) (Garsse, Muyter et al. 2009) and additional contract requirements (SDRs & SWRs) are incorporated to ensure the long-term maintainability (Mobley 2008).

The contractor finances the project and is incentivised by the client to deliver the asset on time by the one-time payment of 200 million (Koster and Hoge 2008). This large sum of money (one-time-payment) could shift the focus of the EPCm more towards constructing an asset on-time as opposed to the long-term objectives. This hampers the continuous incorporation of maintenance considerations and limits the added quality of the design and the performance of assets throughout the contract (Interview 5).

During the exploitation phase, the contractor receives availability payments (PWC 2012) per calendar quarter, which is linked to requirements such as asset quality, safety, the utilisation of a quality management system, and penalty points. Non-compliance directly reduces availability payments to the contractor (Rijkswaterstaat 2012). Furthermore, the availability payments are reduced if the contractor does not carry out the work within the predetermined preventive maintenance VVUs. Payments are also reduced if the contractor has to carry out corrective maintenance work (DBFM Appendix 2 2012). Linking the planning of maintenance, the hindrance to road users, and the level of quality of assets to the payment mechanism is regarded to be a steering mechanism for quality (Garsse, Muyter et al. 2009). There is no incentive to carry out fewer maintenance actions than the predetermined VVUs. Contractors were awarded with a discount on the bid price in the Most Economically Advantageous Tender when they were able to carry out all the work in fewer than 5 million VVUs.

Checking for contract compliance through VISE requirements proves to be challenging, as there is no consensus as to how to carry out the verification (Interview 10). For instance, maintenance experts produce requirements, system engineers process them into the programme, the designers design assets and produce verification plans. However, the people working on the verification are not the people who produced the requirements, which can lead to ambiguity and interpretation errors.

In order to make sure that the level of maintainability and reliability is realised (Mobley 2008) in order for the availability payments to be reduced as little as possible, additional maintenance requirements (SDRs and SWRs) are produced in the tender phase. These documents are contractually binding between the SPC and the EPCm.

4.7.2 Organisation

SAA-ONE Tender Organisation

Due to the functional and non-hierarchical setup of the tender organisation, the design and maintenance experts were able to influence the decision-making concerning the design of assets. However, the number of design staff is so much larger that it is challenging for the maintenance experts to incorporate the necessary knowledge into the project from a capacity perspective and due to the relatively small power to influence the design. Moreover, the division of the teams and the separate budgets lead to fragmentation (Interview 7) in the project. Several design options clearly favour the budget of the design and construct department. Also, some design issues are not even recognised as issues that involve maintenance expertise. As a result, maintenance experts are not involved in those matters (Interview 1).

Such behaviour stems from the fact that DBFM contracts are relatively new, the designers that have experience under D&C contracts are not used to involving maintenance (Interview 1). Decisions are generally based on 'best for design and construct' and not on 'best for project'.

SAA-ONE Project Organisation

Based on observing the organisation chart and the composition of departments in the project company, the design department and maintenance department are separate 'teams' with separate goals. Maintenance expertise is centralised in a maintenance department. Hence, the maintenance experts are physically detached from the designers. Therefore, collaborating integrally is challenging. Cooperation hinges on understanding the goals and constraints of others

(Morieux 2011). Designers, in some cases, proceed with the asset design without considering maintenance, as it is not their focal point (Interview 1). Appointing a design reviewer leads to a better incorporation of maintenance considerations, however, in a reactive manner and based on ambiguous additional requirements.

Knowledge Base Maintenance Department

When assessing the composition of maintenance department, it becomes clear that most of the resources are dedicated to the tactical aspects of maintenance (53%). This furthers the incorporation of maintenance in the project (Too 2010). However, it also becomes apparent that almost 50% of the total department consists of external hires. More specifically, 60% of the tactical staff is external and most VolkerWessels staff is operational (observation).

Tactical knowledge and expertise is vital for the inclusion of maintenance considerations (Sarfi and Tao 2004; Too 2010) in DBFM projects. VolkerWessels has experience aplenty in operating assets, however, the in-house tactical expertise is limited. Knowledge retention proves to be challenging in such projects (Interview 6, 7, 11). Much of the expert knowledge leaves the project when the external hires leave the project (Interview 10).

4.7.3 Collaboration

Interface design and maintain

There is little structure as to how to handle questions from other departments and no structure to manage the interface between the two departments. People make enquiries, while it seems that the maintenance department does not have a complete overview as to how to act (observation). As a result, in some situations it remains unclear who should take responsibility for some issues or what action should be taken to find a solution. Posed questions result in extra work, and staff are not inclined to take on an extra workload. Hence, certain maintenance related issues remain unsolved.

Furthermore, no attempts are made to log the arisen issues in order to acquire a complete overview of maintenance issues or the frequencies of returning issues. An opportunity to acquire full insight into issues that the maintenance department faces is forgone (observation).

Incentive

The contract and its payment mechanism is an incentive to ensure that availability payments are maximised, which is referred to as 'contract incentive'. Therefore, incorporating maintenance is important. However, the project is separated into objects. As a result, teams and budgets are divided per object. This leads to fragmentation (Interview 3, 7, 11). The people working on an object are incentivised to make their deadlines and to keep within budget. However, spending more in the front-end can lead to savings later on in the project (Flanagan, Norman et al. 1989). Making such trade-offs is limited. There is a lack of 'internal incentive' to collaborate and make trade-offs that are best for project over the life-cycle.

BIM sessions

The handling of the input and output of interface meetings such as the BIM-sessions depends wholly on the representatives of the departments and disciplines. When issues are identified and action is taken, the related or responsible people will meet in order to find a solution to the problem. There is no protocol or logging system as to what to propose or how to take further action when maintenance requirements need further consideration. Hence, the situation can very well arise that maintenance issues are identified in the meetings and no further action is taken.

Knowledge Process

When various experts meet in meetings, the sharing of knowledge is done verbally and meeting minutes are provided. The minutes are put into the database; however, interviewees indicate that it proves to be challenging to find the required documents in the database. The training for the staff to work with the platform is "due to success" still provided in the final design phase. The success in this case means that people remain to find it difficult to work with the system. Furthermore, the information that is put into the system is not filtered; lessons learned, reappearing issues, key problems remain unidentified. This limits the ability to learn from the project or to use that knowledge in future projects. The composition of all the maintenance staff is that 50% is external. Since the retention of knowledge is limited, the knowledge brought into on the project leaves when that person leaves.

Focus of Departments over Time

Over the course of the project, the perception and the focus of the project teams and the departments change. During the tender there the focus is on the long term on an optimal solution. After the project is won and the budgets are divided the project becomes more fragmented (Interview 3, 11). The organisation divided the teams in departments, which underlines the fragmentation. With the division of departments and budgets, the focus changes to the short term (Interview 7). The design department is more focussed on designing assets that are in compliance with the set requirements. The maintenance department is more focussed on the mobilisation for the maintenance obligation and on the planning of the 40 days of VVU free maintenance. On top of that, the maintenance department was understaffed (Interview 3, 5), which rendered it difficult to incorporate maintenance in the design. The maintenance department was not able to meet the demands of the design department (Interview 5). The shifting focus of the different departments is displayed in Figure 29 below.

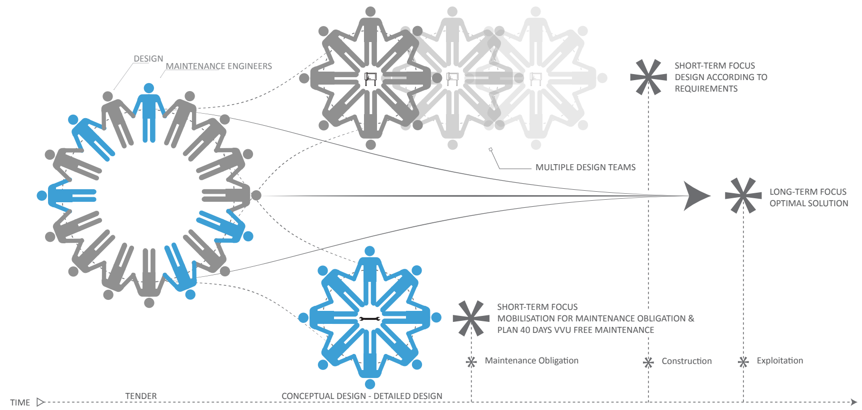

Figure 29: Shift of Focus over Time

4.7.4 Activity

Design Reviews

The design reviews aim at identifying whether produced designs are made according to DBFM contract requirements and the predefined additional contract requirements (SDRs). Furthermore, the design review coordinator and subsequently the maintenance engineers have their expert view. This system functions satisfactorily if the SDRs are comprehensive, accurate, and verifiable. However, the comprehensiveness, accuracy and verifiability of a selection of SDRs are limited (Interview 5, 7). Furthermore, there is generally little consensus as to how to verify design requirements and special design requirements (Interview 10). Therefore, checking on compliance with ambiguous SDRs is challenging and leads to discussion in the project. The focus of the design team is to design assets according to the predefined requirements (Interview 5), which renders the SDRs important. The decision is made not to provide feedback after comments are made on the documents within the platform 'Thinkproject'. The advantage is that there is no risk of having an endless loop of providing feedback to each other (Interview 4). The drawback is that the design department has the final say in how the comments on maintainability are processed and the handling of comments is based on trust (Interview 10). The level of influence the maintenance department has on the design of assets is limited.

4.7.5 Tools

The tool that is utilised in the project to identify what solution is more beneficial in the long-term consists of Trade-Off-Matrixes. Some are on a qualitative and some are on a quantitative basis. The qualitative analysis solely includes an indication of the cost implication for the long-term. The quantitative analysis is only based on added numbers and not on the net present value of the cost. The result of adding the numbers indicates that option (b) is the cheaper solution over the contract period and the net present value indicates the opposite; option (a) is favourable. This proves the importance of making such calculations accurately.

From the Management System, it becomes apparent that maintenance and design are linked. Various outputs of the maintenance department serve as inputs for the design department through outputs such as the maintenance note for both the conceptual design and detailed design. As can be seen in Figure 27, most process steps are linked to ISO norms, some process steps have are linked to results, which were an aid in developing the management system. It entails that elements deemed important by staff are ensured through linking it to output in the management system. One process step is linked to a document.

There are generally no guidelines as to what is expected from these process steps and what results are required. Some descriptions are present, however, they are general and open to interpretation.

For instance, how the design requirements from a maintenance perspective can be set up is unspecified when assessing the management system, as can be seen in the dotted line around this process step in Figure 27. As a result, the maintenance department is not supported by the management system when defining system requirements that will be contractually binding to the design department. The input and output is dependent on the engineers, the added value of the management system in providing guidance to employees is limited. The staff of the maintenance department indicate that they do not use the management system regularly in their daily work (Interview 3, 5). The process steps are in place, however, the management system provides little to no guidance as to how to carry out the work.

COMPARISON
DISCUSSION
CONCLUSION

5 Comparison

This chapter entails a comparison between the SAA-ONE case with SAA-GA and SAA-ONE with A-Lanes. The comparison is made on the five main elements for the inclusion of maintenance in the design of assets that are researched in the SAA-ONE case, which is the main case. These five elements are displayed in Figure 30 below. The number of interviews held in the SAA-GA and A-Lanes project is limited in comparison to SAA-ONE. Therefore, the comparison is made between the cases SAA-GA and SAA-ONE, and A-Lanes and SAA-ONE. No cross comparison is made between SAA-GA and A-Lanes.

Figure 30: Five Levels of Maintenance Inclusion

5.1 Contract Requirements

The general contract requirements are similar to the SAA-ONE project, as all projects are DBFM projects. The standard DBFM template is adapted to the different projects (Rijkswaterstaat 2012). Therefore, the payment mechanism is similar in nature. The 'contract incentive' is similar, as payment is dependent on asset performance. All projects employ some form of additional contract requirements to ensure the long-term maintainability of assets (Mobley 2008). Both Volkerwessels' projects use Special Design Requirements that are produced during the tender.

SAA-GA

The scale of SAA-GA project is smaller in comparison to SAA-ONE. The amount of VVUs that are rewarded maximally in the MEAT is 1.2 million (Interview 14), as opposed to 5 million in SAA-ONE. Based on the number of VVUs, the project is four times smaller. In order to ensure the long-term maintainability of assets (Mobley 2008), several special design requirements are produced.

The SAA-GA project is still in the tender phase and SDRs are still produced. Issues that are discussed by designers and maintenance engineers can result in producing SDRs. However, the additional requirements are generally produced by maintenance engineers and not in collaboration with designers. When the SDRs are added to the DBFM contract and 'imposed' on designers, they are obliged to comply with the SDRs. Currently, a concept version of SDRs is produced and is presented internally to the EPC. However, no feedback is provided so far (Interview 15). This process seems to have similarities to SAA-ONE. People work on SDRs and they have to be implemented internally. However, people do not seem to foresee the magnitude of the SDRs. This is similar to SAA-ONE, as it results in ambiguities and discussions later in the design phase. As a result, little seems to be learned from the challenges the SDRs posed and remain to pose in SAA-ONE.

A-Lanes

The scale of this project is similar to SAA-ONE. The amount of VVUs that are utilised over the contract is 5 million. Based on the number of VVUs, the project is similar to SAA-ONE. A great difference in comparison to SAA-ONE is the manner in which construction work or maintenance work is carried out. That is solely to be done during nights in the A-Lanes project. Furthermore, there are no restrictions to the number of nights that are utilised during construction (Interview 16). The availability payments that are linked to VVUs are only applicable in the exploitation phase (Interview 17), while in SAA-ONE there is a clear distinction in the VVUs that are to be used during construction and exploitation.

During the project, several additional contract requirements are produced. Implementing these requirements is challenging, as it generally requires spending additional money on design and construction in the front-end to save money in the exploitation phase. As a result, the EPC has to spend more in order for the M-Co to save money. Due to the strained budgets of the EPC in the construction phase, this trade-off between the EPC and the M-Co is very limited. Several maintenance requirements cannot be incorporated in the design and have to be realised during exploitation (Interview 16). The setting up of additional contract requirements is not carried out systematically; most of the SDRs are produced ad-hoc when maintenance issues are identified by MEs that have to be incorporated in the design. Other issues are identified in meetings between designers and MEs and a solution is found and formulated into an additional requirement. Some issues are identified, discussed and a solution is found. Such issues are not covered in additional requirements. As a result, the list of additional requirements is incomprehensive and somewhat ambiguous (Interview 17). Furthermore, the design leader of roads indicated that the impact of these requirements is very limited. These requirements do not surface when designing roads (Interview 18). The setting up of requirements in A-Lanes has been ad-hoc and no attempt is made to survey MEs to identify key issues as was the case in SAA-ONE. The maintenance team was surveyed for key issues and several rounds of reviews were organised to make the SDRs 'as smart as possible'. Also, the requirements are not added to the back-to-back contract, as is the case in SAA-ONE.

5.2 Organisation

The organisation of SAA-GA can only be considered for the tender, the A-Lanes organisation is assessed for its current state, which is the project organisation.

SAA-GA

The tender organisation of SAA-GA is a matrix organisation, as opposed to the functional organisation of SAA-ONE. The design and engineering of the main elements in the project, such as the 'land-tunnel' are captured vertically in functions in the matrix. Maintenance engineers connect horizontally to these functions. The benefit is that the maintenance engineers are not centralised in a separate function and people are to work more integrally. However, the drawback is that there is little clarity as to which issues the MEs are to be involved in and how to handle decisions that affect design and construction budgets. There seems to be little clarity as to how design decisions relating the inclusion of maintenance in the design of assets are made and who in the organisation is aware of such decisions (Interview 15). Some discussions between designers and MEs seem to be settled and a decision is reached. However, the same decision can be made again or can be changed over time. Furthermore, the roles and responsibilities of the people in the organisation are not completely clear (Interview 13, 15). The functional organisation of SAA-ONE provided more clarity, as the interface between design and maintenance was more clear (Interview 14).

The knowledge base of this project is not assessed as thoroughly as in SAA-ONE, however, it is estimated to consist of 50-60% of external hires (Interview 13), in SAA-ONE this percentage is assessed for the maintenance department and consists of almost 50% of external hires. The level on which maintenance is recognised as important is on the tactical level. Similar to SAA-ONE, maintenance is not yet on the strategic agenda of the project.

A-Lanes

The project organisation differs from the SAA-ONE project organisation. In SAA-ONE, all functions fall under the EPCm. In the A-Lanes project, the different functions: roads, civil, systems, tunnels and the Botlek-Bridge are separate joint ventures under the EPCm (Interview 17). Maintenance engineering is a separate department that connects to these functions. The benefit is that maintenance engineering knowledge is centralised (Interview 16). The drawback is that the joint ventures are responsible for the design and construction of the assets. They have their own goals and budgets (Interview 17). This set-up limits the incorporation of maintenance in design of the assets, as incorporating maintenance considerations generally requires spending additional money on the design and construction of assets. The knowledge base is not assessed in this project. The level on which maintenance is recognised as important is on the tactical level. Similar to SAA-ONE, maintenance is not yet on the strategic agenda of the project (Interview 16, 17, 18).

5.3 Collaboration

The manner in which the designers collaborate with maintenance experts in SAA-GA and A-Lanes is compared to SAA-ONE.

SAA-GA

The collaboration between design and maintenance engineers can be typified as bottom-up collaboration. The issues that are discussed depend on individuals (Interview 13). Little collaboration is facilitated top-down by higher management. Structural meetings between design and maintenance experts are introduced from the lower levels within the organisation (Interview 13).

Maintenance considerations for systems in the land-tunnel are integrated into the design, mainly due to the impact on the overall costs of the maintenance on the lifetime (Interview 13). Issues where maintenance issues have a less direct affect on costs, if there is no financial gain for design budgets, or where the maintenance considerations are less clear, the maintenance considerations are incorporated less incomprehensively in the design of assets (Interview 15). This is similar to the SAA-ONE project, wherein little maintenance considerations are incorporated when there is no clear financial gain for the design and construction budgets.

A-Lanes

The collaboration between design and maintenance engineers can be typified as bottom-up and ad-hoc collaboration (Interview 18). This is similar to SAA-ONE, however, the collaboration in SAA-ONE is more structured and facilitated in regular 'interface meetings'. As mentioned, the financial situation of the EPC of A-Lanes limits the comprehensive incorporation of maintenance considerations in the design.

5.4 Activity

The types of activities such as maintenance input and design review as researched in SAA-ONE are compared to SAA-GA in the tender and for A-Lanes during the project.

SAA-GA

As mentioned above, Special Design Requirements are produced, which are a means to ensure that maintenance considerations are incorporated in the design. These requirements are generally the result of meetings between design specialists and maintenance experts and the outcome is specified in requirements. This is similar to the manner in which SDRs were initially produced in SAA-ONE, as MEs identified key maintenance issues through incorporating maintenance issues in a central document (Interview 15).

Design reviews are currently not carried out, however, there are steps taken to ensure that there will be a design review coordinator when the tender is won. This is done through incorporating a design review coordinator in the organisation diagram for the project organisation (Interview 15). This review coordinator is already in place in the SAA-ONE project organisation.

A-Lanes

As mentioned above, several additional requirements were produced in the project and several are still produced (Interview 17). The contractual status of these requirements is unclear. They are not added to the back-to-back contract, as is the case in SAA-ONE. Furthermore, the maintenance department reviews the designs, several issues are then identified and solutions are sought (Interview 16). However, the basis for the design reviews is unclear. The designs in SAA-ONE are reviewed based on the list of SDRs and on 'expert judgement'. Furthermore, maintenance input in the design is provided in the trade-off-matrixes, which are discussed in the 'tools' paragraph below.

5.5 Tools

The tools that are utilised in the project are assessed. The management system is not part of the comparison, as it is not yet implemented in SAA-GA and it is not accessible at the A-Lanes project.

SAA-GA

The tool that is utilised to arrive at a decision is a trade-off-matrix. These TOMs are generally employed to support the decision-making process (Interview 13).

No specific matrixes are assessed in this research. The utilisation of TOMs is similar to the utilisation of them in SAA-ONE.

A-Lanes

Similar tools are used in the A-Lanes project. The TOMs are produced in a template. The TOMs utilise quantitative and qualitative information to arrive at decisions (Interview 18). The time value of money is incorporated in the matrix (Interview 17). However, it is not clear how that is done, as there is solely one possibility to indicate the 'timing' of costs, while the costs for this specific TOM occur monthly over the complete contract period. It becomes clear that the TOMs are utilised as an indication of actual costs to support the decision-making. However, the TOMs are in some cases highly subjective and used to support a preferable decision (Interview 18). The TOMs in SAA-ONE do not seem to be based on a template. They are dependent on the individuals producing them (observation). The quantitative and qualitative basis for the TOMs in A-Lanes is similar in nature to the basis for TOMs in SAA-ONE.

5.6 Summary

SAA-GA

From an overall perspective, SAA-GA bears similarities to SAA-ONE. Several differences are identified such as the organisation structure of the tender organisation. Little indications are found as to how the project learned from SAA-ONE, apart from the tacit knowledge that people acquired when working on SAA-ONE and taking that knowledge to SAA-GA when working for both projects. Furthermore, the comparison is limited in depth as the project is in the tender phase and much is still to be decided. Also, the organisation structure for the project, the DBFM contract requirements and activities such as the design review are not yet in place in the tender phase.

A-Lanes

The A-Lanes project bears resemblance to the SAA-ONE project on the scale of the project based on assessing VVUs throughout the complete contract. However, the manner in which maintenance is incorporated seems less structured than the way in which it is considered in SAA-ONE. Most collaboration and the providing of input from maintenance engineers to designers are ad-hoc and bottom up (Interview 18). However, the research substantiating these findings is limited. The interviewees indicated that it is difficult to make trade-offs that result in a the EPC spending more in order for the M-CO to save money during exploitation, as the construction company is currently going over budget. Therefore, spending extra now to save later is not a viable option (Interview 16). The vertical split of the project into various joint ventures with their separate budgets leads to a fragmented focus throughout the project. As a result, integrating maintenance considerations in the design of assets is limited (Interview 17).

6 Discussion

6.1 Infra in comparison to various industries

In existing literature on the inclusion of maintenance considerations in the design of assets, various elements are indicated to be important to consider. These are captured in the key factor checklist in the literature study. Several elements that are used in the industries can be applied to the infrastructure industry as they can further the incorporation of maintenance in the design of assets under DBFM contracts. The elements that are applicable to the infra sector are discussed below.

Explicit asset knowledge in the infra is limited. Therefore, maximising assets knowledge, which is vital in the space industry (Perrons and Richards 2013) can be an aid to further incorporate maintenance in the design of infra projects. The maintenance departments in the projects determine the maintenance strategy. However, literature on capital intensive manufacturing companies indicate that maintenance objectives are to be deduced from the corporate strategy and that maintenance objectives are to be prioritised top-down in the organisation (Van Horenbeek and Pintelon 2013). Furthermore, literature on the space industry indicates that the number of unique service tasks through component commonality and modularity can increase maintenance efficiency (Perrons and Richards 2013). This can be further applied and developed in the infra sector. Various industries such as manufacturing and the process industry indicate that the continuous measuring, monitoring, controlling of maintenance is essential (Tan, Matzen et al. 2010). This data is to be transformed into calculable documents and serves as input in the design (Hwang, Tien et al. 2007). Furthermore, the manufacturing industry points out that focusing on four elements furthers the development of designing assets that are easily maintained. These consist of: (1) incorporating maintenance requirements in an early stage in the design, (2) providing maintenance engineers and managers with power to influence the design, (3) focus on life-cycle cost and not on initial investments, and (4) focusing on maintenance considerations as opposed to asset features. These elements need further attention in the infra sector. The literature on manufacturing indicates that matrixes are to be used to evaluate design alternatives (Tan, Matzen et al. 2010). This is currently incorporated in the Trade-Off Matrixes. The focus of these matrixes could be on maintenance costs, task duration, part costs, diagnosis time, technician requirements (training) and part availability, as indicated by Tan, Matzen et al. (2010)

In order for asset designs to be based on reliability, availability, serviceability, usability and installability in the design, the following elements need further consideration: (1) adapt the organisation to work towards a mutual goal and (2) translate TCO to engineering deliverables, effective knowledge management, LCC tools and skills, and the identification of potential deterioration of assets over time. Also, an information system is indicated by the petrochemical industry as vital to maximise asset performance. Such a system enables maintenance engineers to provide input to design by collecting, storing and analysing data of asset performance through monitoring asset and fault detection (Hwang, Tien et al. 2007).

6.2 Managerial Implications

In order to be able to carry out future DBFM projects integrally with a focus on the incorporation of maintenance; several managerial implications are to be considered. These are considered on the five levels on which the case study is based, namely: contract requirements, organisation, collaboration, activity and tools.

6.2.1 Contract Requirements

Additional Contract Requirements

In order to be able to make sure that design and construction work is carried out as it is decided in the front-end of the project, additional requirements to the DBFM contract should be produced. These consist not solely of sound requirements from a maintenance perspective; they have to be aligned with the project aims. The requirements have to be 'best for project', they maximise asset performance and are based on life-cycle costs.

These project corporate aims have to be coupled to knowledge aims. The key knowledge concerning design and maintenance that are linked to asset performance and maintenance requirements are to be shared between designers and maintenance engineers. Issues that are identified as important factors that influence life-cycle costs and asset performance have to be captured in additional requirements. These requirements should be produced in collaboration with designers and maintenance engineers. No requirements are enforced upon the design team. As a result of the collaboration and the sharing of knowledge concerning design and maintenance, more innovative solutions can be found and implemented. The key issues that are incorporated in the additional requirements are to be stored on a knowledge platform for the application in future projects. Such requirements can be produced to describe functional (performance) requirements, describe specific requirements or eliminate certain design options.

Important is to produce these requirements systematically and comprehensively. In order to do so, the development of key asset knowledge is important. Such knowledge consists of initial costs, construction costs, exploitation costs, asset performance and asset deterioration. Such knowledge can be developed through the monitoring of DBFM projects and projects under maintenance contracts under VolkerWessels.

After information is gathered, it can be analysed and the projection of the life-cycle cost and the maintenance strategy can be evaluated and compared to the actual situation. It can then become clear whether decisions taken in the front-end resulted in life-cycle benefits. If the benefits are clear, this information can function as best practice that can be implemented in future projects.

In producing such requirements, the directors of the SPC and EPCm have to agree on distributing the risk between the companies. Therefore, the type of requirements that are produced and adopted is of importance. The more specific the requirements are, the more risk is to the SPC and vice versa (Interview 6). The more functional the requirements, the more difficult it is to verify compliance (Interview 1). However, more functional requirements leave room for optimisations throughout the contract.

In order to further the development of SDRs for future use, the following points are important to take into account.

- Increasing key knowledge of assets and systems
- Making a clear distinction between specific requirements and functional requirements
- Smart functional performance requirements (reducing ambiguity)
- Smart specific requirements (what should be built, how should it be built)
- Relating SDRs to the aim of the requirement through the specification of “the spirit of the law” (reduce ambiguity and interpretation errors)
- Relating functional performance and specific requirements to verification plans.
- Relating all SDRs to maintenance requirements
- Relating all SDRs to maintenance strategy
- Relating All SDRs to A or B requirements (direct relation to availability discounts)
- Focus on requirements that are not already in the DBFM contract
- Create a standalone document for ease of use
- Continually update the SDR document for future use through the incorporations of lessons learned from operational assets

6.2.2 Organisation

The design team and the maintenance team have to collaborate intensively from the outset in order to be able to share key knowledge related to the design and asset performance over the life-cycle. The structure of the organisation can partly facilitate the collaboration. The vertical division of design and maintenance into separate teams and subsequently into departments with their own budgets leads to fragmentation. Fragmentation hinders integral collaboration. The project aims are to realise assets at the lowest life-cycle costs. However, dividing the projects into objects and assigning design teams to it with their own budget leads to a focus on that budget, which is on the short term. Trade-offs between design and maintenance experts in order to realise the lowest life-cycle costs are then limited. Therefore, such vertical divisions between design and tactical maintenance in the organisation need to be minimised as much as possible. This can be accomplished through implementing an organisation structure in which the management of the design department not solely consists of design managers but also of maintenance managers and engineers for the incorporation of strategic and tactical maintenance considerations respectively. The maintenance engineers are specifically hired to incorporate maintenance considerations in the design through the sharing of maintenance knowledge related to asset performance, maintenance requirements, maintenance costs with design managers and designers to be able to make life-cycle cost calculations including initial costs and develop maintenance strategies.

These maintenance engineers have the required skillset, knowledge, and experience to be able to ensure that key maintenance issues are considered in the design of assets. They have to be able to carry out life-cycle calculations correctly in order to evaluate design decisions over the life-cycle of assets (Taylor 1981). The collaboration between designers and maintenance engineers should be facilitated by an integrator such as an LCC coordinator who is able to support the execution of accurate life-cycle cost calculations in order for 'best for project' decisions to be made over the life-cycle of assets (Woodward 1997).

The team of tactical maintenance engineers is physically detached from the maintenance department that focuses on exploitation. The vertical split is then between operational maintenance staff and tactical and strategic maintenance staff. As a result, there is no split between the design department and the maintenance department. Meetings between these two groups of maintenance personnel enables for knowledge to be shared (Nonaka 1994) and for operational knowledge to be applied in the design (see Figure 31).

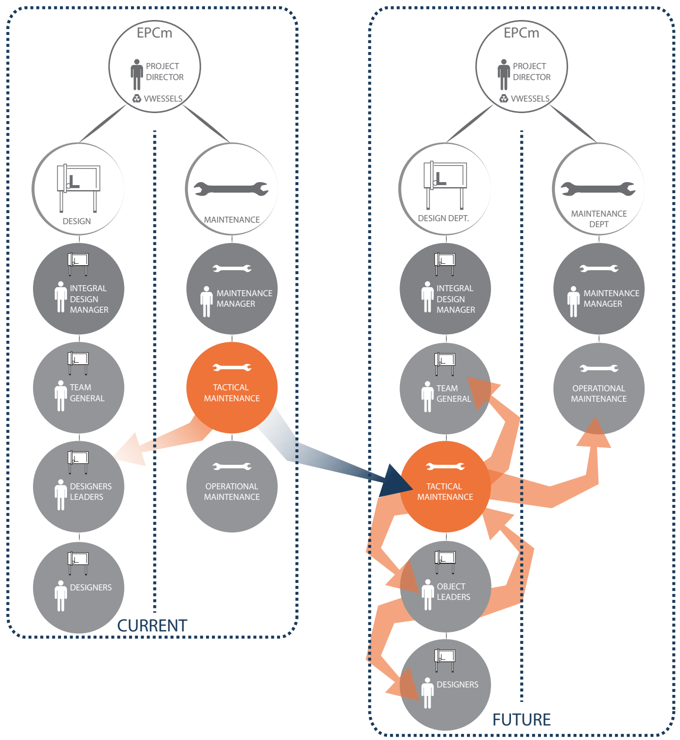

Figure 31: Current and Future Organisation

Important to note is the capacity of this team of maintenance engineers, the peak in capacity is likely to materialise towards the end of the tender and in the conceptual design phase. This needs to be anticipated in time. The number of team members can be adjusted over time to meet the workload.

Currently, maintenance is considered on the operational and tactical level. In order to further the development of the incorporation of maintenance, it should be managed more from a strategic perspective (Parida 2006; Too 2010). Maintenance needs to be on the strategic agenda of the project and linked to the project aims. Maintenance has to be managed top-down while stimulating bottom up initiatives (see Figure 32).

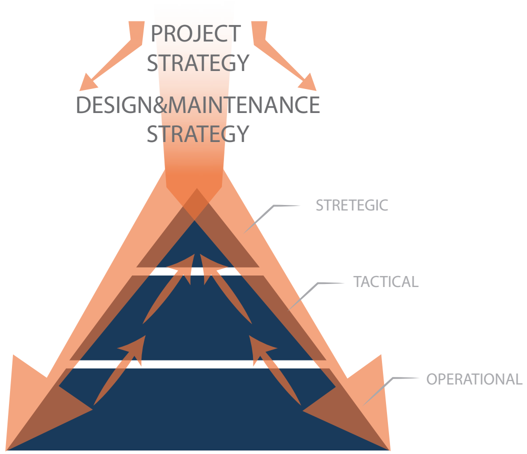

Figure 32: Levels of Maintenance

6.2.3 Collaboration

The incorporation of maintenance depends on collaboration between design teams and maintenance engineers. The people from both teams have to know one another on a personal level (Interview 12) and work towards a mutual goal. The collaboration between design and maintenance experts needs to be facilitated by an integrator (Morieux 2011). The integrator is someone who understands both worlds (design and maintenance) and has time available to bring these two worlds together (Morieux 2011). This integrator replaces the function of design leader by the role of object leader. In order to incentivise the complete team to incorporate maintenance and life-cycle considerations in the design of the assets, an 'internal incentive' to collaborate is required. Designers should not solely consider realising assets according to contract requirements (Amadi-Echendu, Willett et al. 2010). An 'internal incentive' can be realised by enlarging the shadow of the future (Bruijn and Heuvelhof 2008; Morieux 2011) through extending the budget responsibilities of object leaders. They become responsible for the life-cycle budget of objects. Decisions are based on 'best for project' considerations over the complete life-cycle (Garsse, Muyter et al. 2009).

DBFM contracts span decades and object leaders will move to other projects before the project is completed. However, the object leaders have responsibility over life-cycle budgets and they are incentivised to incorporate life-cycle considerations in decision-making.

In order to be able to let the people collaborate more intensively, they have to understand what their co-workers are working on, what their goals and constraints are (Morieux 2011). Therefore, the awareness of the contract and its characteristics (payment mechanism, penalty points, maintenance obligation, etc.) has to be increased (Interview 6).

This requires an understanding of the fact that the amount of maintenance work required (VVUs) is directly linked to the bid price as it is rewarded in the MEAT. The payment of the company depends on asset performance (Koster and Hoge 2008). Carrying out maintenance is coupled to the VVU model, carrying out more preventive maintenance than expected, or carrying out maintenance correctively reduces the quarterly payments from the client to the company. Therefore, the design team needs to take heed of the importance of considering these aspects in the front end of the project (Flanagan, Norman et al. 1989). Through training and workshops, people in the project organisation can be familiarised with this type of contracts and its characteristics.

Strategy

The project aims of the project company needs to be clear to all the staff. Important to consider is how to operationalize that strategy into a comprehensive design and maintenance strategy (Parida 2006). It should be clear that if the strategy is to realise the assets 'as cheap as possible' over the complete life-cycle, that comprehensive life-cycle costs considerations are to be incorporated in the design. This strategy should be linked to knowledge aims. It has to be clear what knowledge is to be developed, what is to be shared and what is to be applied in the projects.

6.2.4 Activity

Monitoring

The information pertaining to the cost implications of certain options in the design is of vital importance in designing assets for the long term (Perrons and Richards 2013). Maintenance engineers in the design management need such information in order to make informed decisions. Therefore, key asset knowledge is to be developed through the monitoring of: asset performance, maintenance performance (Van Horenbeek and Pintelon 2013), cost monitoring (initial and exploitation) throughout DBFM projects as well as the monitoring of similar infrastructural maintenance projects under VolkerInfra is important. Storing that information and making that explicit, calculable and accessible can function as a sound basis for the provision of accurate input for LCC analysis in future projects (Jonker and Haarman 2006). As a result, data becomes available and more refined over time, key maintenance issues can be identified, and the decision-making concerning the incorporation of long-term maintenance becomes more informed and more strategic (Sarfi and Tao 2004). Developing and storing key asset knowledge pertaining to the performance of assets and affiliated costs over time is costly. However, applying such knowledge in the design can result in life-cycle cost reductions and the better performance leads to the maximisation of availability payments. Furthermore, the better incorporation of maintenance considerations in the design can lead to more advantageous tender offers.

6.2.5 Tools

Learning and knowledge retention

Furthermore, an effort has to be made to collect data in order to learn from the projects that are carried out. Specifically, an evaluation of the performance of assets has to be made. The projections of life-cycle costs and the maintenance strategy have to be compared to the actual situation. Evaluating this can further the decision-making in future projects and best practices can be deduced from operational assets. Such knowledge is to be shared with VolkerWessels' design and maintenance companies. Utilising a database or web-based application in which documents are more easily findable, quicker to use, dynamic and more user friendly allows for knowledge to be stored and shared.

Trough training, workshops and the sharing of this information online on a more social platform or a wiki could facilitate this process. Such a tool is not the solution to the problem; the most vital part is the implementation of it, to familiarise the people with it.

Through the utilisation of the platform, evaluation of operational assets and adjusting files throughout projects, the information remains up to date. It is important to note that the writers, editors, and the management need to agree on the exact goal of this platform. Such a system allows people to get involved, which result in invaluable insights, suggestions and solutions that contribute to better project outcomes. Hence, people need to be educated as to how to utilise this system as early as possible. Such a system needs to be tested before it can be implemented in projects.

6.3 Limitations of this Research

This research carried out for the master programme Construction Management and Engineering at the TU-Delft in collaboration with van Hattum en Blankevoort (VolkerWessels) has its limitations. The most important are summarised below.

Firstly, the character of this research is explorative in nature, which limits the substantiation of the qualitative information with quantitative data. Furthermore, the main source of information is through interviewing employees, which can be affected by the perception of interviewees and the possibility that suggestive questions are asked throughout the interviews. Therefore, the conclusions of this thesis are to be regarded an indication of how maintenance is currently incorporated in DBFM projects. However, due to the checking of findings with several key informants, the findings seem to have been deduced correctly from the varying sources. Concluding how maintenance is to be incorporated comprehensively in the design DBFM projects is nearly impossible as it affects so many functional fields in the project organisation and is rooted in the corporations in the joint ventures. Therefore, further research is required.

Secondly, the representativeness of the cases that are selected is questionable. Three cases are selected and researched of which one is a main case, and the two other cases merely function to check the findings of the main case. However, the main case (SAA-ONE) is in its design phase nearing the construction phase, while SAA-GA is in the tender phase. These two cases cannot be compared adequately as many people from the SAA-ONE tender have moved on to other projects, which limits the possibility to compare both tenders. Comparing the project phase of SAA-ONE to the tender of SAA-GA is debatable. During the tender, many decisions are still not taken and structures are not in place. Moreover, the number of interviewees in the SAA-GA project is substantially smaller than the number of interviewees in the SAA-ONE project. Several interviewees worked for both SAA-ONE and SAA-GA, which can lead to a biased view on the inclusion of maintenance in the projects.

Comparing SAA-ONE to A-lanes is not entirely representative as VolkerWessels is not part of the A-lanes consortium. This limits the accessibility for the researcher as the research is carried out in collaboration with VolkerWessels. However, the findings in A-Lanes substantiate the findings in SAA-ONE. These two consortia incorporate maintenance in a similar way, which suggests that the findings in these cases could be generalizable to the infrastructure industry.

Thirdly, the strategic behaviour of the interviewees could play a role. There are some contractions in statements in the interviews. People might feel that the research is carried out to assess how people carry out their work in contrast to researching what the current modus operandi is of DBFM project with regard to the inclusion of maintenance.

7 Conclusions

How is maintenance incorporated in projects?

Maintenance is incorporated in the design of DBFM projects through delivering input in the design and through design reviews. Input is delivered through producing additional requirements internally. These requirements are incorporated to ensure the maintainability of assets in the long term in the design (Parida and Kumar 2009). Also, they aim at ensuring that future maintenance interventions limit the effect on the VVUs to maximise availability payment and that maintenance actions are carried out within the limits of the VVUs. In addition, the SDRs are regarded to be a document that governs the interface between the design and maintenance department. Design reviews are carried out to ensure that the additional requirements are incorporated in the design and a possibility is provided for maintenance engineers to provide their expert views on drawings and documents produced by designers.

How is the collaboration between designers and maintenance engineers facilitated in projects?

The collaboration between designer and maintenance engineers is facilitated through organising regular interface meetings. Such meetings consist of BIM sessions in which maintenance engineers meet with designers and engineers to discuss the designs. Maintenance engineers have the possibility to make sure that maintenance issues are incorporated in the design. However, the input and output of interface meetings such as the BIM-sessions depends entirely on the representatives of the departments and disciplines attending these meetings. When issues are identified and action is taken, the related or responsible people will meet in order to find a solution to the problem. There is no protocol or logging system as to what to propose or how to take further action when maintenance requirements need further consideration. Furthermore, no attempts are made to log the arisen issues in order to acquire a complete overview of maintenance issues or the frequencies of returning issues. An opportunity to acquire full insight into key maintenance issues is forgone. Furthermore, the management system is set up in such a way that certain outputs of maintenance are input for design and vice versa.

How are design decisions made?

Design decisions are generally based on Trade-Off Matrixes. These are weighted models in excel in various design options are considered. The models are mostly based on qualitative information and offer limited life-cycle calculations. The aim of such a Trade-off-Matrix is to identify the cheapest solution over the lifetime of that asset (Takata, Kirnura et al. 2004). However, the amount of calculable information and the skills to produce correct calculations based on NPV is limited.

How is the design process currently organised within project companies?

The design process is organised in such a way that maintenance is incorporated on five levels. (1) Designers design assets according to DBFM contract requirements and additional requirements (SDRs). (2) The organisation is set up in such a way that function of design reviewer is incorporated in the organisation. (3) The collaboration between designers and maintenance engineers is facilitated through organising regular interface meetings. (4) The design review coordinator has the 'activity' coordinate the reviewing of designs by the maintenance department. (5) Tools such as the Trade-Off Matrixes are employed to arrive at design decisions and the management system guides designers and maintenance staff to collaborate as their input and output are linked in the workflow.

Main research question

How can maintenance considerations be incorporated comprehensively in design projects under a DBFM contract?

Incorporating maintenance in the design of DBFM assets hinges on the collaboration between design and maintenance experts. This can be realised through increasing the responsibilities of the people in charge of 'objects'. Not only should the object be designed according to contract requirement, it should be designed according to a long-term project strategy, which is closely linked to the maintenance strategy. Subsequently, this strategy should be translated into maintenance objectives on a tactical and subsequently on an operational level (Parida 2006). As a result, maintenance is important and managed adequately on all levels of the project organisation: namely on the strategic, tactical and the operational level.

The function of 'design leader' should be replaced by a role called 'object leader'. Their responsibilities are extended and their budget responsibility is increased. They are responsible for the design budget that affects the construction and for the life-cycle budget of that object. Thereby, the shadow of the future is increased (Morieux 2011) and they are incentivised to make best for project decisions over the complete life-cycle continually as opposed to best for project decisions up to construction. Such decisions can be made from early stages in the project, contributing to life-cycle cost reductions (Flanagan, Norman et al. 1989). The object leader functions as an integrator between designers and maintenance engineers and makes sure that these teams understand each others objectives and constraints in order to make sure that people collaborate and work towards a mutual goal (Morieux 2011).

The team of maintenance engineers have to be part of the design team in order for the maintenance considerations to be incorporated comprehensively in the design. This could be realised through placing tactical maintenance engineers under 'team general', which is a team focussing on ensuring the long-term performance of assets and ensuring the integrality of the project. This team should be headed by a LCC coordinator who supports and facilitates the life-cycle decision-making in the design of assets. Decisions can be made through the utilisation of LCC calculations and TOMs (Interview 1, 3, 12).

When best for project decisions are made, these can be translated into smart Special Design Requirements, thereby focusing on the character of these requirements. These can be set in performance standards or in detailed specifications. The former leaves room for optimisation and innovation, however, they are more challenging to make them smart and there is room for strategic behaviour. The latter leaves no room for optimisations. Collaboration between design and maintenance experts can lead to more optimal solutions than one party imposing requirements. When such requirements become contractual binding documents, it is important to collaborate with a legal advisor as to how to ensure that these requirements are not open to interpretation.

In order to contribute to the comprehensive incorporation of maintenance considerations and more informed decision-making, more knowledge needs to be developed e.g. knowledge relating to the performance of assets, degradation, initial costs, exploitation costs, which is essential for more informed life-cycle decision-making needs to be developed. Such knowledge is to be evaluated as to how that relates to the projections of the LCC in the front end of projects. Such knowledge is to be made more explicit in order for it to be on a know what level (Hertog and Huizenga 2005) and stored for future reference (Jashapara 2011).

Also, knowledge should be transferred from tacit knowledge to tacit (among people) and from tacit to explicit (externalisation) to retain more knowledge in the organisation (Nonaka 1994).

For the comprehensive incorporation of maintenance four elements are important: having an integral life-cycle strategy for the project, having ‘internal incentives’ to collaborate, the sharing of knowledge, and the continuous creation of asset knowledge for informed decision-making.

7.1 Recommendations

Having and integral life-cycle strategy

Working towards a mutual goal is important. Therefore, a clear strategy that covers the performance of the asset over the life-cycle is vital. This strategy should be formed on a high level in the organisation (strategic) and should be translated to the lower levels in the organisation and is to be operationalized into objectives. The objectives are translated into requirements that are to be achieved by integral collaboration. Having a mutual goal diminishes the fragmentation in the project (Interview 7). As a result, more integral best for life-cycle decisions are made as opposed to best for object decisions that focus on design and construction costs.

Having 'internal incentives' to collaborate

Generally, the focus of the designers and construction contractor is on the realisation of the assets (Interview 7). Maintenance is a phase that commences after completion. As a result, maintenance is on the background in the design phase. Therefore, incorporating maintenance in the design is dependent on an incentive to collaborate. The contract and the payment mechanism are an incentive to design assets for the long-term contract duration. However, due to the division of the project into objects, the goals and the budgets become fragmented (Interview 11). On the 'smaller' scale, there is little internal incentive to collaborate with maintenance as the focus is on keeping deadlines and budgets (Interview 7). Maintenance considerations can lead to additional front-end expenditures in order to save money during exploitation. This is not the focus of the design team. Therefore, there is a need to introduce an 'internal incentive' to collaborate. Increasing the budget responsibility of object leaders to life-cycle budgets including exploitation can support the decision-making to be based on best for project decisions over the life-cycle of assets.

The sharing of knowledge

Incorporating maintenance in design is dependent on the sharing of knowledge between designers and maintenance engineers. However, the knowledge is currently mainly tacit and can be characterised as functional knowledge. This type of knowledge is challenging to share. Therefore, the project company is to be organised in such a way that the sharing of knowledge is furthered. For instance by having 'integrators' in the project company, people who understand both processes and are able to connect them. Collaboration hinges on the people understanding each other's goals and constraints, however, the sharing of knowledge can be limited due to strategic behaviour of the partners in the joint venture.

Continuous creation of asset knowledge

The maintenance considerations in assets should be based on data and knowledge of operational assets. Therefore, assets are to be monitored throughout the project. Asset performance can then be compared to the original outset of the project. It can be assessed whether the additional money spent in the front-end did lead to savings during exploitation. This information can be put into evidence and be utilised in future projects. Also, asset performance in maintenance contracts is to be monitored by VolkerWessels. Furthermore, the knowledge of assets should be made explicit and documented into calculable data. Maximising asset knowledge leads to more informed decision-making in the design of assets. Furthermore, attracting more maintenance engineers that work on the strategic and the tactical levels of maintenance furthers the inclusion of maintenance considerations in the design and allows for better knowledge retention.

7.2 Research Implications

This research was explorative and assessed the incorporation of maintenance in the design of assets under DBFM contracts from a broad perspective. The incorporation of comprehensive life-cycle cost calculations is essential in the front-end of projects. However, the implementation is slow (Flanagan, Norman et al. 1989). The collaboration of people hinges on having an incentive to collaborate and increasing the shadow of the future (Morieux 2011). Literature identified that developing asset knowledge is vital for the incorporation of maintenance considerations in the design of assets (Tan, Matzen et al. 2010). Furthermore, maintenance is to be viewed as a value driver (Haarman 2011), incorporated in the front-end of projects (Waeyenbergh and Pintelon 2002) and maintenance is to be managed on all levels of the organisations (Parida 2006; Van Horenbeek and Pintelon 2013). Therefore, several recommendations for further research are to be considered:

- How the collaboration can be furthered between the design and maintenance experts.
- How life-cycle costing can be comprehensively incorporated in the decision-making in the design of assets under DBFM contracts.
- What key asset knowledge is and how that key asset knowledge can be developed, shared, stored, requested and kept up-to-date.
- How project companies can ensure that all that is designed in the front-end of the project is constructed according to the plans.
- How lessons learned from operating assets can be fed-back to designers and maintenance engineers working on the design of future projects.
- How maintenance can be managed strategically in construction projects

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APPENDIXES

9 Appendixes

A. Literature

1.1 Asset Management

According to the Publicly Available Specification (PAS 55) by the British Standards Institution (BSI), asset management is defined as "Systematic & coordinated activities and practices through which an organisation optimally manages its physical assets and their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organisational strategic plan" (Woodhouse 2007).

The definition of AM according to PIARC is: "A systematic approach of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organised and flexible approach to making the decisions necessary to achieve the public's expectations (OECD 2001; Peters and Kamnitzer 2012).

These definitions provide an overview of the domain of asset management. The definitions are different; however, there is similarity between them. It becomes apparent that AM is about optimising return and performance through a systematic business-like approach. It covers all phases of assets' life-cycle and AM is to fulfil a strategic role. The definition provided by Sarfi and Tao (2004) is clear-cut and captures the essence of asset management as it is based on: management: optimising return, scrutinising performance, making key strategic decisions, all phases of an assets life-cycle. Therefore, this definition is used as a reference in this report.

1.2 Common PPP structures

The family of common structures of PPPs consist of the following: Build-Operate-Transfer (BOT), Build-Own-Operate-Transfer (BOOT), Build-Own-Operate (BOO), Turn key, Design-Build-Finance-Maintain-Operate (DBFMO), Design-Build-Finance-Maintain (DBFM), Design-Build-Finance-Operate (DBFO), Design-Construct-Manage-Finance (DCMF), Concession Model and Independent Power Producer (IPP). Each of these contracts have specific characteristics. DBFMO contracts are regarded to be similar to DBFMs, as operation normally includes maintenance (Koster and Hoge 2008; Delmon 2011; Herrala, Pakkala et al. 2011). DBFM is the most common PPP scheme in the Netherlands (Eversdijk, Beek et al. 2008).

1.3 Phases in DBFM contracts

Design

When a company or joint venture engages in a tender, a complete design is to be delivered to the client. When the tender is won, the company details the plans and drawings before construction (of that particular asset) commences. Up to that point, the design is likely to be altered and decisions about the design are made. The design phase is therefore considered to be from the decision that the company will participate in the tender up to construction of that (sub)project.

Build

The construction of projects is executed by private parties in all contracts ranging from traditional models to contracts such as the DBFM model and the like (Garsse, Muyter et al. 2009).

Finance

Project companies can be financed either through Government financing, Corporate financing or Project financing. Government financing refers to governments borrowing money (debt) at low interest rates and lending it to SPVs (debt). However, the fiscal space of governments is generally limited (Delmon 2011). Fiscal space is defined by the difference between the present public debt and the maximum set debt by international bodies or market constraints (Ostry, Ghosh et al. 2010). Corporate financing means that major umbrella contractors (shareholders of SPVs) borrow money (debt) to finance SPVs (investment). Umbrella contractors have a proven credit profile, which is often not the case with SPVs. Project financing means that SPVs directly borrow money (debt) from creditors. These loans are limited recourse debts. Banks rely on the cash-flow of projects for the repayment of these loans (Koster and Hoge 2008; Delmon 2011).

Maintenance

The M-component in DBFM contracts refers to 'maintenance' and physically maintaining assets, which is the operational level of Asset Management. Maintenance normally starts when a contract is won; existing infrastructure is maintained up to replacement, which is the maintenance obligation. If there is no existing infrastructure, maintenance commences after completion of a project or subproject. Furthermore, maintenance is an inherent part of the DBFM contract and it is carried out throughout the duration of the contract. Therefore, maintenance considerations are to be incorporated into the project as a whole and in the organisation on all levels.

1.4 Maintenance Strategies

Predictive Maintenance (Pd.M.), which is also known as condition-based maintenance (CBM) is a strategy that initiates maintenance after a certain level of predetermined deterioration of asset condition or asset performance is reached. PM and Pd.M. are similar in nature, however, they differ in how the maintenance demand is determined. Pd.M. initiates work when there is an absolute necessity as opposed to a predetermined time interval (Ahuja 2009). PM is increasingly used by highway agencies (Lamptey, Labi et al. 2008).

Maintenance Prevention (MP) is a strategy that consists of designing maintenance-free assets. MP aims at ensuring that assets are reliable and easily maintained.

Reliability Centred Maintenance[19] (RCM) is a systematic and cost-effective approach to determine maintenance requirements of assets in the context of operations and preserving the level of system functionality. It focuses on system function as opposed to maintenance operations. RCM involves several

[19] RCM was originally designed for the aircraft industry Waeyenbergh, G. and L. Pintelon (2002). "A framework for maintenance concept development." International Journal of Production Economics **77**(3): 299-313.

elements which are to be determined; the first of which is determining what functions of assets are related to performance requirements. Of these functions, possible events that lead to failures are identified and subsequently their causes and effects. The types of effects are categorised as follows: hidden, safety & environmental, operational and non-operational consequences (Siddiqui and Ben-Daya 2009). In fact, RCM analysis start with a Failure Modes Effects and Criticality Analysis (FMECA) (Waeyenbergh and Pintelon 2002). Next, the categories are prioritised and maintenance tasks are selected and planned to prevent or detect the commencement of failure (Siddiqui and Ben-Daya 2009).

Business Centred Maintenance (BCM) is a maintenance concept that is based on the business objectives that are translated into maintenance objectives. The aim of BCM is to maximise profit as opposed the aim of RCM, which is to maximise reliability (technical performance). BCM is especially suitable for process-related industries (Waeyenbergh and Pintelon 2002)

Productive Maintenance (Pr.M.) is a strategy that reduces the total cost of maintenance over the life-cycle of assets. Key elements are asset maintainability and reliability.

Total Productive Maintenance (TPM) aims at optimising asset effectiveness, while keeping asset available. The objective is to improve productivity, efficiency, quality and safety continually and prevent degradation. It encompasses a complete life-cycle approach and TPM minimises failure. (Mobley 2008; Ahuja 2009). TPM can be divided into three categories: autonomous maintenance, planned or preventive maintenance and maintenance reduction. Autonomous maintenance refers to routine work (cleaning, inspecting, etc). Maintenance reduction refers to incorporating asset's performance in the redesign of next generation assets, which is also known as: 'design for maintenance' (Mobley 2008).

1.5 Building Information Modelling

In the field of Architecture, Engineering and Construction (AEC), many disciplines are involved in the design and construction process in projects. In early stages of projects, tools such as Building Information Modelling (BIM) can be utilised to share knowledge and to support decision-making. It allows various disciplines to assess and simulate asset performance virtually (Flager, Welle et al. 2009). According to the National BIM Standard (NBIMS) "A Building Information Model (BIM) is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward" (NBIMS 2007). It can be used in the design and construction phase, as well as operation and maintenance phase (PPSNetwerk 2011). Albeit BIM displays various benefits, construction companies are familiar with a tradition modus operandi (responsibilities, leadership and opportunity), therefore, change towards integrated project delivery is slow (Porwal and Hewage 2013). BIM aims at integrating various phases over the life-cycle of assets, which renders it useful for DBFM contracts. As of 2011, BIM is compulsory in DBFM projects tendered by RWS (PPSNetwerk 2011).

1.6 Systems Engineering

The Life Cycle of SE and the V Model

Systems engineering is generally focused on the beginning of the life cycle, however, governments and companies are increasingly of the opinion that SE should be applied throughout the complete life cycle (INCOSE 2006). There are six life-cycle stages namely: concept, development, production, utilisation, support, and retirement (see Figure 33). The V-model visualises the SE focus, specifically in the concept and development stage. In the V-model, there is a continuous need to carry out verification and validation assessments (INCOSE 2006).

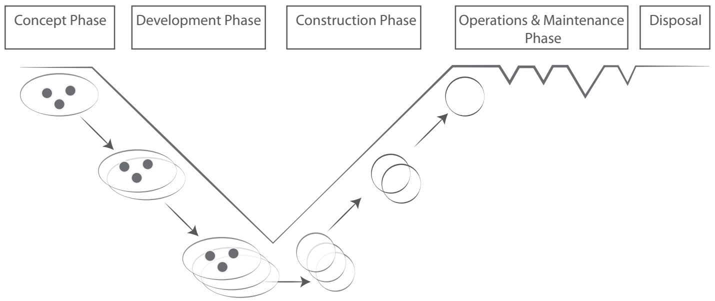


Figure 33: V-Model, adapted from: Rijkswaterstaat (2011)

Verification and validation

Although the exact definition is unclear to many and RWS refrains from making a distinction between the two (Rijkswaterstaat 2011). However, NASA (2007) states that the process of product verification and validation are similar, however, their objectives differ fundamentally. "Verification of a product shows proof of compliance with requirements" and "Validation of a product shows that the product accomplishes the intended purpose in the intended environment – that it meets the expectations of the customer and other stakeholders". Both processes can be proven through testing, analysing, inspecting or demonstrating. Verification relates to drawings and product or asset specifications and can be tested throughout different phases in the life-cycle. Validation tests are carried out in real or simulated conditions in order to be able to determine suitability and effectiveness of assets (NASA 2007).

1.7 Knowledge Management Definitions

Jashapara (2011) provides an overview of definitions of Knowledge Management. Three definitions are provided below:

Davenport and Prusak (1998) define KM as; "Knowledge management draws from existing resources that your organisation may already have in place – good information systems management, organisational change management, and human resource management practices".

Swan et al. (1999) relates KM to "any process or practice of creating, acquiring, capturing, sharing and using knowledge, wherever it resides, to enhance learning and performance in organisations"

Skryme (1999) defines KM as "The explicit and systematic management of vital knowledge and its associated processes of creating, gathering, organising, diffusion, use and exploitation, in pursuit of organisational objectives."

According to Jashapara (2011) KM is "the effective learning processes associated with exploration, exploitation and sharing of human knowledge (tacit and explicit) that uses appropriate technology and cultural environment to enhance an organisation's intellectual capital and performance".

These definitions of knowledge management provide insight into the matter; the first definition describes the basic principles KM is based upon. The last three definitions also clarify the purpose of KM. Which entails enhancing performance, pursuing organisational objectives, and enhancing organisations' intellectual capital and performance. These elements are similar in nature and these goals are reached through learning and knowledge processes such as; creating, gathering, exploitation and sharing of tacit and explicit knowledge. The definition of Jashapara (2011) provides a distinction between tacit and explicit knowledge that is an important notion in knowledge processes. Furthermore, Jashapara (2011) underlines that the goal of KM is to enhance organisations' performance that can be linked to the strategic role of asset management that also aims at increasing performance. The definition by Jashapara (2011) is used as reference in this research.

1.8 Knowledge Management

The definition of knowledge can be clarified when relating it to the concepts of data and information (Hertog and Huizenga 2005). These concepts are widely discussed throughout literature, however, R.L. Ackoff was the first to interrelate them in a hierarchical order in 1988. This order is known as the Data-Information-Knowledge-Wisdom hierarchy (DIKW) and is captured in a pyramid (see Figure 34). Every category includes the categories that fall below it. The top of the pyramid is wisdom, with which Ackoff relates the system to an ideal state (Bernstein 2011). These concepts are explained more in detail in the next paragraphs.

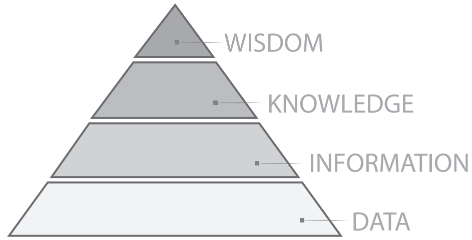


Figure 34: DIKW hierarchy as a pyramid, adapted from Bernstein (2011)

Data

According to the Oxford Dictionary, the definition of data is "facts and statistics collected together for reference or analysis" (Oxford 2013). Data is gathered from an external source, through the senses, and processed in an attempt to make sense of it. This is done through experience. Data can be excluded by focusing on other data, which is referred to as the 'cocktail party' effect where the background noise is filtered out. The description of data above focuses on the receiver of data, not on the sender (Jashapara 2011).

There are two types of data, quantitative and qualitative. Quantitative is numerical in nature and are context dependent. Qualitative data is dependent on the sender and on the receiver of data. Data is "value laden", "there is no perception of data without concepts" (Jashapara 2011).

Information

According to the Oxford Dictionary, the definition of information is "facts provided or learned about something" and "is conveyed or represented by a particular arrangement or sequence" (Oxford 2013). However, these definitions make no distinction between data and information (Jashapara 2011). Information is 'systematically organised data'; in order to inform data has to be shaped and organised that aims to provide insight. Another notion of information is that data is provided with meaning and significance (subjective or scientific) (Jashapara 2011). Information is a strategic and significant resource for organisations; it is "received or acquired and transmitted or utilised in and out" of organisations. Information can take many forms, it can be: "formal (and or informal), compressible (and or expandable), substitutable, textual (and or pictorial), transportable (and or storable), diffusible, shareable, quantitative (and or qualitative), verbal (paper based and or electronic) and individual (and or aggregate)" (Morabito 2013).

Knowledge

According to the Oxford Dictionary, the definition of knowledge is: "facts, information, and skills acquired through experience or education" and "theoretical or practical understanding of a subject" (Oxford 2013). According to (Jashapara 2011) knowledge is "actionable information" and it allows people to act more effectively as opposed to information and data. Knowledge cannot exist until predictions can be made. Knowledge is regarded a collection of information and rules or algorithms that can be used to fulfil functions (Hertog and Huizenga 2005). Knowledge is complex and it is dependent on human perception, as everyone has an individual framework. Jashapara (2011) states that people all wear coloured glasses and that individuals are not necessarily aware of their 'coloured' view. Hence, the interpretation of data and information varies depending on peoples' perceptions and their knowledge base (Jashapara 2011). Knowledge base is referred to as "the total of knowledge" people or organisations can have. This can be individual, collective or corporate knowledge (Meadow and Yuan 1997).

There are two extremes in the continuum of knowledge, on one side is tacit knowledge and on the other is explicit knowledge. These are generally referred to as know-how and know-what respectively. Converting tacit knowledge into explicit knowledge is a great challenge to organisations (Jashapara 2011).

In this research the following meaning of data, information and knowledge are utilised as reference. Data is considered a set of symbols without meaning. Information is a set of symbols with meaning. Knowledge is considered to be the accumulation and incorporation of information that is received and processed by receivers (Meadow and Yuan 1997).

B. Interview protocol

The interview will be semi-structured, which allows the researcher to cover key themes and questions. A list of questions is used, however, the order of these questions can be altered. Also, additional questions may be asked to explore certain topics more in depth (Kajornboon 2005).

When the interviews are planned, interviewees will not receive the interview protocol in advance. Before the interview commences, the interviewee is requested whether the interview may be recorded in order to facilitate note taking and transcribing the interviews. It also communicated that all information is only used for the master thesis and that audio recordings are erased after they are transcribed. The interviews are planned to last one hour. If time is running short, it might be necessary to interrupt to push forward in order to cover all questions. When an interview is carried out and transcribed, the interviewee will receive the transcription of the interview for verification.

Introduction

You have been selected for this interview because you have been identified as someone who can share a great deal in the field of: (I) design processes, (II) maintenance engineering, (III) collaboration, and (IV) knowledge sharing within VolkerWessels projects in DBFM projects.

The research as a whole focuses on improving the design process of DBFM projects with long-term maintenance obligations. With a specific interest in understanding what the role of maintenance is (or can be) in these design processes. And how maintenance expertise is (or can be) shared between the engineers and designers.

Maintenance

1. What is the role of maintenance in this project?
2. What are the contract requirements that require the incorporation of maintenance in the design?
3. When in this project did you work with/consider maintenance?
4. When should maintenance be incorporated?
5. How do you handle maintenance in this project?
6. On what level in the organisation is maintenance important?
7. What is the maintenance strategy in this project?
8. How much knowledge and skills are present to incorporate in the design?
9. How much knowledge and skills are present to make LCC calculations?

Design process

10. What is the design strategy?
11. How are design decisions made?
12. How integral and inclusive are VHB or VolkerWessels projects? (are DBFMs managed and designed integrally?)
13. What is the role of maintenance in the utilised management system?
14. Are there guidelines as to what and how to incorporate maintenance expertise in the design of assets?

15. How are designs processes carried out in relation to the management system?

Collaboration

16. How do you (as a designer) collaborate with experts from back-end phases (maintenance experts) of assets in DBFM contracts?
17. How do you (as a maintenance engineer) collaborate with experts from front-end phases (designers) of assets in DBFM contracts?
18. How do you as a design manager facilitate collaboration and knowledge sharing between back-end and front-end experts?
19. How is knowledge shared between experts and departments?
20. How is knowledge extracted from projects and stored within (project) companies?

System Improvement

21. What are elements that are up for improvement in light of the incorporation of maintenance? (How?)
22. How can maintenance become strategic?
23. How can expert knowledge be shared between maintenance engineers and designers?
24. How can expertise be extracted from experts working on projects and stored in the company database?
25. How can maintenance engineers be integrated in the design process?

C. List of Respondents

	Role Interviewee	Project
1.	Senior Maintenance Manager	SAA-ONE
2.	Maintenance Manager	SAA-ONE
3.	Maintenance Engineer	SAA-ONE
4.	Design Reviewer	SAA-ONE
5.	Integral Design Coordinator	SAA-ONE
6.	Quality Manager	SAA-ONE
7.	EPCm Director	SAA-ONE
8.	Maintenance Engineer	SAA-ONE
9.	Contract Coordinator	SAA-ONE
10.	Internal Audit VolkerInfra (maintenance engineer, team general, process coordinator)	SAA-ONE
11.	Design Leader Systems	SAA-ONE
12.	Design Leader Sound Barriers	SAA-ONE
	Informal meetings	
	Maintenance manager, Team general, Maintenance engineer(s), Process Coordinator	SAA-ONE
13	Maintenance Engineer *(informal)*	SAA-GA
14	Senior Maintenance Manager	SAA-GA
15	Maintenance Engineer *(informal)*	SAA-GA
16	Maintenance Manager	A-Lanes
17	Maintenance Engineer	A-Lanes
18	Design Leader Roads	A-Lanes

D. Empirical Research

1.1 Calculating the Performance Discount (PD)

The performance discount is calculated by multiplying the gross availability payment by a discount percentage (DP[20]) minus a bonus percentage (BP[21]). This is captured in the following formula: PD=GAP*(DP%-BP%) (DBFM Appendix 2 2012).

Discount Percentage

The discount percentage is calculated by multiplying penalty points times 0.1%. Penalty points are laid down in the DBFM contract. If the contractor fails to meet contract requirements, RWS has to give the penalty points to the contractor. Such contract requirements consist of A&B and issues or situations are that are related to penalty points. The issues consist of: safety, process management, maintenance and 'other' and can be found in DBFM Appendix 2 (2012). The A&B requirements are laid down in DBFM Appendix 2 Annex 3 (2012).

Bonus Percentage

The bonus percentage during the exploitation phase is equal to 0.3% if the discount percentages of the two previous payment periods are equal to zero. Otherwise the bonus percentage is equal to the bonus percentage minus the discount percentage of the previous payment period. In all other cases, the bonus percentage is equal to zero. The minimum value of the bonus percentage is zero (BP>0) (DBFM Appendix 2 2012).

[20] Discount Percentage is freely translated from Kortingspercentage

[21] Bonus Percentage is freely translated from Bonuspercentage

1.2 Special Design Requirements

This section assesses the content of the SDRs in more detail. From an overall perspective; the existence of the SDRs indicates that maintenance requirements are incorporated in the design. However, when zooming in on specific requirements, interesting observations can be made.

This section contains the following elements: first, the elements that are covered in SDRs and the involved maintenance disciplines are explained. Second, a table that contains a selection of 15 SDRs is provided. Third, two examples are discussed to give more insight into the content of the SDRs.

The disciplines within the maintenance department that produced SDRs consist of: systems, geotechnic, pavement, construction and routine maintenance.
A selection and analysis of 15 Special Design Requirements is provided in Table 1. The table consists of three columns, the first contains the requirement, the second displays the discipline and the third contains the observations and the discussion per requirement.

	Special Design Requirement	Section	Observation
1	Sufficient measures to be executed during the construction phase at all these locations to fulfill in connection to residual settlements all requirements defined within the contract in respect to smoothness and slope of the pavement surface along the complete concession period. In this context special consideration to be placed on requirement FN_01639 and FN_02135.	Geotechnik	Sufficient means enough or adequate (qualitative language, not measureable). Specifically what measures are regarded sufficient is not indicated. This SDR makes a reference to FN_01639 and FN_02135 to indicate that these contract requirements are important. Therefore, special consideration is required. However, how FN_01639 and FN_02135 have to be realised and verified remains uncertain. This SDR can be verified if both FN requirements are verified, the added value of this SDR is limited.
2	Sufficient measures to be taken during the construction phase (length of transition slab), to ensure, that especially requirement FN_01640 is fulfilled at each transition zone up to the end of the concession period in respect to residual settlements.	Geotechnik	Sufficient means enough or adequate (qualitative language, not measureable). This SDR makes a reference to FN_01640. However, how FN_01640 has to be realised and verified remains uncertain. This SDR can be verified if the FN requirements are verified, the added value of this SDR is limited.
3	Pavement design has to be based on the traffic loads provided within the traffic study (Royal Haskoning, Trend SAA) as minimum. This includes also the additional notice requiring calculating total traffic load with 296 working days /year. The considered traffic load has to be counted from opening to traffic to end of concession period (Design life span equal to time span of use within concession period).	Pavement	Pavement design has to be based on a traffic loads study executed by RH. Which must be a minimum requirement. This is a clear statement. However, further invesitgation is needed to determine the exact specifications of this requirement.The additional note is in unclear language.
4	Rhinophalt (or equivalent) has to be added to the wearing course of truck lane and adjacent driving lane within the pavement construction. The required dosage has to be determined within the test program for RWS acceptance. Placement according to the suppliers specifications.	Pavement	Clear requirement. However, further invesitgation is needed to determine the exact specifications of this requirement. What happens if RWS does not accept this requirement. It is unclear how to proceed.
5	Minimum design thickness of asphalt pavement to be constructed on the main carriageway is 200mm.	Pavement	Clear and measureble requirement.
6	Polymer modification of wearing layer and binder layer required to prevent rutting. Thickness design has to verify, that no strengthening is required during the maintenance period to fulfill FN_00997 at end of concession period.	Pavement	Ploymer modification to prevent rotting. What modification/ which polymer is unclear. Asset should not be strengthened in the conceccsion period. However, how that is ensured remains unclear.
7	Thicknesses (base and asphalt) of pavements as specified in the pavement design should be interpreted as minimum thicknesses, related to the quality control (toetsingsprocedure) as described further on in this document. It is left to the contractor to choose his own tolerances bases on the management of his own processes to meet this requirement.	Pavement. check: generiek ontwerpnotities verharding	Contradictory statement: The thickness is specified in the pavement design and the contracter can choose its own tolerances. (Tolerance should only be allowd when asphalt is thicker than 200mm)
8	Design of emergency lane needs to provide ample width in order for having maintenance vehicles +1.10m (according to CROW96a). The width of the emergency lane needs to be a minimum width of wider or equal 3.25m. If the emergency lane does not provide this room, a hardened shoulder or parking space behind the barrier should be constructed.	Systems	Clear definition of the width of the emergency lane, however 'ample' width is unbiguous. +1.1 in relation to what is unspecified. It is also clear that if there is no emergency lane, a hard shoulder has to be constructed. What is to be constructed is unspecified.
9	Gantries (VDC, verkeerskundige draagconstructies) must have a surface treatment resulting in a lifetime without need for additional conservation activities of at least 25+max 5 years (+5 depending on phasing). A single additional conservation activity of the A-frames is allowed and taken into account of the current calculation.	Systems	Gantries must have a maintenance free period (of its surface) of 25-30 years; one treatment is allowed. Clear statement.
10	Existing gantries that will be re-used must be guaranteed to have a remaining structural lifespan of at least 25+max 5 years (+5 depending on phasing). A single additional conservation activity of the A-frames is allowed and taken into account of the current calculation.	Systems	Existing gantries must have a guaranteed lifespan of 25-30 years. However, how this is measured and who guarantees this lifespan is unclear. What the current state of the gantries is allowed is unclear.
11	The CCTV camera system shall be fitted out with a healthcheck system in order to establish degrading camera and PTZ functionality, resulting in timely (preferably >1 week ahead, but at least 24 hours) warning messages usefull for deciding on early replacement and other preventive measures.	Systems	Camera requirements are specified, however, somewhat ambiguous. What type of camera meets these requirements is unclear. What type of maintenace requirements this system has to meet is unspecified.
12	The roadside traffic management system shall be fitted with a monitoring system (VIMS) in order to receive realtime failures and errors and the means for remote diagnostics and possibly remote intervention.	Systems	The requirement is that the management system is fitted with 'a monitoring system'. However, which type of camera meets the requirements is unclear. What type of maintenance performance requirements this system has to meet is unspecified. What sort of failures this system has to measure is unspecified.
13	The width of the emergency lane has to be at least 3.25 meters.	Systems	Clear and measurable requirement, this is the second SDR that specifies the width of the emergency lane.
14	The bends (rijcurve) at the rest area's should be constructed in a way or should have provisions based on the rijcurves of the CROW publicatie 164a so that busses, trucks with or without will not damage the profiles of the bend by 'cutting corners'.	Systems	Clear and measureable requirement. However, further invesitgation is needed to determine the exact specifications of this requirement.
15	Construction of surface water drainage in central strip with a plastic water-permeable box wrapped in geotextile with a cover of about 10cm permeable material as permanent working system without decrease of buffer volume within the system. No interventions should be expected to be required during whole concession period to maintain the function of drainage, except of in worth case exchange of cover material.	Routine Maintenance	unclear specifications as to what to construct, at what location and how the lifespan is realised.

Table 1: Selection of Special Design Requirements, adapted from (SDR 2012)

General Observations: SDR Table

A number of requirements are specific and detailed as to what is expected to be the outcome of these requirements, some of which are coupled with NEN-standards or contract requirements. Examples of detailed specific requirements are the thickness of new top layers (e.g. SDR 5), type of finish of top layers (e.g. SDR 4), and width of emergency lanes (e.g. SDR 13). These (specific) requirements are easily verified for compliance. Others prescribe a clear performance standard (e.g. SDR 9), which is vital when acquiring the materials and systems.

However, much of the language in the SDR document is qualitative in nature (e.g. SDR 1,2,6,11,12), ambiguous (e.g. SDR 7,8,15), refers to other documents (e.g. SDR 3, 14) refers to contract requirements (e.g. SDR 1,2), further investigation is required (e.g. SDR 4), are mentioned two times (e.g. SDR 8,13), and are challenging to realise and verify (e.g. SDR 10). As a result, these requirements are difficult to translate into measurable criteria and it is challenging to verify for contract compliance.

Two Examples

Two examples are provided and analysed in more detail to get insight into the Special Design requirement 1&2 and 9&10. Requirements 1&2 and 9&10 are paired because of their resemblance to each other; the pairs are selected because they are different from the other pair.

Requirement 1&2 indicate that 'sufficient' action needs to be taken. The description does not offer guidance as to what is expected to be sufficient or how that is to be realised, which leads to ambiguity. Also, these two requirements stress the importance of contract requirements FN_01639 & FN_02135, and

FN_01640 respectively. This means that if the FN (contract) requirements are met, both Special Design Requirements are also realised. Which seems to be of little added value since they are already incorporated in the DBFM contract and contractually binding.

SDRs 9&10 describe a performance standard; new gantries (SDR 9) and existing gantries (SDR 10) have to have a remaining lifespan of the 25-30 years (until the end of the contract). One life extending maintenance action is taken into account. The lifetime of new gantries is to be guaranteed by the supplier. However, how the lifetime is to be guaranteed of existing gantries or what state of the gantries is permissible in order to ensure that particular lifespan is unspecified. Nor is it specified when the single maintenance action is to be carried out, either specified in time or as a 'performance level'. As a result, it is unclear how these requirements can be realised and verified. In a contractually binding document, that seems to be of limited value.

SDR Section Summary

The selection of SDRs displays a variety of requirements that are incorporated in the SDR document. From an overall perspective, there does not seem to be a guiding principle as to how these requirements are set up. Some are specific and detailed requirements as to how thick the top layer of the asphalt needs to be. Others indicate the importance of existing contract requirements, some prescribe performance standards for new and existing systems, resulting in some ambiguous, superfluous and some clear and measureable SDRs (either specific or functional). Measuring how to comply or verify these requirements is not specified in the SDR document.

The aim of the SDRs is not part of the document. As a result, the aim of certain SDRs is unclear.

It is important to stress that the SDR document is added to the DBFM contract. Therefore, the SDRs become contractually binding. As a result, when specific requirements are implemented, these have to be enforced within the contract period (up to 30 years) or a contractual change is required (Senior Maintenance Manager 2013).

1.3 Professionalising Special Design Requirements

The SDRs have to be further developed and professionalised. By detailing the requirements, reducing ambiguity in SDRs, focussing on requirements that are not already in the DBFM contract and making clear distinctions between detailed specifications and performance requirements. When exact requirements are incorporated in the document, it should be clear what is expected from the asset/system and how that is to be realised and how that is to be verified. For clarity purposes; the amount of references in the SDR document should be limited as much as possible. The SDR document should be regarded as a 'standalone' and comprehensive document in order to limit the need for further investigations when assessing SDRs. Further attention should be paid to 'how' to determine, for example, the lifetime of gantries (SDR 9,10) and how the functional level can be specified. It is important to make clear how one can assess and guarantee whether gantries have a remaining lifespan of 25-30 years. And it is important to make clear when the need arises to carry out that single lifetime extending maintenance operation. Therefore, mapping the state of assets, the degradation and monitoring the performance of maintenance actions is important (increasing asset knowledge) (Van Horenbeek and Pintelon 2013). As a result, functional requirement levels can be developed, which allow for easy monitoring and checking for compliance. Furthermore, for system requirements such as the CCTV camera (SDR 11), it should be clear what the function of a CCTV camera is, what is required of the mentioned health-check system and what the maintenance requirements need to be. Such information is clear to the persons who devised the requirement, however, that information is not laid down in the requirement. System knowledge needs to be increased in order to further specify the system requirements. Every SDR should be coupled with a description of the intended result of that SDR in order to reduce uncertainty and make sure that interpretation errors are reduced. Also, the SDRs should be clearly linked to the project's maintenance strategy. Hence, the functional or specific requirements of assets/systems should be linked with maintenance performance requirements (Sarfi and Tao 2004). This SDR document is developed through a 'survey' in the maintenance department. As a result, issues that arise in the operational phase of the 'assets area'[22] are not incorporated in the SDR document. In order to draw from lessons learned from operational assets the SDR document should be continually updated by deducing SDRs from operating assets. This can be applied to projects in the future and available to the companies in the consortium and the parent company they are part of. Developing and professionalising the SDRs will also further the review process, as the reviewer has the task to base the reviews on the current SDRs.

[22] Freely translated from areaal

1.4 Scenario – LED/SON-T

This section aims at identifying what the influence is of considering or neglecting maintenance requirements. This is clarified through the example of lighting in the aqueduct that is part of the SAAONE project.

The financial implication of opting for LED or B son-t is calculated in a financial model. The financial model contains: purchase costs, replacement cost, labour costs, road closure cost, energy consumption cost and system failure cost. The LED system consists of 264 units and the son-t system consists of 165 units.

This model only considers the isolated system of lighting under the aqueduct. Hence, the costs for VVUs[23] are excluded, as it requires the assessment of the complete road section. Figure 35 displays the cost structure of the options; the upper left hand graph displays the total cost over the contract period. The two graphs on the right display the cost structure of both options. The costs consist of energy consumption cost, failure costs, road closure costs, purchase costs and replacement costs.

Two types of calculations are made, the first is by adding up all the costs (upper row of circles) and the second method is the Net Present Value (NPV) method (lower row of circles). The former method is utilised in a TOM in the project company. The blue circles on the left represent the son-t system, the orange circles on the right represent LED. The calculations include: initial cost (purchase + installation) and operation cost to arrive at the total cost over the contract period. The cheaper option is indicated by a smaller or lager than symbol (< or >) and the difference is indicated by the symbol **Δ** (delta).

[23] VVU stands for Voertuig Verlies Uren

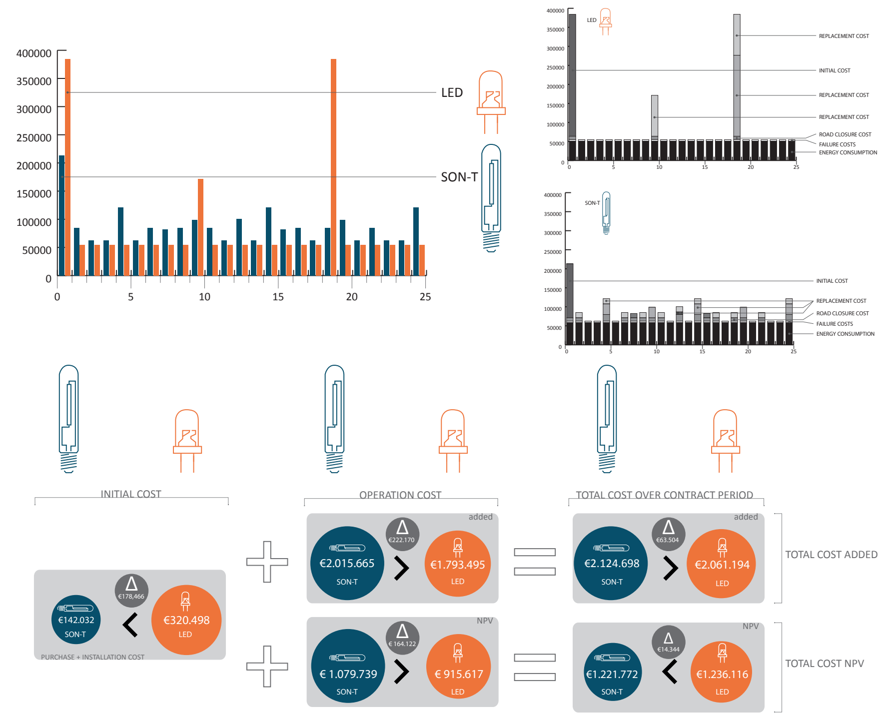


Figure 35:Cost of Lighting System

Initial cost (son-t<led)

When assessing the initial cost in year 0, which includes purchase cost and installation cost, it can be seen that the cost of LED is more than double the cost of son-t.

Operation cost over the contract period

The operation cost over the contract period includes: energy consumption, replacement costs, purchase cost of spare parts and road closure costs.

Trade-Off-Matrix (son-t>led)

The total costs during exploitation of LED is 222.170 less costly than son-t.

NPV (son-t<led)

When calculating the NPV of both systems during exploitation; LED is almost €165.000 less costly.

Total cost over contract period

The total cost over the contract period of 25 years is calculated;

Trade-Off-Matrix (son-t>led)

The engineers in the maintenance department of SAA-ONE produced a trade-off-matrix, which is a financial model that aims at identifying the least costly option. The total costs are determined by adding the costs for all operations. For instance, when three maintenance actions are required over 25 years, the cost of each operation is added. Hence, the time value of money is not considered. As a result, the led system is almost €63.500 less costly than son-t.

NPV (son-t<led)

When making a Net Present Value calculation, the time value of money is accounted for. The costs in the future are discounted to the value of today for the appraisal of long-term projects. The discount factor and the inflation rate that are utilised are the to the rates which are utilised in NPV calculations in the SAA-ONE project. As a result, the son-t system is almost €15.000 less costly than LED.

Number of Maintenance Operations

When assessing the frequency of maintenance operations, it becomes apparent that without the clustering of operations; son-t requires up to 15 maintenance operations. LED solely requires two maintenance operations. However, the number of operations is irrelevant as long as the total of maintenance operations does not exceed the number of VVUs that are determined in the tender.

Section Summary

The result of the calculations display that the purchase cost and the initial cost are both cheaper for the son-t system. The operation costs are less costly when opting for the led system. Considering the total system and calculating the NPV, the son-t system is the cheapest, although the difference over the contract is solely €14.344. When the decision is based on the TOM that is produced by the maintenance engineer, which neglects the time value of money, the led system is the cheapest option, which is the exact opposite result. This shows the relevance of utilising the right calculation method.

1.5 Scenario – small versus large waste containers

This section aims at identifying what the influence is of considering or neglecting maintenance requirements. This is clarified through the example of small versus large waste containers at a service area. A certain amount of waste container volume is required and can be realised through the placement of small 'park bins' or large underground containers.

Initial cost (small<large)

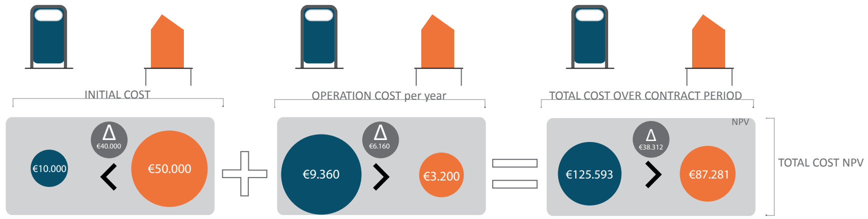
When assessing the initial cost in year 0, which includes purchase cost and installation cost, it can be seen that the cost of large containers is more than five the cost of small bins.

Operation cost over the contract period

When assessing the operation costs of emptying and maintaining the waste containers year, the operation costs of the large containers is almost one third of the cost of the small bins.

Total cost over contract period

When assessing the total cost over the contract period, it becomes clear that the small bins are €38.000 more expensive than the large containers.



Section summary

As can be seen in this example, optimising a sub system (design and construct) leads to a sub optimisation of the complete system. The initial cost of the smaller bins is less, while the total cost of the complete system (including operations) is less for the option with the highest upfront costs. Design optimisations need to take heed of the complete system, including operations and maintenance.