Towards a better incorporation of maintenance into DB(F)M projects

Supporting the contractor in the tender-, design- and construction phase by a role structure design

TU Delft Delft University of Technology

BRINK GROEP

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PREFACE

This report is the final product of my research on the incorporation of maintenance in DB(F)M projects. It marks the completion of the MSc Construction Management and Engineering, studied at Delft University of Technology. I would like to use this preface to thank all the people and organisations involved. In one way or another, you all made an essential contribution to my graduation process.

First I would like to thank the supervisors from the University. Hennes de Ridder, Sander van Nederveen and Ellen van Bueren have always been very willing to help out when I was in doubt on how to continue my research. I found the discussions during our committee meetings very instructive.

I also would like to thank Brink Groep for providing me the internship position. My daily supervisors Pascal Kersten and Jim Teunizen have always been ready to help providing the support I needed. Your support was great, especially in shaping the research at the start. I experienced our cooperation as enjoyable and fruitful. Thanks!

Besides the University and Brink Groep, many other people and organisations were involved. In particular I would like to thank Ballast Nedam Beheer. Peter van der Pijl provided me with the explanations, contacts and files I needed to gain an understanding of the current practice. The two case projects you provided me with made an essential contribution. In addition, I would like to thank all the other interviewees who were enthusiastic to provide me an insight into the field of infrastructure maintenance.

Last but not least... I owe special thanks to my parents, sister and friends. Your support was of great help!

Paul

Rotterdam, 20 October 2011

SUMMARY

Introduction

Design, Build & Maintain- (DBM), and Design, Build, Finance & Maintain contracts (DBFM) are increasingly applied in the Dutch civil engineering industry. These project delivery methods have in common that the private party is made responsible for the aspects design, build and maintenance. By integrating these three aspects, client organisations aim to stimulate an increasing role for life cycle costing in the early life cycle stages, which results in a high-quality infrastructure system with optimal life cycle costs. A DB(F)M-contract requires a different approach from the market than a traditional contract. The contractor is supposed to combine its expertises in the field of design, build & maintenance in order to win the contract, and subsequently execute the project successfully.

Research methodology

During the explorative phase of this research, several experts indicated that the life cycle cost optimisation potential of a DB(F)M contract is not fully realised because 'maintenance' is insufficiently incorporated into the early project phases. A research has been set up with the objective to study this phenomenon, and subsequently make a contribution to an improved incorporation of maintenance in the tender -, design - and construction phase of DB(F)M projects, by:

1) Developing a formal role structure design that prescribes an improved approach towards responsibilities, positions, tasks and authority;
2) Developing an informal role structure design that prescribes the knowledge, skills and attitude that are required;
3) Giving recommendations on how client organisations can facilitate and stimulate contractors to improve itself.

The research is split up in three parts. Part 1 is a literature study, concentrating on infrastructure asset management, DB(F)M contracts and maintenance engineering. Also a framework is presented that is used to describe the current practice and to prescribe an improved approach. Part 2 contains the empirical study, which aims to provide insight into the current working methods. In part 3, the key findings of the literature study and the empirical study are combined into a set of recommendations that facilitate an improved incorporation of maintenance.

The framework that is used to structure the empirical study (part 2) and the solution design (part 3) of this research is based on design management literature, which describes that a design process can be designed by means of a process design. The role structure is the organising part of the design, specifying the actors and their roles within the design process. As illustrated in Figure 1, the role structure can be further split up into a formal part and an informal part, both consisting of several elements. The framework is only used describe and prescribe the role of the contractor. The role of the client organisation will be dealt with separately.

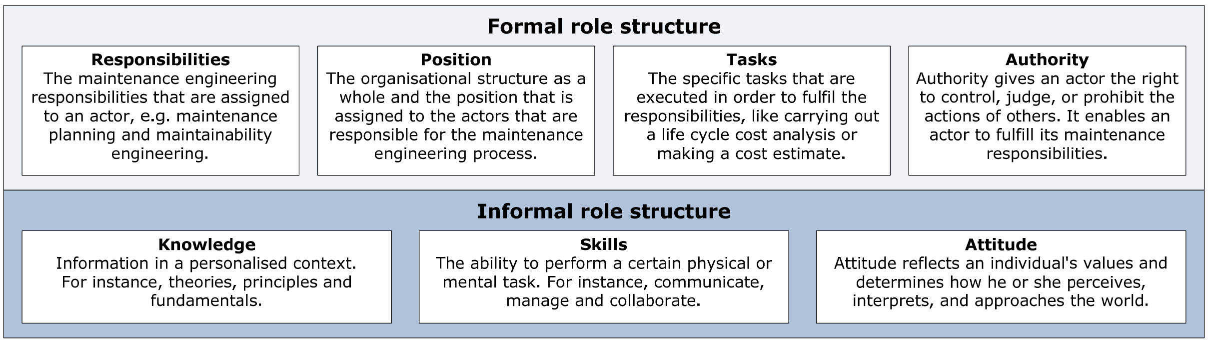

Figure 1: Role structure framework

Conclusions

The empirical study consists of an in depth study of one DBM- and one DBFM project. In addition, numerous experts are interviewed from several organisations, among which engineering consultants, contractors and client organisations. Based on the study, several conclusions can be drawn about the way maintenance is currently approached in DB(F)M projects. First, the role structure framework is used to describe the contractor's current approach. Next, the conclusions are given about the extent to which client organisations currently facilitate and motivate the contractors to incorporate maintenance.

The formal and informal role structure

Considering the formal role structure, generally most emphasis is laid on the responsibility of maintenance planning. Design optimisation in terms of maintainability and life cycle costs receives only limited attention. Besides, both responsibilities are rarely combined into an integrated, cyclical approach. This flaw is, among others, caused by the way maintenance is positioned within the organisational structure of the companies and projects. The different entities that are usually established within a project organisation, result in a situation in which only a part of the organisation benefits from a life cycle cost effective design. Especially in the early phases, a lack of authority is experienced by the parties that become responsible for the maintenance phase.

The second part of the analysis deals with the informal role structure. The general opinion is that the civil engineering industry lags behind other industries with regard to maintenance engineering competencies. Civil engineers with maintenance engineering knowledge and - skills are very rare. The result is that maintenance engineering tools and methodologies are seldom properly applied. Another issue is the attitude of the engineers that are typically involved. Especially at the contractors, most maintenance positions are held by people with a focus on hard project management aspects. Only very limited attention is paid to learning and improving.

The role of client organisations

How is the market's approach towards the incorporation of maintenance in DB(F)M projects affected by the procurement strategy of client organisations? The main conclusion is that client organisations have an important role to play in facilitating and stimulating the market to incorporate maintenance. The current fulfilment of this role leaves quite some room for improvement. Optimisation can especially take place in the contract awarding criteria, requirement specifications, permit procedures, payment mechanism and scope of the maintenance obligation.

Key conclusion

The key conclusions are combined and visualised in Figure 2. There is quite some room for improvement in the field of infrastructure maintenance. The formal role structure of the contractor and the role of the client organisation have a considerable influence on what knowledge is applied and developed. The same applies to the attitude of the actors involved in the maintenance process. The empirical study will be therefore finalised with the conclusion that a continuous and sustainable process of improvement will only emerge if the application and development of knowledge is in the heart of role structure design.

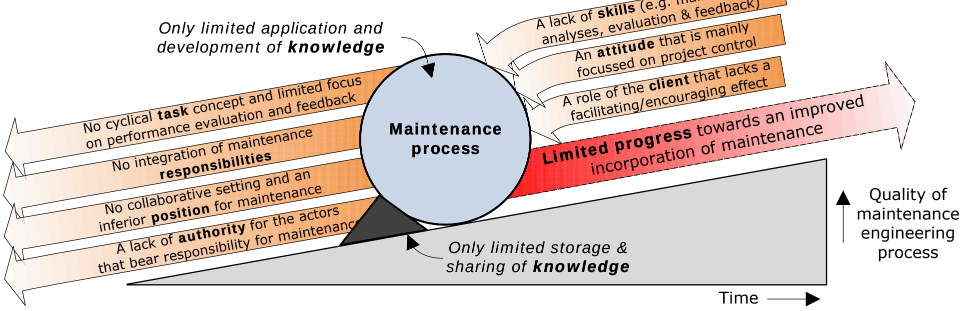

Figure 2: A visualisation of the key conclusions regarding the current situation

Recommendations

The formal role structure design

What formal role structure enables an continuously improving incorporation of maintenance into DB(F)M projects? At first, it is important that the responsibilities of maintenance planning and maintainability engineering, and its role throughout the process, are clear for all the actors involved. Special attention should be paid to maintainability engineering, which gets easily ignored or sidelined compared to maintenance planning.

Optimal fulfilment of these responsibilities subsequently requires an organisational structure in which all the actors benefit from a life cycle cost effective system. Such a collaborative setting ensures that enough authority is given to the actors responsible for maintenance.

Finally, a wide range of tasks have to be executed. The concept that is presented in this research combines these tasks into a cyclical concept, consisting of six steps: (1) initiate the process, (2) develop a model, (3) perform a criticality analysis, (4) design the maintenance policies, (5) implement and evaluate, and (6) provide feedback.

The informal role structure design

Based upon the conclusions of the empirical study, an informal role structure design is developed. It describes the competencies that enable an improved incorporation of maintenance in the early phases of DB(F)M projects. The profile, summarised in Figure 3, can be used to gear the formal and informal role towards each other, select the most suitable employees for a project, or improve the personnel training and hiring policy.

Knowledge	Skills	Attitude
Maintenance process knowledge • Organisational structure & strategy • Competency resources • Knowledge management system • Risk management • Market knowledge • Sustainable design Maintenance engineering knowledge • General infrastructure maintenance • Maintenance engineering tools • Input information • Maintenance policies - and tasks • Material knowledge • Maintenance cost figures • Economic factors	• Manage • Collaborate • Perform analyses and apply tools • Estimate costs • Learn new technology • Evaluate and provide feedback	Blue-print thinking *Managing the hard organisational aspects* Red-print thinking *Managing the soft organisational aspects* White-print thinking *Increasing creativity* Green-print thinking *Enabling a process of continuous improvement* Yellow-print thinking *Facilitating an optimal formal role structure*

Figure 3: Maintenance engineering competency profile

Recommendations for client organisations

Client organisations can play a very important role in facilitating and stimulating the market to improve its approach towards maintenance in DB(F)M projects. At first, it is important that DB(F)M contracts are procured on value, so that the contractor is not only rewarded for the lower life cycle costs that are realised by incorporating maintenance, but also for the created additional value.

Second, clients should not underestimate the effect of the payment mechanism on the focus of the contractor. Rewarding the contractor for achieving milestones early in the process results into lower finance costs, but de-motivates the contractor to focus on the long term performance of the infrastructure system.

Finally, the life cycle optimisation potential is largely determined by the requirement specifications. It is important that clients ensure that the specifications are consistent, and on the right level of detail. Besides, the contractor should be given the freedom to design its own processes. No tools or analyses should be prescribed.

Towards a sustainable process of continuous improvement

The empirical study concluded that there is quite some room for improvement in the field of infrastructure maintenance. Therefore, the recommended role structure design has been designed in a way that it stimulates a sustainable and continuous process of improvement. The contribution of the design to this process is visualised in Figure 4.

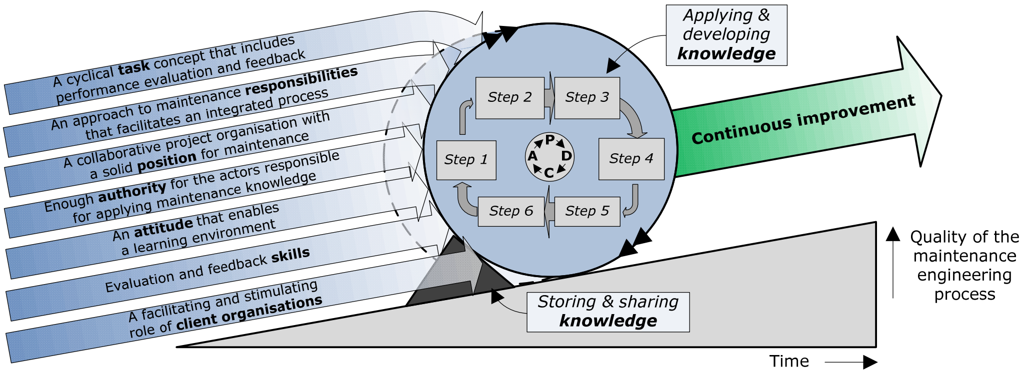

Figure 4: Towards a continuously improving incorporation of maintenance

Final discussion

The final part of the research is used to elaborate on the subject of research on a more strategic level. The discussion will reflect on the road that is followed by the public infrastructure management organisations. Given the findings of this research, is it wise and justified to continue the current course and increasingly apply DB(F)M?

Based upon this research, I am tempted to believe that the current level of competencies is not solid enough to justify the continuation of the current course. The lack of competencies hinders an accurate consideration of the strategy and its consequences. This is problematic because the organisational changes that are processed and the long duration of the DB(F)M contracts make it difficult, or even impossible, to reverse part of the consequences.

I would therefore suggest to insert a phase of consideration and reflection. This period should be used to (further) assess the current level of maintenance competencies at both client organisations and private organisations. Based upon this assessment, decisions can be made about what specific competencies have to be further developed and how this can be achieved. Only if the right level of competencies is achieved, a well founded, long term strategy can be developed regarding the management of the infrastructure network and the desired division of responsibilities between the public and private parties involved.

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1 RESEARCH DESIGN

1.1 Introduction

The requirements from the different stakeholders in the field of road infrastructure are challenging: despites the increasing traffic intensity, congestions due to maintenance have to be minimized, just as the environmental impact and the number of road accidents. Besides, the road agencies wants to cut back its workforce and realise savings. All these developments together make infrastructure maintenance an interesting, but complex field of study.

The infrastructure that is managed by the Dutch national government falls under the responsibility of Rijkswaterstaat, the executive arm of the Ministry of Infrastructure and the Environment (former Ministry of Transport, Public Works and Water Management). Aiming to improve the quality of the Dutch infrastructure, several changes have been processed the last decade. One of these changes is that infrastructure development projects will now be only put on the market as integrated contracts. The same trend is noticeable at smaller client originations, like for instance provinces and municipalities.

Two kind of integrated contracts that are increasingly applied are Design, Build & Maintain (DBM) and Design, Build, Finance & Maintain (DBFM). Both project delivery methods have in common that the private party is made responsible for the aspects design, build and maintenance. The duration of this maintenance obligation can vary from 15 to 30 years. Both project delivery methods aim to stimulate an increasing role for life cycle costing in the early life cycle stages, resulting in a high-quality infrastructure system with optimal life cycle costs.

A DB(F)M-contract requires a different approach from the market than a traditional contract. The contractor is supposed to combine its expertises in the field of design, build & maintenance in order to win the contract, and subsequently execute the project successfully.

1.2 Problem definition

In order to successfully execute a DB(F)M contract, the contractor needs to apply a different approach than traditionally. This research has been set up because several experts of Delft University of Technology and Brink presume that:

> *"The life cycle cost optimisation potential of a DB(F)M contract is not fully realised because 'maintenance' is insufficiently incorporated into the early project phases"*

The causal relationship between the presence and incorporation of maintenance in the development phase, and the realization of the life cycle cost optimisation potential is broadly confirmed by literature: expertise about the system's long term performance and the required maintenance is essential for the life cycle optimisation process. This optimisation process is on its turn of major importance for a contractor because:

- In a tender procedure, it supports the development of a bid design an optimal value/cost ratio. More optimal bids result in more successful tenders, and a better company performance;
- After contracting awarding, further optimisation within the margins of the bid design is allowed. Further optimisation enables the contractor to improve the project returns.

Brink Groep believes that the observed problems offers an interesting opportunity to expand its services in the civil engineering industry. Earlier already, Brink Groep has been approached by an investor for an advising role in a consortium that was intended to tender for a DBFM contract. The proposed role was to act as a 'cost and concept challenger', stimulating the designers to pay attention to life cycle cost reductions and to interact proactively with the contractors in the process of price making. A research has been set up in order to further examine this problem, and to develop a solution. The central subject within this research is the role of 'maintenance' in the early phases of a DB(F)M project.

1.3 Research objectives & questions

1.3.1 Research objectives

This research aims to achieve the following three objectives[1]:

Research objective 1

To make a contribution to an improved incorporation of maintenance in the tender -, design - and construction phase of DB(F)M projects, by developing a formal role structure design[1] that prescribes an improved approach towards responsibilities, positions, tasks and authority.

Research objective 2

To make a contribution to an improved incorporation of maintenance in the tender -, design - and construction phase of DB(F)M projects, by developing an informal role structure design[1] that prescribes the knowledge, skills and attitude that are required.

Research objective 3

To make a contribution to an improved incorporation of maintenance in the tender -, design - and construction phase of a DB(F)M projects, by giving recommendations on how client organisations can facilitate and stimulate contractors to improve itself.

1.3.2 Research questions

The following overview contains the questions that have to be answered in order to achieve the objectives. The research questions 3.1, 3.2 and 3.2 are directly linked to research objective 1,2 and 3, respectively. Answering these questions results in the achievement of the research objectives.

Part 1 - Literature study

1.1) What is the current status of the road infrastructure development and -maintenance industry?

1.2) What do DBM and DBFM comprise, and what are the potential advantages?

1.3) In what way can maintenance engineering contribute to the performance of infrastructure?

1.4) What framework can be used to study the current practice and prescribe an improved approach?

Part 2 - Empirical study

2.1) What formal role structure is currently applied in DBM and DBFM projects, and how does it affect the incorporation of maintenance?

2.2) What informal role structure is currently applied in DBM and DBFM projects, and how does it affect the incorporation of maintenance?

2.3) How is the market's approach towards the incorporation of maintenance in DB(F)M projects affected by the procurement strategy of client organisations?

Part 3 - Solution design

3.1) What formal role structure enables an improved incorporation of maintenance in the tender -, design - and construction process of DBM and DBFM projects? *(→ Research objective 1)*

3.2) What informal role structure enables an improved incorporation of maintenance in the tender -, design - and construction process of DBM and DBFM projects? *(→ Research objective 2)*

3.3) How can client organisations facilitate and stimulate the contractors to improve the incorporation of maintenance in DBM and DBFM projects? *(→ Research objective 3)*

[1] The term 'role structure design' that is used in the objectives will be elaborately explained in chapter 5 of this research.

1.4 Research scope

The main objective is to develop a role structure that facilitate an improved incorporation of maintenance into the early project phases, so that the life cycle optimisation potential of the DB(F)M project delivery method is better realised. When solving a practical problem, several phases have to be passed through before the actual solution can be designed. Figure 5 illustrates these different phases. This research will only cover the first three phases of the cycle. The scope is defined as follows:

- Studied are large infrastructure projects, procured by means of DBM and DBFM contracts. The integration of the aspects design and maintenance constitutes the core of this research. The interaction with the finance aspect included in DBFM, will be limited to the incentive that it creates to the contractor to incorporate maintenance;
- The subject will be mainly studied from the perspective of the private market. The role of (public) client organisations will be limited to how it facilitates and motivates the private parties to optimally incorporate maintenance in the early project phases;
- As described in the research objectives, focus will be on the design process during tender-, design- and construction phase. The maintenance phase itself will not be explicitly considered;
- This research concentrates on the incorporation of maintenance into these early project phases. To already give an idea, this so-called maintenance engineering deals with, among others, optimising the system design and preparing the maintenance phase.

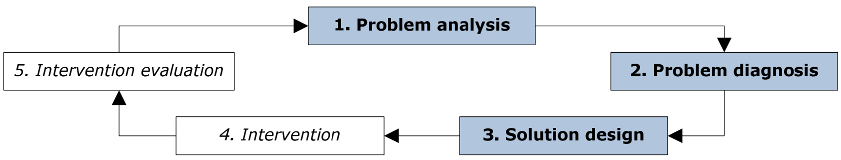

Figure 5: Intervention cycle (adapted from Verschuren & Doorewaard, 2007, p. 49)

1.5 Research methodology

Figure 6 presents the research model that will be applied. The research is split up in three parts, just as the research questions: the literature study, the empirical study and the solution design. The research strategy will explained by addressing each part more in detail.

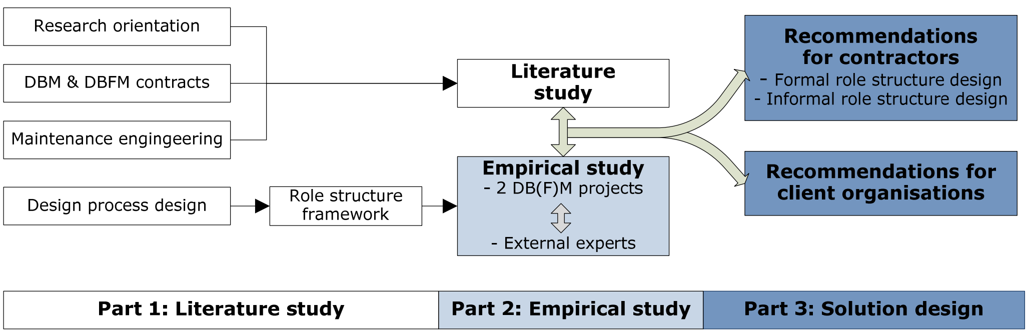

Figure 6: Research model

1.5.1 Literature study

The first purpose of the literate study is to provide insight into the problem and its context. Subjects that will be studied are infrastructure asset management, DBM- and DBFM contracts. Second purpose of the literature study is to gain an understanding of the field of maintenance engineering. This understanding supports the analysis of the current problems and the development of an improved approach later on. Final purpose of the literature study is to develop a framework that can be used to structure the empirical study (part 2) and the role structure design (part 3).

1.5.2 Empirical study

Part 2 of this research is the empirical study. It aims to gain an understanding of the current working methods and collect suggestions for improvements. Fortunately, the Dutch contractor Ballast Nedam has been found willing to contribute to this research by providing two case projects. These projects will be studied by means of a document study and interviews.

The number of DB(F)M project that is executed in the Netherlands is still rather limited. That fact that only one contractor was involved, further limited the selection criteria that could be put forward on the case portfolio:

- It must contain at least one DBM and one DBFM project;
- The projects deal with substantially different civil engineering objects;
- At least one of the case projects must be in the maintenance phase.

Fortunately, Ballast Nedam Beheer was able to provide two projects that met these criteria. In order to ensure the external validity, also experts from other companies will be interviewed. A more in depth explanation of the empirical study approach is described in chapter 6.

1.5.3 Solution design

Part 3 finally contains the solution design. The key findings of the literature study and the empirical will be combined into a set of recommendations that facilitate an improved incorporation of maintenance. The recommendations that focus on the role of the contractor are incorporated into a role structure design. The recommendations that deal with the facilitating role of the client organisation are listed separately, and incorporated in the chapter that deals with the overall conclusions and recommendations.

1.6 Research organisations

1.6.1 Delft University of Technology

The research forms the last part of the MSc Construction Management and Engineering, studied at the Delft University of Technology. The Master in Construction Management and Engineering (CME) is a two-year study programme. CME addresses the growing need for reforms within the building and construction industry and teaches students how to deal with present and future transitions. The CME courses are given at the faculties of civil engineering, building architecture and technology, policy & management. This research is supervised by the Design and Construction Process department of the Civil Engineering faculty.

1.6.2 Brink Groep

Management, consultancy and computerization for the construction-, real estate- and housing industry is the core of the services provided by Brink Groep. The company, founded in 1972, offers among others consultancy in the fields of urban development, real estate, construction management, housing, portfolio management, maintenance strategies, procurement and cost estimating. Currently, Brink Group has around 275 employees, all active in the Dutch construction industry. In 2009, these employees together realised a turnover of ca. €30 million.

At the moment, Brink Groep has around 7 FTE active in the civil engineering industry. One of the company's aims is to increase the involvement in this industry. This aim is pursued by looking where the already available knowledge and experience (in the field of real estate) in the engineering industry. The final goal is to offer a similar range of services for the civil engineering industry as is currently available for the real estate industry.

The research is primarily executed for the business Accommodation Advice & Construction Management, part of Brink Groep Management & Advies bv. This unit deals with all the activities that go along with the development of the actual real estate and infrastructure. It offers services in the field of process- and project management, procurements and risk management.

1.6.3 Ballast Nedam Beheer

The second company that is involved is Ballast Nedam, which is one of the largest contractors of the Netherlands. It contributes to this research by providing insight into the way it currently approaches the field of maintenance. The subsidiary of Ballast Nedam that is dealt with is Ballast Nedam Beheer, which can best be typified as an in-house asset management organisation.

Ballast Nedam Beheer has been founded only a few years ago. Currently around 40 to 50 employee deal with managing consisting, or newly build objects. The following types of objects are currently managed:

- Real estate (buildings, offices, etc.);
- Infrastructure (roads, public utilities, concrete- and waterworks);
- Energy (windmills, natural gas stations).

Ballast Nedam Beheer aims to relieve organisations of asset management and maintenance activities. The organisation focuses on the strategic and tactical services required. It supplies a 24/7 service centre and also executes condition inspections. Large maintenance interventions are subcontracted to other subsidiaries or companies.

1.6.4 Graduation committee

The graduation committee governing this thesis consists of the following persons:

- Professor (chairman): Prof. dr. ir. H.A.J. (Hennes) de Ridder
- 1st supervisor TU Delft: Dr. ir. G.A. (Sander) van Nederveen
- 2nd supervisor TU Delft: Dr. E. M. (Ellen) van Bueren
- 1st supervisor Brink Groep: Ing. P.W.J. (Pascal) Kersten
- 2nd supervisor Brink Groep: Ir. J. (Jim) Teunizen PDEng (formally not part of committee)

1.7 Reading guide

As described in the research methodology, the research has been split up in three parts. As illustrated in Figure 7, the same division is used to structure this report.

Part 1 contains the literature study. Each chapter is dedicated to one subquestion. The first chapter (2) explains the context of this research, by introducing infrastructure asset management. The following chapter (3) is dedicated to the project delivery methods that have a central position within this research: Design, Build and Maintain (DBM) and Design, Build, Finance and Maintain (DBFM). The next chapter (4) deals with the subject of maintenance engineering. Finally, chapter 5 will present the framework that will be used to structure the empirical study (part 2) and the solution design (part 3).

Part 2 of this report describes the empirical study. Chapter 6 explains the approach that has been applied for the empirical study. It shortly introduces the case projects and the additional interviews. The following chapter (7) presents the most important conclusions of both the project analyses and the additional interviews.

Part 3 of this report contains the solution design. Chapter 8 describes the formal role structure design that has been developed. This is followed by the informal role structure design in chapter 9. The next chapter (10) contains an overview of the key conclusions and recommendations. Finally, chapter 11 concludes the research by providing a brief reflection in terms of, among others, reliability and validity.

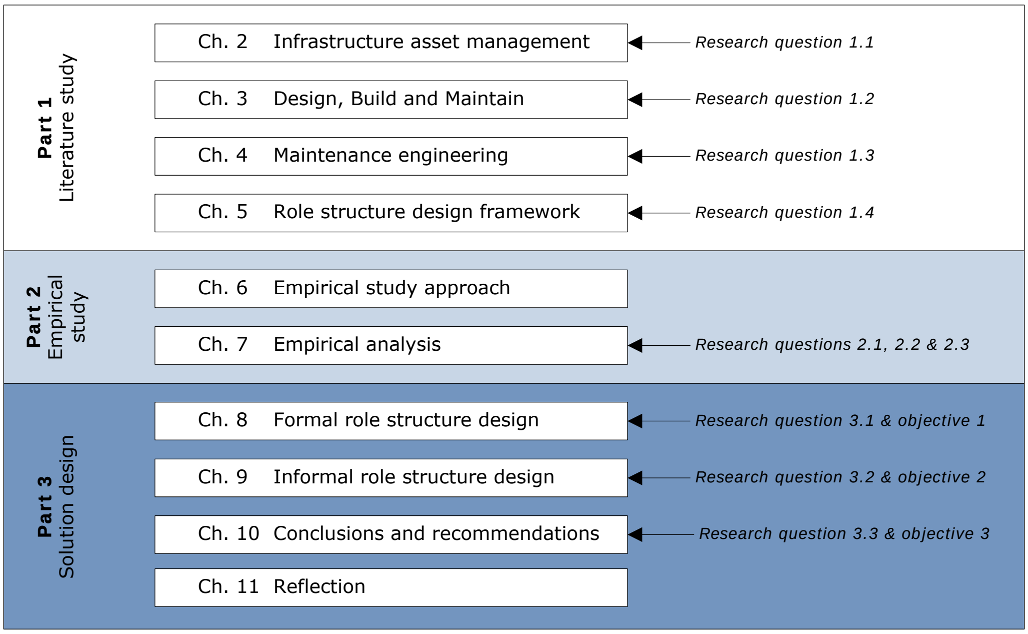

Figure 7: Reading guide

Part 1

Literature study

2 INFRASTRUCTURE ASSET MANAGEMENT

This chapter describes the context of this research by answering the following question:

1.1 What is the current status of the road infrastructure development and -maintenance industry?

This chapter will start with an introduction of the largest infrastructure asset manager in the Netherlands: Rijkswaterstaat. Subsequently, a description will be given of the developments in requirements and demand. Then, the supply side of the industry will be described, followed by some words about the resources in terms of knowledge and personnel.

2.1 Introduction

In our modern society, the quantity, quality and efficiency of the infrastructure systems have a great influence on the quality of human life and the economic progress. Road infrastructure and associated structures have a central role in the ground transportation system. A study done into the Dutch civil engineering industry, showed that the MIRT 2011[2] contains 183 infrastructure projects in the planning and construction phase, representing a total value of €56 billion. As illustrated in Table 1, five infrastructure categories can be distinguished. The road construction industry consumes approximately half of the total projects costs, thereby being the largest category in the civil engineering industry.

The road infrastructure network in the Netherlands is managed by several governmental bodies, namely the national government, provinces and municipalities. Table 2 shows the share of the roads managed by each of these organisations. The share of the roads managed by the national government falls under the responsibility of Rijkswaterstaat, the executive arm of the Ministry of Infrastructure and the Environment. Rijkswaterstaat is the largest infrastructure client organisation in the Netherlands.

Rijkswaterstaat is only responsible for around 4% of the total road length in the Netherlands. This share however contains all the highways (A-roads) and part of the motorways (N-roads), forming the main road infrastructure system in the Netherlands. Rijkswaterstaat, also responsible for other national infrastructure systems like, for instance the waterways, has a yearly budget of more than €5 billion. The continuation of this report will mainly focus on the industry that consists around the expansion and maintenance of the road infrastructure managed by Rijkswaterstaat.

Infrastructure system	Project costs [mln €]	%
Main road system	22.292	44%
Railway system	12.521	25%
Water defence system	5.744	12%
Regional / local infrastructure	3.841	8%
Water ways & management	5.253	11%
Total	**49.651**	**100%**

Asset manager	Road [km[1]]	%
Municipality and Water authority	124.377	91%
Provincial authorities	7.861	6%
National authorities (RWS)	5.109	4%
Total	**137.347**	**100%**

Table 1 (left): Division projects costs in 2011 (Groot, 2010, p. 10)
Table 2 (right): Kilometre[1] of car road managed per authority (Centraal Bureau voor de Statistiek (CBS), 2010)

2.2 Asset management in the Netherlands

2.2.1 Introduction

An infrastructure system or object can considered as an 'asset', generally defined as a physical item that has distinct value to an organisation. How to manage these asset is addressed by the theory of Asset Management, defined as "The combination of management, financial, economic, and engineering and other practices applied

[2] 'Meerjaren programma Infrastructuur, Ruimte en Transport': Dutch long term program for infrastructure, space and transport

to physical assets with the objective of providing the required level of service in the most cost-effective manner" (NAMS, 2006).

This objective can only be achieved if the assets are managed throughout its total life. It starts with deciding on what assets have to be acquired or created. Subsequently, the asset manager has to determine how to operate, maintain and decommission the asset.

Dealing with such issues requires careful consideration of trade-offs between, for instance, performance, cost and risk. Decisions have to be made considering the whole life cycle, taking into account conflicting factors like short-term versus long-term benefits, expenditures versus performance levels and capital costs versus operating expenditures. The fact that the whole life cycle of an infrastructure asset can cover more than 50 years, and that expectations and requirements of stakeholder are likely to change over time gives an idea of the job its complexity.

Assets can be identified and managed on different levels, ranging from individual assets (e.g. a lamppost) to asset systems (e.g. a tunnel system) or even whole asset portfolios (e.g. all infrastructure in one province). Asset management literature describes that these different levels have to be integrated in one asset management system in order to cope with the opportunities, performance challenges and risks.

2.2.2 Asset management budget

As indicated in the introduction, Rijkswaterstaat is the largest infrastructure asset manager in the Netherlands. Since 2006, Rijkswaterstaat is officially a government agency, meaning that it is functions to a large extent independently of the ministry. Part of the budget is reserved for the management & maintenance of existing infrastructure, and part for the development of new infrastructure. Figure 8 illustrates Rijkswaterstaat its expenditures in 2009. Approximately half of Rijkswaterstaat its budget has directly been spend on expanding, managing and maintaining the main highway network.

For the management and maintenance of existing infrastructure, Rijkswaterstaat concurs with the ministry on performance based agreements. In exchange for the work done, Rijkswaterstaat receives an agency fee that should be sufficient to cover both the project and organisational costs[3]. It can incur a loss or make a profit on these fees. A different fund[4] is available for the construction and expansion of the national infrastructure. Rijkswaterstaat cannot make a profit or incur a loss on this group of expenditures (Rijkswaterstaat, 2010a).

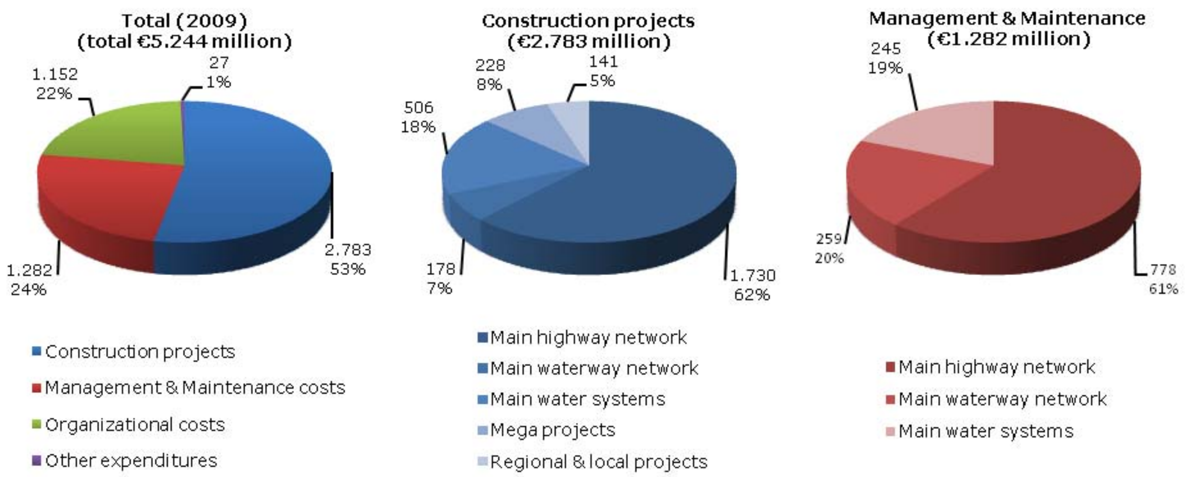

Figure 8: Expenditures Rijkswaterstaat 2009 (Rijkswaterstaat, 2010a, p. 10)

[3] The fees come from chapter XII of the national budget, belonging to the ministry of Infrastructure and Environment

[4] The Ministry funds these expenditures directly from the Infrastructure Fund, part A of the national budget.

2.2.3 Asset management strategy

This paragraph describes the most important developments that Rijkswaterstaat has gone through in its role as an asset manager. The reforms aimed to make Rijkswaterstaat a more public-oriented organisation, which only concentrates on its tasks as a network manager (Rijkswaterstaat, 2008a).

In January 2004, it presented a strategic plan for the coming years with some serious reforms. First, the building fraud had made clear that relationship between the government and the construction industry had to be renewed dramatically. Secondly, the Ministry imposed Rijkswaterstaat the objective to realise more quality with less people. As a result, Rijkswaterstaat formulated the target to cut the amount of FTE from 11.300 (2003) to around 9100-9500 (2008) (Rijkswaterstaat, 2004).

In June 2008, Rijkswaterstaat presented a strategic plan for the coming four years again. The most important goal of the Business Plan 2008 had been realised: the amount of FTE's was reduced from 11.600 in 2004 to 9.400 late 2007. Nevertheless, Rijkswaterstaat has been forced to decrease the number of FTE's further with around 500 FTE. Not an easy challenge, especially since the production was required to increase with around 25%.

The only way the cutback in FTE's could be realised was by increasing the efficiency and outsourcing more activities to the market. The slogan 'The Market, Unless…' was introduced. Since then, all activities that private parties can do just as good, or even better, have been put on the market. This is for instance done by choosing integrated contracts as the principal project delivery method (Rijkswaterstaat, 2008b). The same trend is recognizable at regional government agencies like provinces and municipalities, which have also been forced to increase its efficiency and leave more to the market.

The new contracting method has affected the division of roles between the governmental asset managers and private parties. A contractor is now expected to bear responsibilities that were previously borne by the asset management organisations itself. The new division of roles requires a different approach from all the parties involved.

2.2.4 Demand complexity

One of the tasks of Rijkswaterstaat as an asset manager is to determine what requirements the infrastructure has to meet. This asks for consideration of the requirements and expectations of a variety of stakeholders: the ministry, regulators, employees and of course the future users. The last decades, a few developments are noticeable with regard to the requirements that the road infrastructure system is expected to meet.

First, increasingly attention is paid to minimizing nuisance for the road user. The availability of infrastructure is considered to be essential for the Dutch welfare and economic growth. The intensity of the traffic jams, however, still increases every year. The government has set clear goals to tackle this problem.

Second, everyone is getting more and more aware of the fact that a substantial share of the life cycle costs is spend on maintenance activities. Client organisations realise that maintenance needs to get more (and earlier) attention. As will be elaborately described in the next chapter, new contracting methods have been introduced to stimulate the market to develop life cycle cost effective systems.

Third, more attention goes out to reducing environmental damage. The central aspects considered are the reduction of noise and fine particles. Some improvements have been made the last years, for instance by applying different wearing courses. Unfortunately, most 'solutions' turn out to have its cons as well, for instance in terms of durability properties.

Fourth, demands in terms of traffic safety have been further increased. A decrease of 50% of the lethal traffic casualties is aimed for. Furthermore, more strict demands are made on the safety of the people working on the road. Client organisations now for instance require reduction in working hours and extra safety measures.

Summarizing, road construction and maintenance is not longer only about ensuring the structural integrity. The society desires environmental friendly infrastructure with maximal availability and minimal life cycle costs. These demanding requirements have made Rijkswaterstaat its role as an asset manager more complex. As a result of the new procurement strategy of Rijkswaterstaat, much of these complexities are passed on to the market. Consequently, the private sector not only has to deal with a whole new category of activities, but also with an increased complexity of requirements.

2.2.5 Demand growth

Besides that the industry is faced with more demanding requirements, it is also expected that the demand is going to increase in terms of quantity. This growth will be especially caused by an increase of expansion and maintenance projects. Already in 2003, the Ministry published a plan of action for the control and maintenance of the national road infrastructure. During the development of this plan, the ministry observed serious backlogs in maintenance. This backlog resulted in additional costs, but also in unnecessary nuisance for the road users. On top of the €654 million per year, €600 million extra has been made available for the period 2004-2010 to catch up. In the meantime, this backlog is largely caught up on. The expectation is however that the number of large maintenance interventions will increase the coming years as a result of several reasons (Ministerie van Verkeer en Waterstaat, 2007, p. 5).

Firstly, the share of heavy traffic is expected to increase from the current 15% to 20% in 2020. The deterioration process is likely to speed up, increasing the amount of required interventions (Rijkswaterstaat, 2010c, p. 16). Secondly, open graded asphalt concrete (OGAC) wearing courses have been applied since the 90's. Compared to the previously applied dense asphalt concrete (DAC, 17 years), the lifetime of OGAC (12 years) is relatively short. The decision made in 2005, to make 2-layered OGAC the standard wearing course makes the situation even worse, since this type has to be replaced every 8 years[5]. Figure 9 illustrates the fluctuation of the required asphalt pavement maintenance in relation to long term average. As can be seen, the demand will gradually increase the coming years[6] (Dienst Verkeer en Scheepvaart (DVS), 2008, p. 9; Rijkswaterstaat, 2010c, p. 25).

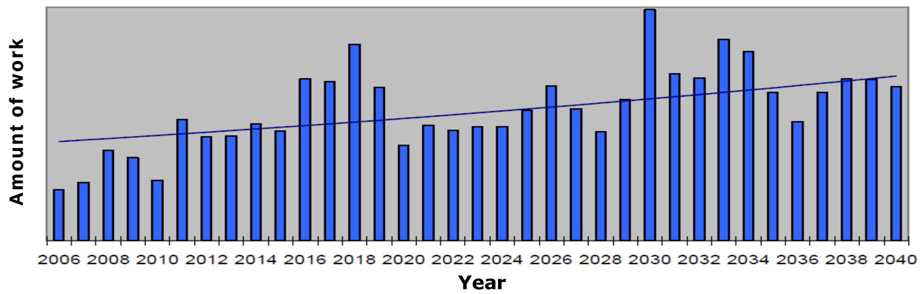

Figure 9: Replacement of asphalt pavements on Dutch highways (Ministerie van Verkeer en Waterstaat, 2007, p. 9)

2.3 The private market

The strategy of Rijkswaterstaat is to concentrate on its role as a network manager. Tasks that the private market can do just as good or even better are left to the private market. This paragraph will briefly describe what the structure of this supply side looks like. Only companies that are currently established in the Netherlands will be addressed.

As a result of the obliged public tender procedures, the presence of foreign contractors on the Dutch construction market has increased. But, foreign contribution has till now however mainly been restricted to the involvement in consortia responsible for mega infrastructure projects like the High Speed Line and Betuwelijn. Language, industry culture and the specific physical environment are however still considered to be substantial entry barriers when the product has to be made (or at least installed) on location (Groot & Jansen, 2004).

More than half of the turnover in civil engineering is realised by contractors with more than 100 employees[7]. Most work is taken care of by the five biggest contractors, namely BAM, VolkerWessels, Heijmans, Ballast

[5] These wearing courses have been introduced because of its better characteristics in terms of noise reduction and road safety.

[6] The presented predictions are based upon the application of traditional OGAC. The fact that 2-layered OGAC is applied since 2005 will only further increase the maintenance need.

[7] The figures are published by the EIB (Economisch Instituut voor de Bouw) (as referred to by Verster, 2009)

Nedam and Dura Vermeer. Each of these companies consists of several subsidiaries. Besides a construction unit, each of these contractors also has an in-house engineering unit.

There are several medium-sized contractors (21-100 employees), consuming around 30% of the total turnover. These companies usually work on a regional scale. They focus on one or two disciplines and usually have no in-house engineering department. To get involved in large projects, they need to work as a subcontractor or form an alliance with other medium size or large contractors. Examples are GMB, Mobilis and MNO Vervat.

Finally, there are numerous small contractors in the Netherlands, together responsible for around 15% of the turnover. These usually only have one specialty and focus on local projects. When involved in larger projects, they are hired as a subcontractor by the medium or large contractors.

The civil engineering consultancy market is mainly dominated by six large engineering firms: Fugro, Arcadis, Grontmij, DHV, Oranjewoud and Royal Haskoning. Each of these companies is able to advice on each of the civil engineering disciplines. Depending on the type of the project delivery method, they are hired by the client directly or by a contractor.

2.4 Knowledge resources and human resources

The current developments in the civil engineering industry resulted in an increasing demand for knowledge. Technical knowledge is asked for, but as a result of new contracting methods, also legal and financial knowledge is required. In some fields of expertise, there is a need for simply sharing already existing knowledge. This especially applies to tasks that were previously done by Rijkswaterstaat, and are now left to the market.

The last years, several research initiatives have been launched to develop new knowledge in the field of road infrastructure, like for instance PIM (Partner program Infrastructure Management) and IPW[8] (innovation program road management). Looking at the research programs recently initiated, two directions are visible:

1) Research into coping with the short term (10-15 years) increase of maintenance on existing infrastructure (and its consequences). This category of research deals with:
    - Life extending measurements (e.g. sun creaming and sealing);
    - Low nuisance maintenance (e.g. cyclical maintenance approaches).
2) Research focussed on the long term, by improving the current working methods so that the new systems are more effective in terms of life cycle costs. This category of research deals with:
    - Processes (e.g. design management, risk management);
    - Materials (e.g. ceramic wearing courses);
    - Usage (e.g. carpooling, tire improvement, etc.);
    - Models (e.g. traffic growth, road deterioration, etc.).

Obviously, human resources are required to develop this knowledge. Dutch Construction and Infrastructure Federation 'Bouwend Nederland' already stated a few years ago that the construction industry is going to be confronted with an increasing demand of highly educated technical personnel. The steady inflow of students at the universities is generally expected to be insufficient to fulfil this demand. Another issue observed is the decreasing inflow of technical (V)MBO students. Compensating this shortage with technical lwoo students[9], is expected to lead to qualitative issues. The consequences of the current developments on the labour market are expected to result in (Rijkswaterstaat, 2007, p. 20):

- Decreasing innovation power (due to a lack of high educated personnel);
- Decreasing quality (due to a lack of knowledge in construction technology and material properties);
- Insufficient capacity, especially for less attractive activities (e.g. construction activities at night).

[8] IPW is an abbreviation for 'InnovatieProgramma Wegbeheer'
[9] (V)MBO is a (preparatory) middle-level applied education route; lwoo is a lower-level educational route with additional support

2.5 Chapter summary

This chapter described the context of this research. The Dutch national infrastructure network is managed by Rijkswaterstaat, the largest infrastructure asset manager of the Netherlands. Rijkswaterstaat is faced with some tough developments. The coming years, a lot of maintenance needs to be done to ensure the functionality of the existing system. On top, the requirements of the stakeholders in terms of availability, safety and life cycle costs become increasingly demanding. On the long term, these demands can only be satisfied if the new infrastructure systems are more life cycle cost effective than the current systems. This requires, amongst others, an improved approach towards maintenance.

One way the Dutch client organisations try to facilitate a more life cycle cost effective approach, is by means of its contracting strategy. Rijkswaterstaat now aims to leave as much work as possible to the market and integrated contracts have become the standard project delivery method. National agencies like provinces and municipalities have followed this example.

The new contracting strategy has changed the division of roles in civil engineering industry. Private parties are now asked to bear responsibilities that were previously borne by the asset management organisations itself. On top of that, private parties like contractors are also expected to deal with the constantly increasing complexity of the requirements in terms of availability, safety, life cycle costs, et cetera. This all together presents a huge challenge for the parties involved.

The following chapter will enlarge on two relatively new contracting methods, in which the contractor is faced with a lot of new responsibilities and complexities: Design, Build & Maintain (DBM) and Design, Build, Finance & Maintain (DBFM).

3 DESIGN, BUILD & MAINTAIN

The previous chapter described the current strategy of Rijkswaterstaat and regional asset managers: act as a network manager and leave as much work as possible to the market. An important aspect of the implementation of this strategy is the introduction of integrated contracts. This chapter will address two kinds of integrated contracts:

1.2 What do DBM and DBFM comprise, and what are the potential advantages?

At first, the reasons for introducing integrated contracts will be discussed, followed by a description of the advantages of DBM and DBFM in specific. Subsequently, the organisations will be introduced that are usually established to deal with these contracts. Finally, the tender- and design phase of a DB(F)M process will be addressed.

3.1 Life cycle integration

3.1.1 Life cycle optimisation

Traditional contracting has been replaced by integrated contracting because of several reasons. Often mentioned is that integrated contracts enable more competition, more innovation, less legal disputes and an increased life cycle optimisation potential in the early project phases (Rijkswaterstaat, 2008b).

The advantage of the life cycle optimisation potential will be enlarged on throughout this chapter. The life cycle of an asset is defined as “the time interval that commences with the identification of the need for an asset and terminates with the decommissioning of the asset or any liabilities thereafter” (NAMS, 2006). Several phases can be distinguished in between[10]. As Figure 10 shows, particularly decisions made in the early phases influence the life cycle costs. As the project progresses, the cost reduction potential decreases while the costs to implement changes increase. As a result, the life cycle optimisation potential decreases throughout the project.

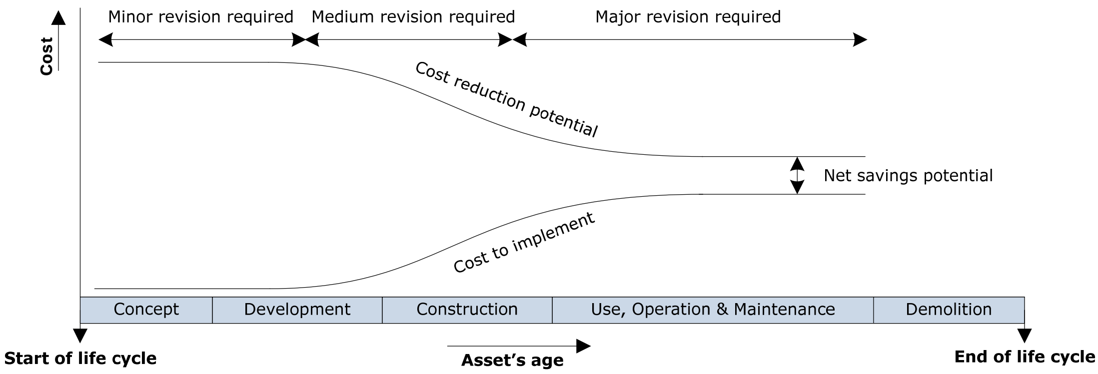

Figure 10: The relationship between life cycle cost savings and time of implementation (adapted from Flanagan, Norman, & Furbur, 1989)

3.1.2 Integrated contracts

How do integrated contracts increase the life cycle optimisation potential? In case of a traditional contract, each stage in the cycle is taken care of by a different party. As a result, there is no continuity in the roles and responsibilities. This working method makes it very difficult to optimize the total life cycle early in the asset’s life. This fragmented construction process is shown on top of Figure 11.

[10] First is the Concept phase (1), carried out to develop and asses new opportunities, and to develop temporary system requirements and feasible design solutions. A feasibility assessment and a rough draft of the user requirements form the input for the Development phase (2), in which a system is developed that meets the client’s requirements. After the development phase, the system elements can be produced and integrated during the Construction phase (3). After realization, the Use, Operation and Maintain phase (4) is passed through. Finally, the system is dismantled and removed in the Demolition phase (5). (Prorail & Rijkswaterstaat, 2009, p. 20)

An integrated contract aims to enlarge the optimisation cycle by combining several stages into one contract. Several kind of integrated contracts have been developed during the last decades. Figure 11 illustrates some examples of integrated contracts and the stages that are clustered per variant. The more stages are put together, the larger and more effective the optimisation cycles that is created, and the larger the presumed added value for the client organisation.

As mentioned already, Rijkswaterstaat has decided to choose integrated contracts as its standard project delivery method. The following kinds of contracts are currently applied:

- Performance Based Contracts (PBC, 3-5 years) for fixed and (small) variable maintenance work;
- Design & Construct (D&C) for construction and maintenance estimated lower than € 60 million;
- Design, Build, Finance & Maintain contract (DBFM) for projects estimated higher than € 60 million if an in depth analysis shows that DBFM is likely to be more beneficial than D&C (Rijkswaterstaat, 2009).

Nowadays, provinces and municipalities increasingly apply integrated contracts as well. As long as compatible with the public law and other policies, each organisation is free to decide on its own contracting strategy. Some asset management organisations apply for instance Design, Build & Maintain (DBM), a variant applied by Rijkswaterstaat in the past as well. The project delivery methods DBM and DBFM will be the subject of this chapter.

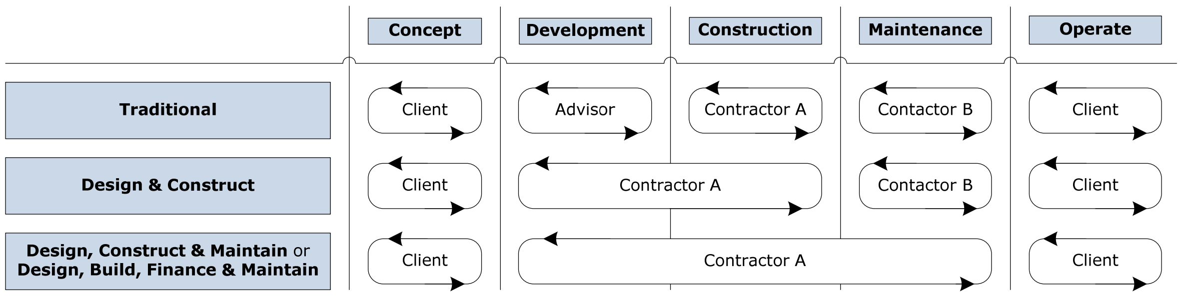

Figure 11: Overview of contract types and optimisation cycles

3.2 Why DBM and DBFM?

3.2.1 The presumed advantages of DBM

A DBM contract is one single agreement existing of the aspects design, build and maintain. A recent example of a design, build and (15 years) maintenance contract in the Netherlands is N322 Beneden-Leeuwen, procured by the Province of Gelderland. What are considered to be the advantages of DBM[11]?

DBM has the potential of integrating several building phases, and thereby increasing the role of life cycle costing in the early project phases. The idea is that an early consideration of the life cycle costs is for the benefit of the value/cost ratio. As will be discussed more in detail later, the contractor is among others stimulated to realise this life cycle optimisation potential by means of the contract awarding - and payment mechanism.

Secondly, the fact that different specialities (design, build, maintain) are involved often leads to the formation of a consortium of private companies. This offers the opportunity of co-specialization and the advantages that go along[12]. The advantages are however not always fully exploited in practice. For instance, research has been done into the risk involved in forming a consortium between different companies. Companies involved will not, or cannot always fully understand each other's interests, leading to unavoidable conflicting interests (van Heuckelum, et al., 2007).

[11] The advantages actually stem from DBFM literature. These specific advantages apply to DBM as well since they are the result of the integration of the aspects Design, Build & Maintain (and not specifically by the Finance aspect).

[12] Companies combine their strengths so that the different task and risks are handled by those parties who do extremely well in that specific field. Besides, different companies have different manners of solving a problem. These different approaches are supposed to keep the parties sharp and alert. (van Heuckelum, Favié, Peekel, van Eekelen, & Maas, 2007, p. 2)

3.2.2 The presumed advantages of DBFM

A contracting method with many similarities to DBM is Design, Build, Finance and Maintain (DBFM). But, in addition to DBM aspects, it also includes a finance aspect. A recent example of a DBFM contract is A15 MaVa, procured by Rijkswaterstaat. The coming years, Rijkswaterstaat expects to procure the (re)construction of the N33, A27 and four projects to improve the Amsterdam ring road (Rijkswaterstaat, 2011b).

A DBFM contract belongs to the family of Public Private Partnerships (PPP): public and private parties are brought together in long-term contracts to produce and provide for instance an infrastructure system. Underlying principle of PPP schemes is that certain construction and operational risks associated with public services should be transferred away from the public sector to where they can be best managed (Ricaurte, Arboleda, & Pena-Mora, 2008).

What are the reasons for applying a DBFM contract? All the advantages of DBM also hold for DBFM. The incorporation of the finance aspect however introduces an additional advantage. Before enlarging on this advantage, it is first necessary to introduce what this finance aspect.

In a D&C or DBM contract, the contractor is responsible for (partly) pre-financing the construction costs only. If the project is delivered successfully, all expenditures made by the contractor are remunerated. In a DBFM project, the client doesn't pay for a realised system, but for the system's availability and performance throughout the maintenance phase. Only part of the construction costs are remunerated after the construction phase. Most of the payments are spread over the maintenance phase. As a result, the contractor has to advance the construction costs for a substantial period of time. The financing principle is illustrated in Figure 12.

Usually, external investors are brought in to obtain the financial resources required. Financial securities for the investors are largely based upon the income that can be received out of the project. The same applies to the contractors itself, which have usually invested a substantial sum as well. As a result of the fact that the private parties have financed the project and that remuneration is dependent on system performance, each of the parties involved has a huge interest in the actual system performance throughout the maintenance phase. This is presumed to stimulate private parties to realise the life cycle potential and develop a system that will satisfy the requirements throughout the contract period.

The downside of private financing however is that it is for a private party generally more expensive to contract a loan than for a public party. Leaving project financing to the market is therefore only beneficial if the above described advantage weighs up against the additional financing costs.

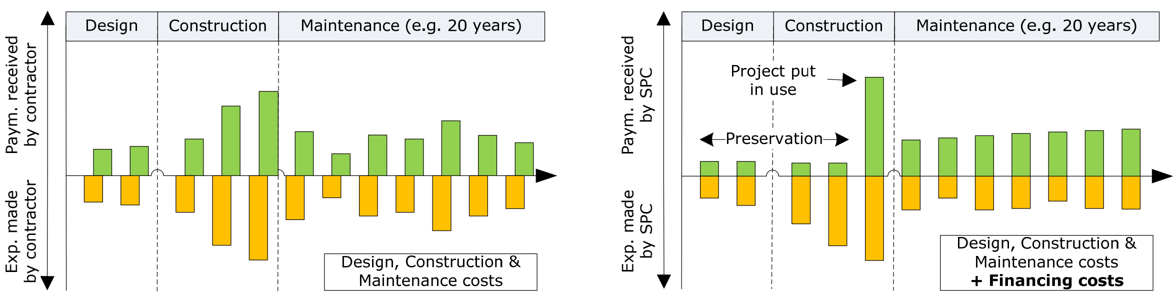

Figure 12: Payment schedules: traditional (left) and DBFM (right)

3.2.3 Maintenance obligation

Both DBM and DBFM have the advantage of a life cycle optimisation potential in the early project phases. A potential that however only will be realised if the scope of the maintenance obligation and size of the availability payments are in proper relation to scope of the construction obligation and remuneration upon realization. The duration of the maintenance obviously plays an important role within this relation: the longer the duration of the maintenance obligation, the larger its contribution to the total project costs and the more the private party is stimulated to pay attention to it.

Regarding the actual scope of maintenance, Rijkswaterstaat has formulated a few criteria that have to make sure that the proposed life cycle optimisation is actually realised. Preferably, the private party is made responsible for ensuring performance of:

- All objects which it has developed and (re)constructed;
- All objects that influence the total system's availability (e.g. pavement, traffic management system).

The contractor only has to make sure the infrastructure system provides the right functionality and availability. The operational activities like, for instance, traffic management, remains the responsibility of Rijkswaterstaat.

In a DB(F)M agreement, the private party is usually also made responsible for maintaining the existing system during the design and construction phase. The period in between handing over the commencement certificate and the completion of the definitive infrastructure system is referred to as the preservation obligation. The subsequent (e.g. 20 year) period in which the contractor has to ensure availability of the definitive infrastructure system is the actual maintenance period[13].

3.3 DBM and DBFM organisations

In a DBFM contract, the private party is stimulated to realise the life cycle optimisation potential. It has already been mentioned that this private party is often a consortium of companies, sometimes supported by external investors. The extent to which the life cycle optimisation potential is actually realised depends, among other things, on the organisational structure, a subject this paragraph will enlarge on.

3.3.1 DBFM organisation

Several contractual structures can be applied for DBFM projects, of which only the most regular one will be addressed. As in every DBFM project, the DBFM contract is agreed on by the client and the private party, set up as a so called Special Purpose Company (SPC).

This SPC is led by the shareholders and only takes care of the finance aspect. The project is partly financed by equity of the investment units[14] of the contractors involved. Additional means are provided by external investors, which enter into a 'direct agreement': a three-party agreement between themselves, the client and the SPC. The agreement between the SPC and the external investors is non-recourse, meaning that the investors cannot acquire (much) more financial securities than the project's cash flow. Important parts of the agreement are therefore the 'step in rights': rights that provide the investor with the possibility to intervene if the contractor defaults (and the project revenues are in danger) (Koster et al., 2008).

The SPC only takes care of the finance aspect. The design and build responsibilities are passed on to the Engineering, Procurement and Construction (EPC) party. This party usually is a partnership in which several engineering firms and contractors participate, possibly from the same company[15]. The EPC can on its turn involve subcontractors.

The EPC is as good as done after the design and construction phase. The subsequent maintenance phase is passed on by the SPC to the Maintenance (MTC) party, which can also be a partnership of companies[16]. The relationship between the EPC and the MTC is arranged by means of an interface agreement. The EPC remains jointly and severally liable for its work. This means that the MTC can charge the EPC if severe construction errors surface throughout the maintenance phase (Koster, et al., 2008).

[13] A commencement certificate is in Dutch called 'aanvangscertificaat', preservation is 'instandhouding'.
[14] Examples are BAM PPP bv, Ballast Nedam Concessions bv and Dura Vermeer Consessions bv.
[15] An EPC can for instance consist of Ballast Nedam Engineering bv (design), Ballast Nedam Infra bv (construct).
[16] An MTC can for instance consist of Strukton Worksphere bv and Ballast Nedam Beheer bv.

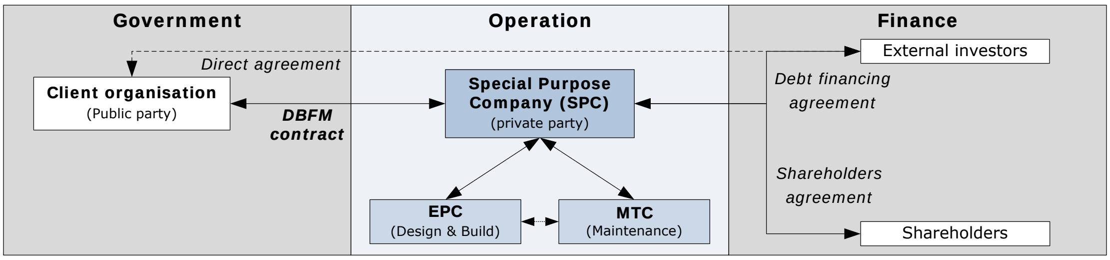

Figure 13: The typical DBFM triangle SPC-EPC-MTC (adapted from Koster, et al., 2008, p. 11)

3.3.2 DBM organisation

The organisation required for DBM projects logically lacks all finance related parties and agreements. The result is a much less complex organisational structure. There has not really been found one 'typical' DBM structure throughout this research. Figure 14 presents some options. Each has its pros and cons and it depends on the project characteristics and the (number of) companies involved what organisational structure is most suitable.

In the single contractor variant, there is one contractor that bears responsibility for both design, construction and maintenance. Optionally, parts are passed on to subcontractors. Second alternative is to establish a consortium, in which several contractors participate. Again, parts can be passed on to subcontractors as well. The last alternative has some similarities to DBFM triangle discussed earlier. One contractor (or EPC if a partnership is established) initially takes care of the design and build aspect. After completion, all responsibilities that go along with the maintenance phase are passed on to contractor B (or MTC if a partnership is established) by means of an internal back-to-back agreement.

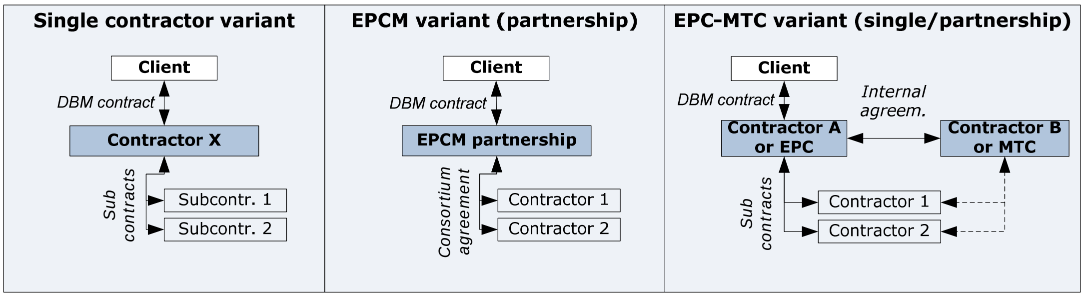

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Figure 14: Three possible organisational structures for DBM projects

3.4 Tender and design process

This research concentrates on the life cycle optimisation potential provided to the private party in the early project phases, namely the tender and design phase. Before addressing these phases more in depth, first a description will be given of the total process. Since the tender and design process of a DBFM and DBM process are largely similar, no distinction will be made throughout this paragraph.

3.4.1 Overall DB(F)M process

Figure 15 shows the DB(F)M process and the most important events. The concept phase is (at least largely) executed by the client origination, possibly with support of external advisors. After deciding to apply a DBFM contract, decisions have to be made about the scope and duration. Subsequently, the market is notified that a tender comes up, followed by the actual tender procedure.

After contact awarding, the private party can start elaborating its design. After satisfying the first conditions[17], the commencement certificate is issued by the contractor. From this moment on, the private party is responsible for preserving the infrastructure system. Meanwhile, the contractor finalizes the design and starts

[17] For instance, the conditions for A15 MaVa were that a financial close had to be reached; the intellectual property rights concluded; a performance measurement system in place; and an integral safety plan made (Rijkswaterstaat, 2011a).

the construction activities. After the final system is put into use, the preservation obligation converts into a maintenance obligation. After completion of the maintenance period, the system is handed back over again to the public party.

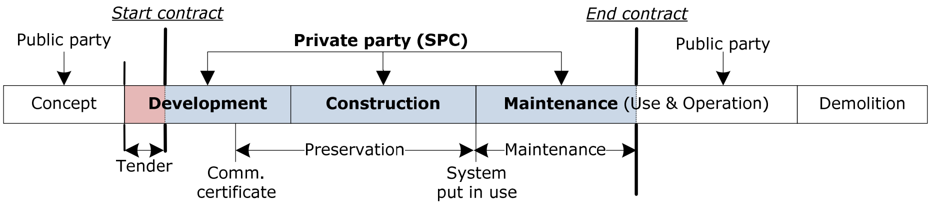

Figure 15: DB(F)M process related to an asset's life cycle

3.4.2 Tender phase

The traditional construction process is characterised by the fact that the contractor is only involved once the client organisation, usually assisted by an advisor, has found a specific solution for its problem. A complete design with technical specifications and a bill of quantities form the basis of the contractors' bidding stage. During a traditional tender, the contractor is only required to come up with a price.

In a DB(F)M project, it is not longer the client's task to define a specific solution. Compared with the traditional situation, the private party moves up-front in the design process. As a result, a different tender procedure is required. For complex DB(F)M projects, client organisations are allowed[18] to apply the competitive dialogue procedure, elaborately described in Appendix A. The most important conclusions regarding the competitive dialogue procedure for the purpose of the research are:

- The public party lays down its needs in a System Requirements Specifications (SRS) and Process Requirements Specification (PRS)[19]. Based upon both, the private parties have to develop a bid design and price offer. This requires each private party to make a design effort during the tender;
- The public party evaluates the bid offers by means of the Economically Most Advantageous Tender (EMAT) award mechanism. In short, this means tot not only the price is evaluated, but also other predefined criteria like, for instance, construction time, capacity, durability, aesthetic value, etc.;
- The private parties that lose the tender get only part of their effort remunerated. Most contractors complain that the tender remunerations only cover a minor part of the costs. Another often mentioned complaint is that time pressure in the tender procedures is in general too high[20].

3.4.3 Design process

In advance of the tender procedure, it is the client's task to formulate the boundaries in between which the solution may be designed. The client collects stakeholder requirements, and formulates the requirements specifications. During the bid development stage, the private party has to analyse the specifications and develop a design with a price offer. Depending on the requirements laid down by the client, several other documents have to be developed, like for instance a construction schedule, risk analysis and a maintenance plan. Usually, a serious design effort has to be made during the tender phase.

The nature and the level of detail of the requirements determine the solution space for the private party. The more detailed the requirements, the less freedom is available for the private party to steer the design. The requirement specifications also prescribe the level of detail of the bid specification. The level of detail of both the requirement specifications and the bid specifications vary per project. Obviously, the larger the difference in level of detail between the requirements and bid design, the more solution space is offered to the market. It

[18] See for a more elaborate description of the conditions that have to be met (M.A.B. Chao-Duivis, 2008, p. 9).

[19] The SRS describe the requirements that must be met by the end-product (the 'what' requirements), the PRS describe the requirements for the development process (the 'how' requirements, e.g. the application of Systems Engineering).

[20] These were complaints of interviewees working for contractors. Regarding the time pressure, client organisations (or its advisors) counter that it does not really make sense to extend the procedures since that will only further increase the costs.

however requires the private parties to make a larger design effort in the tender phase, which makes it more lengthy and costly.

The design process continues after contract awarding. Within the specified margins, the private party further specifies its solution. At the end of the design process, a final, detailed design is ready. The design is worked out till the level of detail required to enter the construction phase.

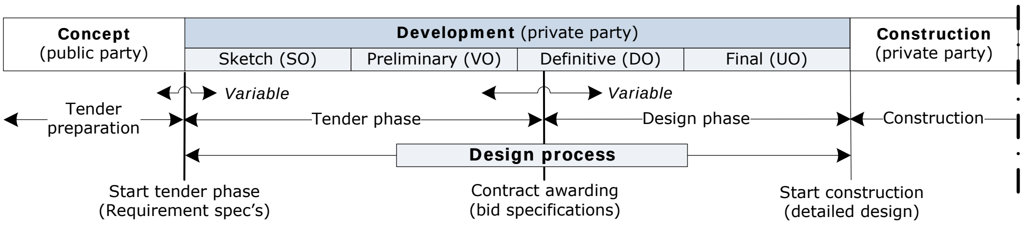

Figure 16: Tender phase related to life cycle stages

3.4.4 Life cycle optimisation potential

The DB(F)M project delivery method is among other things applied to enable life cycle optimisation in the early life cycle phases. Now the tender and design phase have been discussed more in depth, it is possible to enlarge on this optimisation potential. After interviewing several experts, the following can be concluded.

The design process that the private party goes through can be split up in two subprocesses. The first takes place during the tender, and aims to create a reliable and effective bid design. The fact that the EMAT criteria define the effectiveness of a bid, makes the client's strategy a determinant factor in the optimisation process. In addition, the client determines the size[21] of the optimisation potential since this depends on the level of detail of the requirement specifications.

The second subprocess follows after contract awarding, and aims to create a construction ready design. The size of the optimisation potential left depends on the level of detail of the bid specifications and the room for adjustment allowed by the client. Since the price has been fixed already, this optimisation process mainly aims to increase the financial performance. The detailing of this optimisation process depends on the requirement specifications and the payment mechanism that is applied throughout the contract period. The design process, its influence on the solution space and the optimisation potential is illustrated in Figure 17.

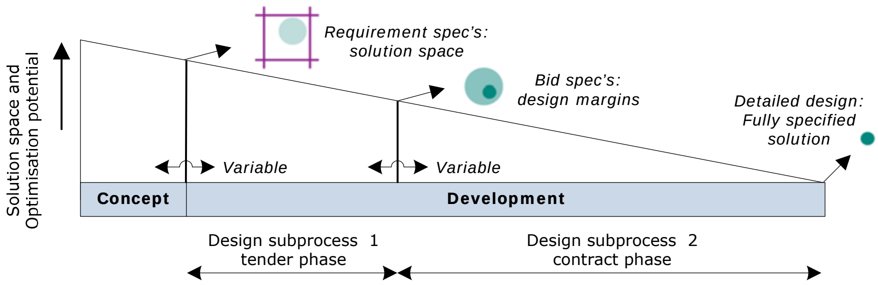

Figure 17: A visualisation of the design process and the optimisation potential

3.4.5 Design process theory

The previous subparagraphs have described how a design process is included in a DB(F)M process. This paragraph will approach the (civil engineering) design process from a more theoretical perspective by presenting characteristics that usually typify a design process. See Appendix B for a more elaborated explanation of each of these characteristics (van Doorn, 2004).

- It consists out of four sub phases: the sketch -, preliminary -, definitive - and final design phase[22];

[21] A small optimisation potential does off course not automatically lead to a bad design. Applying detailed requirement specifications however require the client to deal with life cycle optimisation, especially since it is most effective earliest in the earliest design phases. The nature of DB(F)M is to do the opposite and make use of the market.

[22] In Dutch referred to as schetsontwerp (SO), voorlopig ontwerp (VO), definitief ontwerp (DO) and uitvoeringsontwerp (UO)

- It comprises more than just determining the shape of the object. The process amongst other things consists of designing, research, specifying, scheduling and cost estimating;
- The process is complex and dynamic, as a result of the fact that all system properties and aspects are interrelated and because the design itself and the environment in which the system is being realised, is susceptible to change (Gelderloos, 2010, p. ii);
- There is a discrepancy between the amount of information available to base the decisions on, and the influence that can be exerted on the actual design process. An iterative process is required since the design question and its relation with the environment becomes clear throughout the process;
- The design process can be presented as a cycle, in which three elements can be distinguished:
  - The input, consisting out of both design related, and process design related information;
  - The process itself, in which the requirements are translated into a spatial design;
  - The output, the final design result with the enclosed technical and financial specifications.
- Each design phase has different characteristics, and in accordance, an often informal shift takes place within the division of the tasks and the responsibilities that go along. This so called dynamic leadership is often referred to with the Wheel of Dominance.

3.5 Chapter summary

The DBM and DBFM project delivery methods aim to encourage life cycle optimisation early in the construction process by combining the aspects design, build and maintenance. Compared to the traditional construction process, the contractor is much earlier involved in the process. As a result, a rather elaborated tender procedure is applied, called the competitive dialogue procedure.

The design process already starts in the tender phase. Based upon the requirement specifications, the contractor is expected to develop a bid design and a price offer. In addition, the contractor is often asked to submit a construction schedule, risk analysis and a maintenance plan. The life cycle optimisation potential is determined by the EMAT criteria and the requirement specifications drawn up by the client. The better this potential is realised by the private party, the more likely it is that the contract will be won.

After contract awarding, the design process continues until a 'construction ready' design is developed. Within the margins of the bid design, further life cycle optimisations are possible. The optimisation process that is passed through by the private party after contract awarding, mainly aims to optimise the project's financial performance over the contract period.

In order to realise as much as possible of the life cycle optimisation potential, it is essential to start paying attention to maintenance as early as possible. Already in the tender- and design phase, the contractor should wonder how the system its performance is going to be ensured during the operational life. The following chapter will describe what determines the performance of a system, and how maintenance engineering can make a very contribution in optimising this performance.

4 MAINTENANCE ENGINEERING

The previous chapter described that in a DB(F)M project, the private party is responsible for the aspects design, build and maintenance. The private party needs to realise the life cycle optimisation potential in order to win the contract and optimise the financial performance after contract awarding. Realising this potential requires maintenance to be considered in the design process. This chapter will elaborate on this subject:

1.3 In what way can maintenance engineering contribute to the performance of infrastructure?

This chapter starts with the basic principles of maintenance engineering, followed by some theory about maintenance organisation. Then several concepts and tools will be introduced that can be used to structure and support a maintenance engineering process. Finally, infrastructure maintenance in specific will be addressed.

4.1 Introduction

Irrespective of the quality of the design process and the realization process, almost any infrastructure system will during its life reach a state in which it is unable to deliver the desired functionality. This situation is known as the state of failure. One option is to do nothing, another option is to restore the functionality. The last option describes the maintenance process, defined as "the flow of maintenance tasks selected and performed to retain or restore the functionality of the system during its operational process". Successful completion will restore the status into a state of functioning. Throughout its lifetime, a system experiences failure and repair events. This process can be illustrated by means of a functionability profile (Knezevic, 2009, p. 548).

It is important to have information about the characteristics that determine this functionability profile since the infrastructure system is only of use if it performs the desired function and satisfies the performance requirements. This functionability profile is mainly determined by two factors (Knezevic, 2009, p. 549):

1) "Inherent characteristics of a system, like reliability, maintainability, and supportability, which directly determine the frequency of the occurrence of failures, the complexity of maintenance tasks and the ease of the support of the tasks required, all of which are determined by the decisions made by the designers and constructors at the early stages of the system design";
2) "Operational characteristics of a system, which are driven by the operational scenario, maintenance policy and the logistics support concept, determined by the each user of the each system, with the objective to manage the provision of the resources needed for the successful completion of all operation and maintenance tasks".

4.2 Maintenance engineering

To put it differently, the performance of a system depends on (1) its inherent characteristics and (2) on the way it is operated and maintained. Both determinants are covered by the field of maintenance engineering.

4.2.1 Maintainability engineering

Traditionally, the main purpose and concern of the civil engineers was the achievement of a function at the lowest initial costs. How to maintain this function was left to the people responsible throughout the maintenance phase. The last decades, engineers and decision-makers have become increasingly aware of the large amount of the life cycle costs that is spend on maintenance. It turns out that a large part of these maintenance costs were determined by the system characteristics. Substantial savings can be made by developing a design that can be maintained effectively and efficiently. As a result, several concepts have been developed that basically all have the same purpose: ensure that all the aspect systems which determine the value and costs of a system throughout its life cycle, are taken into account during the design process.

What is meant by aspect systems? Complex systems (e.g. infrastructure systems) are often subdivided into smaller parts, called subsystems (e.g. bridge, pavement) to enables a coordinated contribution of all parties required to design the system. A system can also be approached by considering aspect systems, defined as a subset of the relations of the system including all elements of the system. The system's characteristics are determined by the aspect systems. The aspect systems together with its mutual relationships determine the value and costs of the system (de Ridder & Vrijhoef, 2007, p. 7).

To optimise the value and costs of a system, it is important to pay attention to (or even steer on) aspect systems in the design process. There are numerous examples of aspect systems, for instance reliability, availability and (life cycle) costs. The interrelations between aspect systems have to be taken into account so that the desired balance can be found. All the well-known methodologies like systems engineering, value engineering, life cycle costing and RAMS all take notice of this principle. As more elaborately described in Appendix C, successful system control requires four conditions to be satisfied: there needs to be (1) some index of performance, (2) a model of the system, (3) information about the input and the state of the system and, (4) enough steering variety (de Leeuw, 1976, p. 97).

This research will concentrate on the control of one system characteristic in specific, called maintainability. It is defined as "the probability that a given maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources" (NEN, 1999, p. 9).

4.2.2 Maintenance planning

Besides the system characteristics, the functionability is also defined by the operations and maintenance activities throughout the operational life of the system. This research deals mainly with maintenance[23], defined as "the combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function" (NEN, 1999, p. 9).

This research will focus on the actions that precede the actual operations and maintenance phase. These preparatory engineering actions mainly come down to the development of a maintenance plan: collated information, policies and procedures for the optimum maintenance of a system (NAMS, 2006).

In order to develop such a maintenance plan, decisions have to be made regarding the maintenance policy applied, like failure based -, condition based - or use based maintenance. In addition, a schedule has to be made, indicating when maintenance activities are planned and how they will affect the functionability profile. Finally, a budget has to be made, showing what costs are expected to be made during the maintenance phase.

4.2.3 Integration

As explained above, the maintenance engineering can be split up in two functions. The first is to manage the maintenance related aspects throughout the design process. Since this function concentrates on maintainability, it is referred to as maintainability engineering. The second function is to optimally prepare the maintenance phase, a function from now on referred to as maintenance planning. Both terms are summarised in Figure 18.

It is important to realise that maintainability is a system characteristic in its operational context, and that therefore, an integrated approach is required. In other words, the maintainability of a system depends on the system design itself, but also on its maintenance plan. For instance, if the maintainability of a lamp is defined as the duration of a maintenance task, maintainability can be optimised by putting the lamp on an accessible height (system design); or by providing the crew with a easily collapsible ladder (maintenance plan).

Maintenance engineering	
Maintainability engineering Incorporation of maintenance related aspects in the design process to support the development of a life cycle cost effective system	**Maintenance planning** Development of an optimal maintenance plan in order to be well prepared for managing the maintenance phase

Figure 18: Maintenance engineering

[23] The maintenance definition as applied for the purpose of this research is in Dutch referred to with 'Beheer en Onderhoud'. 'Beheer' is "het geheel van activiteiten, op korte, middellange en lange termijn, die er op gericht zijn om de functies van een constructie gedurende de levensduur te laten vervullen." 'Onderhoud' is "alle technische activiteiten, die nodig zijn om functievervulling van de constructie gedurende de levensduur mogelijk te maken. Deze activiteiten omvatten onder andere schoonmaakwerkzaamheden en herstelmaatregelen" (Rijkswaterstaat Bouwdienst, 2005, pp. 8.7-3).

4.3 The maintenance organisation

The performance of a system can only be properly managed if the importance of maintenance is recognized on every organisational level. The following present an overview of the nature of the strategic, tactical and operational responsibilities that are mentioned in maintenance theory. A summary of these responsibilities is presented in Figure 19 (Mobley, Higgins, & Wikoff, 2008).

4.3.1 Strategic, tactical & operational maintenance

On strategic level, maintenance decisions are being made with a focus on the long term. The prime responsibility is to provide a maintenance strategy that makes sure that the long-term performance targets that are laid down in the business strategy are met. This makes strategic maintenance engineer[24] among other things responsible for:

- Managing the asset portfolio size and composition;
- Assuring efficient and effective operation of the asset portfolio at minimal life cycle cost;
- Guiding efforts to ensure long term reliability and maintainability of the asset portfolio;
- Ensuring that the tactical activities are aligned with the overall business strategy.

On tactical level, the maintenance engineer its prime responsibility is to ensure that the assets meet the present demands. This makes the tactical maintenance engineer on a tactical level responsible for:

- Developing, implementing, and evaluating an effective asset maintenance plan, describing failure modes, maintenance policies, schedules, budgets, etc.;
- Controlling the maintainability aspect during an asset's design phase;
- Supporting the strategic maintenance activities with input information (e.g. best practices).
- Ensuring the operational activities are executed in accordance with the maintenance strategy

The operational responsibilities are borne by the maintenance engineers on site. Their prime responsibility is to execute the physical maintenance activities formulated by the maintenance engineers:

- Inspecting the asset's conditions;
- Executing maintenance interventions;
- Supporting the development of tactical maintenance activities.

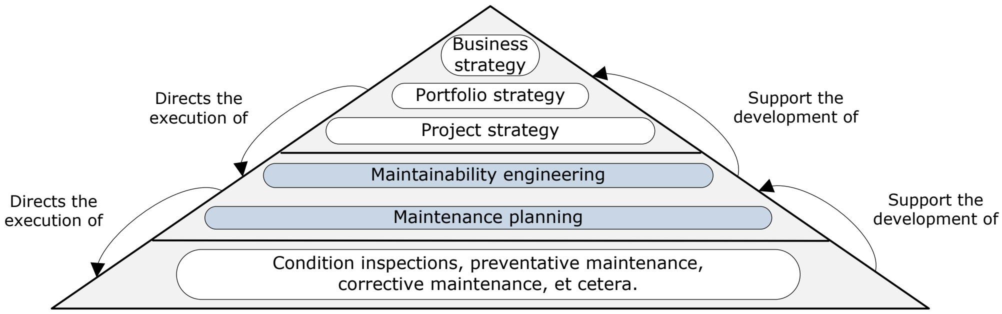

Figure 19: The relations between strategic, tactic and operational maintenance

4.3.2 Integration of managerial levels

Each of the managerial levels contributes to the overall maintenance performance. The fact that the performance of the three levels is closely interrelated makes that a bidirectional flow of information is required. In maintenance theory, special attention is paid to the interaction between the operational and tactical level. On operational level, knowledge is gathered with regard to the actual physical system and maintenance performance. The on-site engineers for instance know whether a subsystem is easily accessible, whether the subsystem is easy to repair and what the actual duration of the maintenance task is. This practical knowledge

[24] In maintenance theory, the strategic maintenance function is often referred to as reliability engineering.

has to be transferred to the tactical level so that it can be used in the maintenance engineering process. The interaction between both levels enables continuous improvement of the design- and maintenance planning process.

4.4 The infrastructure maintenance organisation

4.4.1 Introduction

The previous paragraph dealt with the principles of a maintenance organisation in general. This paragraph will be used to concentrate on infrastructure maintenance in specific. Infrastructure contracts with a long term maintenance obligation, force contractors to take maintenance into consideration during the execution of a project. As illustrated in Figure 20, the nature of the maintenance activities shifts as the project progresses. This starts on a strategic level just after a tender has been notified by a client organisation. The contractor among others has to decide whether the project fits in its portfolio and whether it wants to apply at all. And if so, if it wants to form a consortium or apply individually.

Subsequently, a tender organisation has to be established and the tactical maintenance responsibilities have to be designed: how to ensure that maintainability engineering and maintenance planning is properly incorporated throughout the tender and design process? If these decisions are made, the actual maintenance engineering can start. The (bid) design is made and the maintenance phase is prepared. Finally, the maintenance phase commences and operational maintenance responsibilities become dominant.

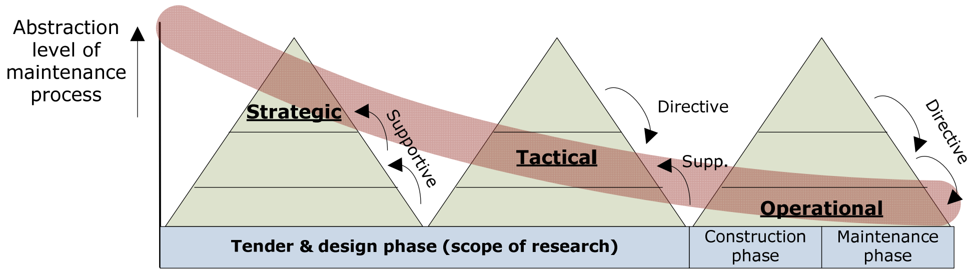

Figure 20: Dominant maintenance level throughout a DB(F)M project

4.4.2 Infrastructure maintenance organisations

Optimal system performance requires maintenance to be recognized on a strategic, tactical and operational level. Moreover, optimal maintenance performance requires the three levels to be connected. How is this organised in the civil engineering industry? Traditionally, Rijkswaterstaat took care of the strategic, tactical and even some operational maintenance activities like inspections. Only the large operational maintenance activities were left to the market. As a result, there was no need for private infrastructure maintenance organisations.

The introduction of integrated contracts with a long term maintenance obligation has resulted in a revised division of roles. The interface between the Rijkswaterstaat and the market has moved upwards in the triangle with managerial levels. As a result, Rijkswaterstaat now only deals with maintenance on a strategic level. Private parties are now contracted to deal with both tactical and operational maintenance. But they also have to deal with strategic maintenance, for instance deciding on the tender strategy or managing an asset portfolio.

As a result of this new division of responsibilities, organisational changes have been carried out by the large contractors in the Netherlands. Interviews have been conducted to gather insight into how the large contractors have positioned maintenance within its organisation. Each large contractor consists out of numerous subsidiaries. Some[25] have established a specific subsidiary that deals with strategic, tactical and some operational maintenance. Others[26] chose to include strategic and tactical maintenance in an existing subsidiary.

[25] For instance, Ballast Nedam nv established Ballast Nedam Beheer bv. This is a subsidiary that deals with strategic, tactical and some operational maintenance. Large operational maintenance activities are passed on to the construction subsidiaries.

[26] For instance, BAM nv has included maintenance in the already existing maintenance department of the BAM Civiel bv.

Another strategy[27] observed is to include tactical maintenance in a engineering subsidiary and to leave all operational activities to the construction contractor subsidiary.

4.4.3 Actors involved in a DB(F)M project

In the Dutch civil engineering industry there is not (yet) one company that covers the total maintenance process. As a result, the maintenance activities in a construction project are often covered by several organisations. To ensure the comprehensibility of this report, some actors that will frequently recur throughout the rest of this thesis, will be introduced and defined.

- The engineering consultant: a contracting party[28] that agrees to undertake responsibility for providing an engineering consultancy service. This can be an in-house, or an external, independent firm;
- The construction contractor: a contracting party[28] that agrees to undertake responsibility for building a pre-specified object. This is what the role of a contractor traditionally looked like;
- The design & construct contractor or EPC: a contracting party[28] that agrees to undertake responsibility for a design and construction service. In a DBFM context, this actor is often referred to as the engineer, procure and construct contractor (EPC);
- The maintenance contractor or MTC: a contracting party[28] that agrees to undertake responsibility for providing a given maintenance service. This may include the provision of a consultancy service. In a DBFM context, this actor is often referred to as the MTC.

Going by the maintenance literature, it seems that there is an important role to play for the maintenance contractor in the early project phases. Involvement of the maintenance contractor (or a party that is very closely related) seem the only way to make sure that knowledge from the operational level is incorporated on a tactical level in the early project phases.

4.5 Maintenance engineering support

4.5.1 Introduction

Maintenance activities are executed by different actors on different managerial levels. In literature, several maintenance concepts are described that support the management of these activities. They guide the development of system-specific maintenance policies that embody the organisations maintenance philosophy. Most of these maintenance concepts have been initially developed for the aeroplane and process industry, sectors that were much earlier aware of the importance of maintenance than the civil engineering industry. For the sake of completeness, Business Centred Maintenance and Total Productive Maintenance will be introduced first. After that, Reliability Centred Maintenance (RCM) and a more flexible framework will be discussed. Finally, a design support methodology will be introduced that is often used in the maintenance engineering process: RAMS.

4.5.2 Business Centred Maintenance & Total Productive Maintenance

Two well-known maintenance concepts are Business Centred Maintenance (BCM) and Total Productive Maintenance (TPM). BCM takes the strategic business objectives are the starting point of the maintenance process. The fact that it is really geared towards the manufacturing industry makes it however less suitable for the application in other sectors, such as the civil engineering industry.

TPM aims continuously improve the efficiency and effectiveness of (industrial) activities. Important objective is maximize the equipment effectiveness by concentrating on the availability, performance efficiency and the quality rate. Some consider TPM not really as a maintenance concept since it goes much further than maintenance only. Simultaneously, it is incomplete as a maintenance concept since it lacks clear rules to decide on for instance the most suitable maintenance policy (Waeyenbergh & Pintelon, 2002).

[27] This is more or less the strategy of Heijmans nv, which leaves all strategic and tactical maintenance to Breijn bv.

[28] This party can be one private limited company, a joint-venture, etc.

4.5.3 Reliability Centred Maintenance

Reliability Centred Maintenance (RCM) is a concept that was originally developed for the aeroplane industry. Later, adjustments have been made to make it, among other things, more applicable for the construction industry. The RCM process seeks to answer seven questions, of which the first five together form the Failure Modes Effects and Criticality Analysis[29] (FMECA). A more in depth description of the criteria that each step has to satisfy is enclosed in Appendix D (Mobley, et al., 2008, p. 2.35).

1) What are the functions and the associated desired standards of performance of the asset? (functions);
2) In what way can it fail to fulfil its functions? (functional failure);
3) What causes each functional failure? (failure mode or functional failure);
4) What happens when failure occurs? (failure effects);
5) In what way does each failure matter (failure consequences);
6) What should be done and by who, to predict, or prevent each failure? (proactive tasks and task intervals);
7) What should be done if a suitable proactive task cannot be found? (default actions).

Waeyenbergh & Pintelon (2002, p. 306) indicate that RCM mainly concentrates on reliability instead of maintainability and availability. This makes RCM especially suitable for sectors in which maintenance is mainly a safety issue (e.g. the aeroplane industry) instead of an economic issue (e.g. the process industry). They further mention that the FMECA analysis tends to become very complex, for instance because failure effects are influenced by several variables (e.g. dynamic environment, organisational response) which are very difficult take into consideration. Besides, the timing of effects can be delayed, and its impact can depend on the degree of failure.

4.5.4 Flexible maintenance concept

A maintenance concept is only successful if it is tailored towards the needs of the specific situation and takes into account technical, organisational, economical aspects. The concept has to be reviewed periodically in order to take into account the changing systems and environment. For this reason, Waeyenbergh & Pintelon (2002) developed a flexible maintenance concept presented in Figure 21. The concept enables an iterative process that is based upon the Deming circle approach, and borrows elements from existing concepts like RCM. Each step will be shortly addressed because it clearly illustrates the main steps that generally have to be passed through in a maintenance engineering process, addressing both maintainability engineering and maintenance planning.

The initiation step mainly consists out of two activities. First, the maintenance objectives have to be formulated, often in terms of reliability and availability. Subsequently, an estimate has to be made regarding the resources (e.g. money, people) required to meet those objectives.

The technical and function analysis step aims to reduce the system complexity by selecting the most important subsystems. Then, the components of which the failure consequences could have an impact on the systems performance have to be identified. The framework indicates that this can for instance be done by means of simplified version of the Failure Mode Effects and Criticality Analysis (FMECA).

The policy design step is subsequently used to select the most suitable maintenance policy for the critical components. Known maintenance policies are failure-based -, condition-based - and preventative maintenance. Worth mentioning is that the framework also recognizes the possibility to design-out the maintenance need by improving the system maintainability, thereby facilitating the integration of maintenance planning and maintainability engineering. An overview of the different maintenance policies that can be applied is presented in Appendix F.

The implementation phase exists of the actual implementation of the maintenance policy. The feedback loop speaks for itself. Information from the performance reporting is used to support continuous improvement of the maintenance process.

[29] In Dutch often referred to as 'Bedrijfzekerheidsanalyse'

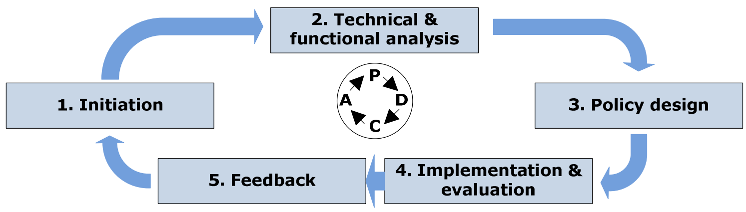

Figure 21: Flexible maintenance concept (adapted from Waeyenbergh & Pintelon, 2009)

4.5.5 RAMS

RAMS is an acronym for Reliability, Availability, Maintainability and Safety. These four aspects can be used to describe, determine and monitor the prime performance of practically every function[30]. The RAMS-methodology provides a set of methods that support these activities. Rijkswaterstaat has only just presented a guideline indicating that it wants to give a more central position to RAMS in its projects.

The objective of RAMS is to map the performance in terms of RAMS aspects, and record it in a way that it can be consulted throughout the life cycle. RAMS can support the maintenance engineering process in two ways. At first, it can be used to compare alternatives, and to improve the design. Secondly, RAMS can contribute to the development of optimal maintenance strategy by delivering input regarding functions, performance, failure modes and maintenance strategies (Rijkswaterstaat, 2010b, p. 7). Below an overview of the definitions of the RAMS aspects (NEN, 1999, p. 8). Figure 22 shows the most important activities that have to be passed through.

- The Reliability of a system is defined as the probability that an item can perform a required function under given condition for a given time interval (t_1,t_2).
- Availability is the ability of a product to be in a state to perform a required function under given conditions at a given time or over a given time interval assuming that the required external resources are provided.
- Maintainability is the probability that a given maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources. See for a further explanation paragraph 4.2.
- Safety is the freedom from unacceptable risk of harm.

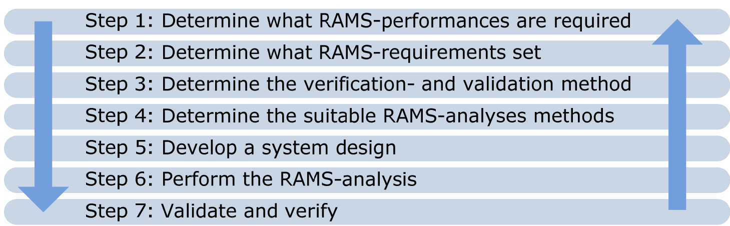

Figure 22: The most important RAMS-activities in steps (adapted from Rijkswaterstaat, 2010b, p. 36)

4.5.6 Life cycle costing

Historically, civil engineering infrastructure has been procured on the basis of lowest initial costs philosophy, resulting in very high maintenance bill. In order to optimize the total cost of ownership, Life Cycle Cost Analysis (LCCA) has been introduced already a few decades ago, defined as a "cost-centred engineering economic analysis whose object is to systematically determine the costs attributable to each of one or more alternative courses of action over a specified period of time" (NAMS, 2006). The primary use is to support in making a (cost) effective choice between competing scenarios (e.g. maintenance strategies). The following six questions cover the key elements that are dealt with in an LCCA:

[30] If a broader view on a system is desired, the scope of RAMS can be elaborated to RAMSSHE (RAMS + Security + Health + Environment) or even RAMSHEEP (RAMSSHE + Economics + Politics).

1) What type of costs have to be included in the analysis, and what costs may be ignored?
2) What cost estimation technique is applied? (probabilistic/deterministic, top-down/bottom-up etc.)
3) Over what specific period of time are the costs to be determined?
4) What technique is used for ranking the alternatives and how is dealt with uncertainties? (NPV/IRR[31])
5) What is a realistic discount rate; and how are the effects of inflation taken into account?

4.5.7 Maintenance engineering toolbox

Each of the concepts and methodologies is supported by different engineering tools. An often used tool is the Failure Mode Effect and Criticality Analysis (FMECA) as also part of RCM. Other tools that can be used are Reliability Block Diagram, Parts Count Analysis, Fault-tree analysis and Markov Analysis. For an elaborate overview of the different tools, its field of application, pros and cons will be referred to chapter 5 of the RAMS guideline, published by Rijkswaterstaat[32] (2010b). A summary in English is enclosed in Appendix E.

4.6 Infrastructure maintenance

4.6.1 Introduction

The previous paragraphs have mainly focussed on the field of maintenance in general. This paragraph will focus on infrastructure maintenance. What are the most important characteristics? In general, there is a increasing need for predictions of failure modes (e.g. life-spans) and optimisations of maintenance strategies. As mentioned already in chapter 2, the demands become increasingly complex. This complexity can only be dealt with a rational approach that supports the trade-off between maintenance costs and benefits. The benefits can only be expressed in risk analytical terms, such as less faults, more safety or a longer life span. As a result, engineers usually apply a risk-analysis kind of approach to deal with infrastructure maintenance supported with methodologies like RCM, FMECA or RAMS (Kuijper, 2006, pp. 8-2).

4.6.2 Technical and functional analysis

The objectives that an infrastructure system is supposed to meet are primarily expressed in terms of availability and safety. The technical and functional analysis is characterised by the fact that the failure rates are not constant. The variations of the strength and the load in time, caused by either external loads or internal processes, is usually referred to as deterioration processes (e.g. metal fatigue, corrosion, wear).

Yet, information regarding the precise deterioration behaviour of a system is almost never available. Mostly, a mathematical expression is formulated, by means of research and system observation. Curve fitting and extrapolation have to be used to obtain a deterioration model since the model research and the observations only cover a limited period of time. Consequently, model uncertainties are introduced. Because the input parameters usually also contain uncertainties, the deterioration process can best be modelled as a statistical process (Kuijper, 2006, pp. 5-38).

A typical civil engineering structure has a time related performance profile that decreases as the life of the object progresses. Throughout this deterioration process, typically two moments can be distinguished:

- Non-structural (or norm) failure, e.g. in theory the road is drivable, but the performance levels of the road in terms of safety, comfort and availability are decreased and considered to be insufficient;
- Structural (or physical) failure, e.g. the road has broken up or deformed so much that it becomes impossible to use.

[31] NPV = Net Present Value calculation, IRR = Internal Rate of Return. Both calculation techniques are used to take account of the time value of money when calculating costs over a longer period of time.

[32] This guideline can be downloaded for free at www.leidraadse.nl

4.6.3 Maintenance strategy

It is very likely that physical failure of infrastructure system leads to accidents and serious injuries. For this reason, asset managers like Rijkswaterstaat base their maintenance strategy mainly upon condition based maintenance. Also some use and time based maintenance is done (e.g. lawn mowing) but these activities (and its costs) are negligible compared to condition based maintenance activities (Dienst Verkeer en Scheepvaart (DVS), 2009, p. 15).

Developing the optimal (preventative) maintenance strategy is a huge challenge. Decisions have to be made regarding inspection methods, intervals, warning limits and action limits. Models have been developed to support this maintenance engineering process. Rijkswaterstaat for instance uses the age replacement model with discounted cost[33]. It not only models deterioration, but also its influence on the (discounted) costs of maintenance. Recently, engineers are becoming more aware of the savings that can be realised by properly gearing maintenance activities towards each other (clustering). Several models have been developed that can support this process (Dekker & van Noortwijk, 2002, p. 7).

4.6.4 Monitoring performance

A lot of literature is available about the type of performance indicators that can be used for infrastructure systems. Many transportation agencies also publish performance data on their website. Actual practice among the agencies however seems to be a relatively limited use (Haas, Felio, Lounis, & Falls, 2009). Interviews amongst experts in the Dutch civil engineering industry confirm this finding: performance measurement in the civil engineering industry is traditionally more focussed on reporting performance (e.g. to road users and ministries) than on improving performance. The civil engineering industry however is becoming more and more aware of the fact that this has to change. The process industry is in that respect far ahead since they are already aware of the contribution of performance monitoring to the improvement of business performance (see e.g., chapter 2 of Ben-Daya, Duffuaa, Raouf, Knezevic, & Ait-Kadi, 2009).

[33] Levensduur Verlengend Onderhoudmodel (LVO)

4.7 Chapter summary

The functionability of a system depends on its design and on how it is maintained and operated. The field of maintenance engineering concentrates on both aspects. Managing the maintenance related aspects (especially maintainability) throughout the design process is referred to as maintainability engineering. Preparing the maintenance phase is referred to as maintenance planning.

A system can only be optimally maintained if the responsible organisation recognizes the importance of maintenance on every managerial level. The quality of the maintenance process can only be managed (and improved) if a cyclical process is realised and an exchange of knowledge takes place between the managerial levels. Several concepts, tools and methodologies are available to structure and support the maintenance engineering process.

In a DB(F)M project, a contractor needs to ensure that maintenance engineering is properly incorporated throughout the tender - and contract phase. Going by the maintenance literature, it seems that there is an important role to play for the maintenance contractor. Somehow, the maintenance contractor's input is required to ensure that knowledge from the operational level is incorporated in the early project phases of future projects.

The following chapter contains the framework that will be used to analyse how maintenance engineering is currently incorporated in the early phases of a DB(F)M project. The same framework will subsequently be used to determine what role structure design enables an improved incorporation of maintenance.

5 ROLE STRUCTURE DESIGN FRAMEWORK

Chapter 3 described that in a DB(F)M project, the private organisation is responsible for the design process. The previous chapter explained how maintenance engineering can make a contribution in realising this potential. This chapter deals with the following subquestion:

1.4 What framework can be used to study the current practice, and prescribe an improved approach?

In other words, the framework will be used to analyse how maintenance engineering is currently incorporated in the early phases of a DB(F)M project, but also to recommend on how it can be done better. This chapter is built up as follows. First, theory will be introduced about design process management in general. Subsequently, each of the role structure elements will be defined and explained. Finally, it will be discussed how the role of the client will be approached.

5.1 Introduction

The construction industry is currently confronted with two design process related problems. At first, the design process often takes more time and/or money than budgeted for. Second, the result of the design process doesn't always match with the client's or users' requirements. The above mentioned observations asked for the development of a new view on the control of design processes, covered by Architectural Design Management (ADM). In short, ADM covers all activities undertaken that aim to realise an optimal project result via an effective and efficient process (van Doorn, 2004, p. 10).

Important starting point of ADM is that the management & control of a design process has to be focussed on both the quality of the process itself and on the quality of the output. The term quality is difficult to define when considering the output of a design process. The quality is dependent on several factors, that can be divided in, amongst others, the functional quality, esthetical quality, construction technical quality and economical quality. The value the different actors attach to the different quality aspects, is largely dependent on the perspective of the own function within the design process.

Not every actor in the construction industry is convinced that a better process quality in the end leads to a better output quality. Van Doorn (2004, p. 18) however concludes that a well managed process in the end does have a positive influence on the output quality. Benefits mainly seem to surface in terms of time, money, information and communication.

5.2 Process design structure

5.2.1 Introduction

As explained in the introduction, the output quality of a design process can be improved by enhancing the process quality. The process quality is on its turn largely dependent on how the process is designed up-front and managed throughout the process. It is especially the design up-front where this research will focus on.

Planning and organising a design process can be seen as making a process-design. It can be used for several purposes: to analyse the design task, to design an action system and to inform all participants in the process about the nature, size, timing and mutual dependencies of their contribution. A process-design consists of two strongly intertwined parts: the process structure and the role structure. Both structures combined describe at what moment in time a step in the process has to be executed, and which actor(s) has to carry out that step (van Aken, 2004, p. 13).

5.2.2 Process structure

The process structure can be seen as the planning part. It specifies the different steps or subprocesses that are determined within the design process, and their sequence and timing. One can for instance fix the different phases in a design process, the subprocesses that have to be completed in order to complete a phase and determine important milestones. This part of the role structure will not be further elaborated on in this research. Instead, the emphasis will lay on the specific contribution made by the actors involved.

5.2.3 Role structure

The second part of the process design is the role structure. It is the organising part of the design that specifies the actors and their roles within the design process. Two role structure elements can be distinguished (see also paragraph 5.3 and 5.4) (van Aken, 2004, p. 13):

- Formal role: describing an actor's responsibilities, position, tasks and authority;
- Informal role: describing the competencies an actor should possess to successfully fulfil the role.

Figure 23 gives an overview of the process design elements related to the design cycle introduced in subparagraph 3.4.5. Only the blue coloured elements belong to the scope of this research.

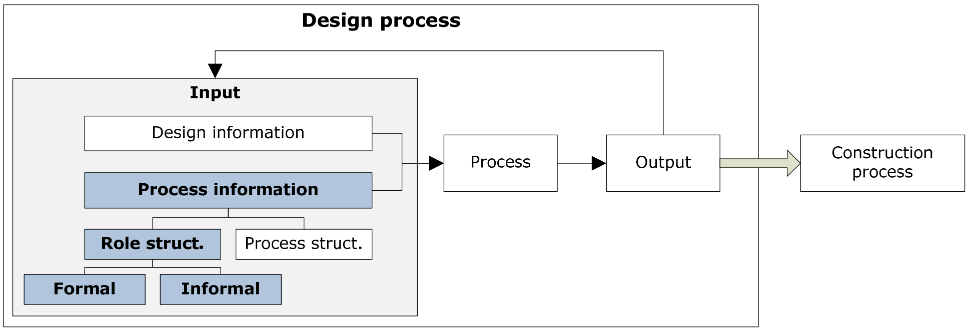

Figure 23: Elements of a process-design structure

5.2.4 Descriptive and prescriptive role structure

Before addressing the formal and informal role structure elements in detail, it is necessary to elaborate on the purpose of the framework. The framework will be used to describe how maintenance is currently incorporated into the early project phases, and prescribe how it should be incorporated. Van Aken (2004, p. 7) indicates that the difference in nature between descriptive and prescriptive models is often unclear. This is understandable: a description of a successful design process can be used as a prescription for future projects, founded by the assumption that it will lead to equal success. Unfortunately, it is not that easy. Contextual differences can make a process design that has been proven to be successful for company A, worthless for company B. This research will therefore try to make a clear distinction between the descriptive and prescriptive role structure design.

The descriptive function of the framework, applied in part 2 in this research, is simply to get a better understanding of how maintenance engineering is currently incorporated in the design process of a DB(F)M project. The input for this analysis consists of two case studies and several interviews.

The findings of part 2 and the literature study will be used to develop a prescriptive role structure design. The prescriptive design aims to support the development of a process design for the tender, design- and construction phase, and allow for subsequent management of this process. The same framework will be used for both the descriptive and prescriptive role structure. The precise application however slightly differs. For that reason will, for each of the role structure elements, be described how it will be applied in the descriptive part (2) and prescriptive part (3) of this research.

5.3 Formal role structure

5.3.1 Introduction

The formal structure regards the patterns within an organisation that develop according formally established instructions. These instructions can be described in, for instance, organisation charts, task profiles and policy documents. Designing an organisation initially deals with the formal structure (van Aken, 1994).

Van Aken (2004, p. 13) points out that design models often only specify the process structure and not the role structure. Going by the interviews conducted as part of this research, it seems that for instance the responsibilities in a design process are only very loosely defined and rarely put in writing. To nonetheless provide some insight in the current practice, the term 'formal' will applied in a more broad sense.[34]

In construction projects, the formal role structure primarily deals with the position, responsibilities, tasks and authority assigned to the parties involved. Both the descriptive and prescriptive formal role structure will therefore only deal with actors in terms of the parties. The informal role structure will be used to enlarge on the role and properties of the individual employees that are involved.

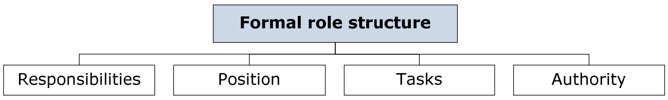

Figure 24: Formal role structure elements

5.3.2 Responsibilities

A responsibility for the purpose of the role structure design is defined as "a duty to deal with or take care of something, so that you may be blamed if something goes wrong". A responsibility describes *what* the actor is obliged to deal with. *How* it should deal with those issues is determined by means of specific tasks, a subject addressed later on. Both the descriptive and prescriptive design will make a clear distinction between the responsibilities that go along with two maintenance engineering functions, namely maintainability engineering and maintenance planning. This approach is adopted because the literature study showed that these are both very important for the performance of an infrastructure system.

5.3.2.1 Descriptive application

The empirical study aims to provide insight into what maintenance engineering responsibilities are assigned throughout the different project phases. Emphasis will be laid on the maintenance responsibilities in the tender-, design- and construction phase. The following questions will be dealt with:

- Which actor is responsible for the maintenance phase?
- To what extent is maintenance engineering addressed as an (important) responsibility?
- Which actors typically bear maintenance engineering responsibilities?
- How do the above affect the incorporation of maintenance?

5.3.2.2 Prescriptive application

The role structure will deal with the maintenance engineering responsibilities in the tender, design and construction phase[35], by answering the following questions:

- What maintenance engineering responsibilities shall be addressed and assigned?
- What aspects have to be taken into account when dividing maintenance engineering responsibilities?

5.3.3 Position

Paragraph 3.3 has already given an overview of the organisational structures that can be applied in DBM and DBFM projects. This part of the role structure deals with the organisational structure as a whole, and the position that is assigned to the actors that deal with maintenance engineering. Focus will be on how the project organisation stimulates and facilitates the parties to realise the life cycle optimisation potential.

Paragraph 4.4 explained that most large Dutch contractors assign a different position to maintenance within its own organisation. The fact that the performance of a maintenance organisation benefits from a good interaction

[34] The focus will initially be on what is put in writing. But, if for instance all actors (including actor A) agree that party A bears a certain responsibility, than it will be assumed to be its responsibility, independent of whether it is put in writing or not.

[35] The scope of the research was initially limited to the tender and design phase. The empirical study however showed that the construction phase is so closely related and important, that the decision has been made to address the responsibilities throughout the construction phase as well. The specific tasks during the construction phase will not be studied.

between the operational and tactical level, is the reason to address the position of maintenance within the (parent) company as well.

5.3.3.1 Descriptive application

The following questions will be dealt with:

- What organisational structure is applied?
- What position is assigned to the actors that deal with maintenance?
- How are the actors stimulated to realise the life cycle optimisation potential?
- What is the position of maintenance within a contractor its company structure?
- How do the above affect the incorporation of maintenance?

5.3.3.2 Prescriptive application

This role structure design will not pretend to present the ideal DB(F)M contractual structure (if there even is one), since this would require a more elaborated study into the financial and legal aspects involved. Instead, the role structure will focus on how the incorporation of maintenance can be facilitated and stimulated by means of the organisational structure.

5.3.4 Tasks

A task is as "a definite piece of work that is assigned to, falling to, or expected of an actor". The tasks executed by an actor are obviously closely related to its responsibilities. Focus will be on maintenance engineering tasks, like for instance carrying out a life cycle costing analysis or making a maintenance cost estimate. The role structure design will also address to supportive function of maintenance concepts and tools in the engineering process, of which the most well-known have been described already in paragraph 4.5.

5.3.4.1 Descriptive application

The following questions will be dealt with:

- What maintenance engineering tasks are executed?
- How are the tasks supported by tools, structured and coordinate?
- How do the above affect the incorporation of maintenance?

5.3.4.2 Prescriptive application

The nature of a design process and the fact that every project is different, makes it impossible to prescribe a set of tasks that guarantee the finding of a solution. Much more helpful, is a rule that facilitates the process of solution-finding instead[36]. It is not an instruction, but a general point of departure for the design of a specific solution in a specific setting (van Aken, 2004, p. 11). That such a task instruction requires certain competencies of the actors will be explained in paragraph 5.4.

5.3.5 Authority

The behaviour of actors within an organisation is also affected by its authority, defined as "the power or right to control, judge, or prohibit the actions of others". While responsibility deals with obligations, authority addresses the right to exercise certain activities. It allows an actor to protect its core values and make sure its interests are served. In general, actor B will follow the orders of actor A as long as the internal conflict at B is smaller

[36] Rules that guarantee a solution are referred to as *algorithmic* technical rules, and have the format 'Do X, and you always have the solution'. Rules that facilitate the finding of a solution are *heuristic* technical, and say 'If you want to achieve Y in setting Z, then do something like X'. The format is only used to explain the intervention-outcome logic. The actual rule description may be a report, drawing, et cetera (van Aken, 2004, p. 11).

than the conflict that is expected to arise with A if the order is neglected[37]. The following sources of authority are, among others[38], mentioned in theory (van Aken, 1994, p. 182):

1) Network centrality: A makes an essential contribution to something that B is a part of;
2) Availability of means: A can reward behaviour of B materially or immaterially;
3) Expert power: A has the availability of competencies that B needs or would like to use (see 5.4);
4) Personal characteristics: the attitude of A affects the extent to which B accepts the authority (see 5.4.5).

The first two sources are aspects that are determined by formal aspects. The last two sources refer to the informal role structure, determined by the competencies of the people involved.

5.3.5.1 Descriptive application

The following questions will be dealt with:

- How are the authorities divided among the actors involved?
- What authority is assigned to the actor(s) responsible for the maintenance process?
- How do the above affect the incorporation of maintenance?

5.3.5.2 Prescriptive application

The nature and purpose of this role structure design makes it difficult to prescribe a specific division of authorities. Instead, the role structure design will focus on how should be dealt with each of the four sources of authority when aiming for an optimal incorporation of maintenance.

5.4 Informal role structure

5.4.1 Introduction

Van Doorn concluded in 2000 that the general opinion within the construction is that the quality of both the process and the output are primarily dependent on the personal and- professional quality of the actors involved. Despites this understanding, usually not much attention is paid to the role structure of a process-design (van Aken, 2004). Van Aken however argues that it is a key part of the process design for large-scale design processes.

The need for an informal role structure design stems from the nature of a design process. A design process is a human action system, supported by materials or tools[39]. Such a human action system is largely driven by thoughts and feelings of the actors involved. The process design can influence these thoughts and feelings, but surely not determine them. As already mentioned in paragraph 5.3.4, a design process cannot be strictly determined up-front. Instead, a prescriptive design is required that facilitates the process of solution-finding. This is realised through internalisation by the designers, and redesigned by them to a design of their own detailed activities (van Aken, 2004, p. 18).

The quality of the realization process largely depends on how the actors understand the contents of the process design, and how they design, manage and execute their own activities according to it. This explains the importance of the informal role structure within the process design: the more suitable the competencies of the actors, the better the design process is actually realised, and the higher its output quality.

5.4.2 Informal role structure framework

Competency is for the use of this research considered as the capacity of individuals to perform within a function or a profession. Spencer and Spencer (as referred to by Garavan & McGuire, 2001, p. 150) defined a

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[37] Van Aken (1994, p. 182) further makes a distinction between power and influence. A has influence over B if it is able to make B behave differently than it would have done without being influenced, but still in accordance with B's own preferences. A has power over B if it is able to make B behave in a way that deviates from its preferences.

[38] The two other sources of authority mentioned are Social position (B more easily accepts exertion of power of A when A has a high position) and Violence (A can enforce B physically). Both sources are not considered to be really useful in this context.

[39] This is different than the realization of, for instance, a building process or a manufacturing process. The latter ones are essentially material processes, which are driven or supported by a human action system (van Aken, 2004, p. 17).

competency as "a set of an individual's underlying characteristics that is causally related to criterion-referenced effective and/or superior performance in a job or situation". It is composed of interrelated elements, which together determine how competencies are expressed. The main principles can be summarized as follows:

- Every human has a set of deep-rooted values and beliefs that are largely invisible for others. These set of norms and values determine the *attitude* of a human towards a situation or action;
- The attitude of a human is amongst others affected by its *motivation*. Motivation is the driving force which make humans achieve their goals;
- A set of *skills* is necessary in order to express certain competencies. These skills are largely visible and to a large extent measurable and trainable;
- An amount of *knowledge* is essential in order to create competencies. Apart from tacit knowledge, knowledge is visible, measurable and trainable.

An informal role structure comes down to a competency profile, which lists the competencies required to successfully perform a job. While the formal role structure dealt with actors in terms of parties, the informal structure will focus on the people involved. The specific competency elements that will be addressed are knowledge, skills, attitude and motivation. The reasons why these four elements have been picked, is because they are generally considered to be the most essential elements of competency. The following subparagraphs explain how each of the elements will be approached the descriptive part (2) and prescriptive part (3) of the research.

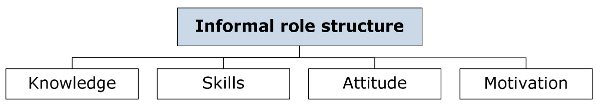

Figure 25: Informal role structure elements

5.4.3 Knowledge

The meaning of knowledge can be explained by relating it to the terms data and information. Data are discrete, objective facts that have no context and interpretation. Data becomes information when it is analysed and interpreted, and value is added by understanding the organisation of data. Knowledge can now be defined as "information in a personalised context, it is information that is experienced, interpreted and processed by a person in a particular situation" (Andriessen, 2006, p. 8). Knowledge consists of theories, principles, and fundamentals. Examples are geometry, calculus and mechanics. The primary source of knowledge is considered to be formal education (ASCE, 2008, p. 10).

5.4.3.1 Descriptive application

The following questions will be dealt with:

- What knowledge is applied by the maintenance engineers involved?
- What knowledge is generally considered to be underdeveloped or missing?
- How does the above affect the incorporation of maintenance?

5.4.3.2 Prescriptive application

The knowledge profile will be derived from the tasks, methodologies and tools prescribed in the formal role structure. It aims to provide an over view the knowledge that is required to optimally fulfil the maintenance engineering responsibilities.

5.4.4 Skills

A skill is defined as "the ability to perform a certain physical or mental task". Skills are generally developed via formal education, focused training, and on-the-job experience. Numerous skills can be distinguished. The American Society of Civil Engineering (ASCE) has developed a skill profile for the civil engineer of the future. It gives a nice overview of some typical civil engineering skills (ASCE, 2008, p. 10):

Skills
Apply basic engineering tools, such as statistical analysis, computer models, design codes etc.
Learn about, assess, and master new technology to enhance effectiveness and efficiency
Communicate with technical and non-technical audiences
Collaborate on intra-disciplinary, cross-disciplinary, and multi-disciplinary teams
Manage tasks, projects, and programs to provide expected deliverables
Lead by formulating and articulating environmental, infrastructure, and other improvements

Table 3: Skill profile of the future civil engineer (ASCE, 2008, p. 10)

5.4.4.1 Descriptive application

The following questions will be dealt with:

- What typical maintenance engineering skills are applied by the engineers involved?
- What skills are generally considered to be underdeveloped or missing?
- How does the above affect the incorporation of maintenance?

5.4.4.2 Prescriptive application

The purpose of the prescriptive role structure design is to provide an overview of the skills that enable an optimal fulfilment of the maintenance engineering responsibilities. The skill profile provided by the ASCE will be used as a point of departure. The relevant skills will be geared towards the role of a maintenance engineer. Other skills will be added if necessary.

5.4.5 Attitude

"Attitudes reflect an individual's values and determine how he or she perceives, interprets, and approaches the world" (ASCE, 2008, p. 10). The notion of attitude consists of several elements, namely values and beliefs, feelings, and behaviour. This research will only concentrate on behaviour: what a person decides to do after (often unconscious) evaluation of values, beliefs and feelings.

The model that will be used to address the notion of attitude is developed by de Caluwé (2008b). Five different ways of approaching a process of change are distinguished, each referred to with a different colour. Table 4 contains the focus and characteristics per profile. There is no such thing as an ideal attitude. The most suitable attitude is determined by the nature of the situation and the other actors involved. A detailed description of the concept is enclosed in Appendix G.

Colour	Focus	Typical characteristics
Yellow	Position and context	Independent, self-control, flexible, diplomatic, power sensitive
Blue	Expertise and results	Rational, result-focussed, control, decisive, expertise
Red	Procedures and atmospheres	Trustworthy, loyal, open-minded, careful, empathy
Green	Setting and communication	Empathy, creativity, openness, inspiring
White	Patterns and persons	Independent, authentic, honest, focus, self-aware

Table 4: The concept of colours (de Caluwé, 2008a, 2008b)

5.4.5.1 Descriptive application

The following questions will be dealt with:

- What attitude is assumed by the maintenance engineer?
- What attitude is assumed by other team members within the process?
- How do the above affect the incorporation of maintenance?

5.4.5.2 Prescriptive application

What attitude is required for a particular role in a specific project depends, among others, on the attitude of the other actors involved. It is therefore impossible to point out what kind of attitude guarantees success. The prescriptive design will therefore limit itself to an explanation of how each of the attitude profiles can be of value in the maintenance engineering process.

5.4.6 Motivation

The attitude of an employee is amongst others affected by its motivation: the driving force which employees make achieve their goals. The psychologist Maslow devised a diagram in the form of a pyramid to express his ideas regarding human needs. When a lower need is satisfied, the next higher level becomes more compelling. The lowest levels reflect extrinsic motivation and the top two levels intrinsic motivation[40]. Typically, an individual has a blend of motives for which a range of different incentives is relevant (Beswick, 2007).

Intrinsically motivated employees are supposed to be more aware of a wide range of phenomena, while giving more attention to the complexities, inconsistencies and unexpected events that go along with a function. It may lead to a greater depth of learning and more creative output. Extrinsic rewards on the other hand tend to focus attention more narrowly and shortening time perspectives. This can result in more standardised products and a more efficient production (Beswick, 2007).

Based upon the literature research, the following can be concluded. The characteristics of a large design process (complex, dynamic) requires foremost intrinsically motivated employees, since attention needs to be paid to complexities, uncertainties and inconsistencies. For the purpose of this research, it is assumed that the challenging nature of DB(F)M contracts and the increasing importance of maintenance will result in enough intrinsic motivation. A further study into the subject of motivation is beyond the scope of this research.

5.5 Role of the client organisation

Chapter 3 described that the client plays an important role in the design process as well, since the scope of the maintenance obligation, contract awarding criteria and requirements specifications have a considerable influence on the optimisation potential. This is the reason why this study will also touch upon the role of the client organisation.

5.5.1.1 Empirical study

The following questions will be dealt with in the empirical study:

- What contract awarding criteria are set?
- What is the quality of the requirement specifications?
- What is the scope of the maintenance obligation?
- What other aspects affect the approach of the contractor towards the incorporation of maintenance?
- How do the above affect the incorporation of maintenance by the contractor?

5.5.1.2 Recommendations

For the abovementioned aspects will be described how they can motivate and facilitate the contractor to improve its approach to maintenance. Since the role of the client will be mainly studied from the perspective of the private parties involved, some restraint is called for when recommending on these subjects. This part of the recommendations is not included in the role structure design, but separately described in chapter 10.

[40] Extrinsic motivation: the task is considered to be a means to an end that is rewarding or satisfying. Intrinsic motivation: a feeling of satisfaction experienced from carrying out an activity itself, rather than its result.

5.6 Chapter summary

This chapter gave a description of the framework that will be used to analyse how maintenance engineering is currently incorporated in the early phases of a DB(F)M project. The same framework will subsequently be used to prescribe what maintenance engineering role should be involved to ensure realisation of the optimisation potential.

The selected framework stems from design management literature, that describes that a design process can be designed by means of a process design. Such a process design consists of a process structure and a role structure, of which only the latter one will be considered. The role structure is the organising part of the design, that specifies the actors and their roles within the design process. It can be further split up in a formal and an informal role structure. The former structure describes the responsibilities, position, tasks and authorities of the actor. The latter one describes the competencies an actor needs to posses in order to successfully fulfil its role. The competency elements that will be addressed are knowledge, skills and attitude.

The framework will be used to analyse the current situation and advise on future projects. An approach that has led to success in the past does however not automatically guarantee future success. This is the reason why for each of the framework elements, a clear distinction has been made between its descriptive and prescriptive application. Since the client organisation plays an important role in the optimisation process and incorporation of maintenance as well, it has also been addressed how the role of the client will be approached in both the analysis and the design.

This chapter was the final chapter of part I. The second part of this research contains the empirical analysis, starting with an explanation of the methodology and the sources that will be used.

Part 2

Empirical study

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6 EMPIRICAL STUDY APPROACH

The previous chapter presented the framework that will be used to structure the empirical study. This chapter describes what empirical study approach will be applied. First, the case projects will be introduced, followed by a few words on the additional interviews.

6.1 Case projects

The contractor Ballast Nedam has been found willing to contribute this research by providing insight into the way it currently approaches the field of maintenance. The subsidiary of Ballast Nedam that is dealt with is Ballast Nedam Beheer, which can best be typified as an in-house asset management organisation. Usually, when BN executes a DB(F)M project, BN Beheer is involved as a maintenance contractor.

The following subparagraphs contain a short introduction of each of the projects and the analysis approach that is adopted. The total analyses itself are enclosed in Appendix H and Appendix I. The most important findings of each of the analyses will be combined into one set of conclusions and presented in the next chapter.

6.1.1 N31 (DBFM)

6.1.1.1 Project introduction

In the beginning of the nineties, the government decided that the road safety of the N31 had to improve. Around 1999, the Dutch knowledge centre for public private partnerships (PPP) drew up a list with projects that were considered to be suitable for a PPP. The Ministry of Transport, Public Works and Water Management (V&W) finally decided to go for a DBFM contract and use the N31 as a pilot project. Because it was the first DBFM project ever for Rijkswaterstaat (RWS), it was made one of the prime objectives to gain practical experience and knowledge. The key characteristics of the project are (Buck Consultants & John Cooper Consulting, 2004):

- Contract:
  - Client: Ministry of V&W and RWS Noord-Holland;
  - Contractor: Consortium Wâldwei.com (Ballast Nedam, BAM, Dura Vermeer);
  - Value: ± € 80 mln (construction costs: € 60 mln, maintenance costs: € 20 mln).
- Scope:
  - Design and reconstruction of the motorway between the exit Leeuwarden and Nijega;
  - Design and construct of the aquaduct 'Langedeel' and the moveable bridge 'Fonejachtbrug';
  - Finance, maintain, and partly operate the above mentioned objects and the existing double lanes motorway between Nijega and Drachten (ca. 22 km) for around 20 years.
- Timeline :
  - Tender: March 2002 – December 2003;
  - Design and construct: January 2004 – October 2007;
  - Maintenance: January 2004 – December 2022.

6.1.1.2 Analysis approach

The tender, design and construction phase have already been completed for several years now. For that reason, it is difficult to perform an in depth study into these early project phases. Above all, it is questionable whether such an analysis would give a proper reflection of the current practice. The reasons is that the N31 was the first time Rijkswaterstaat applied a DBFM contract. Assumedly (and hopefully), the parties involved have already learned from its mistakes.

The fact that the project is already for a few years in the maintenance phase also has its advantages. It provides the opportunity to study how the plans that have been made in the maintenance phase finally work out. In addition, it can be studied how the organisations evaluate its performance and apply these learning experiences in other projects. These are the reasons for why the analysis mainly concentrates on the maintenance phase itself, and less on the early project phases. Interviews will be conducted with the project director, the project leader of the maintenance phase, the maintenance site manager and an engineer involved in the design process of Aquaduct Langedeel. Besides, documents have been studied from both the public and private parties involved.

The analysis will also make use of an evaluation performed by Buck Consultants and John Cooper Consulting (2004). The evaluation, which is performed at the request of Rijkswaterstaat and the Ministry, mainly concentrates on the tender procedure. Though it doesn't really concentrate on the incorporation of maintenance, it nevertheless contains some useful insights.

The analysis itself is enclosed in Appendix H. The most important findings will be combined with the findings of the other case study, and described in the next chapter.

6.1.2 Capacity expansion Johan Frisosluis (DBM)

6.1.2.1 Project introduction

The Johan Frisosluis in Stavoren is the connection between the channel Johan Frisokanaal and the lake IJsselmeer. It is the most important entrance for the recreational lakes situated in the Province of Fryslân. The Province observed that the capacity of the existing lock did not any longer satisfy the demands. In order to solve this issue, a project has been initiated. Besides aiming to increase the capacity, also ambitious objectives were formulated in terms of durability, ecology, and public information service. The key characteristics of the project are:

- Contract:
  - Client: The Province of Fryslân;
  - Contractor: Ballast Nedam (BN Infra bv and Ballast Nedam Beheer bv);
  - Value: ± € 15,3 mln (construction costs: € 9,8 mln, maintenance costs: € 5,5 mln).
- Scope:
  - Design and construction of additional lock capacity;
  - Modification of the mechanical & electrical systems of the movable bridge Brug Warns;
  - 20 Years maintenance of Invalspoort Stavoren and Brug Warns.
- Timeline:
  - Tender: March 2010 – June 2011;
  - Design and construct: June 2011 – December 2013;
  - Maintenance: December 2013 –2023.

6.1.2.2 Analysis approach

The analysis is made just after Ballast Nedam has won the contract. Since the purpose of the empirical study is to gather insight into the actual working methods, the analysis is mainly used to look back upon the tender phase. Less emphasis is put on the expectations regarding the future course of the contract phase.

The analysis will pay special attention to the role of Ballast Nedam Beheer. At first, because Ballast Nedam Beheer is the party that will finally become primarily responsible for managing the maintenance phase. Going by the literature research, it is interesting to see what maintenance engineering contribution Ballast Nedam Beheer has made in the early project phases, in order to be optimally prepared for the maintenance phase. The second reason, which is more of a practical reason, is that Ballast Nedam Beheer provided the opportunity to study this project, and that it has given most information regarding its role within the project.

The analysis is enclosed in Appendix I. The most important findings will be combined with the findings of the other case study, and described in the following chapter.

6.2 Additional interviews

In order to ensure the research validity, additional interviews have been held at client organisations, contractors and (engineering) consultants. An overview of the interviewees is enclosed in the references section. The interview protocol that is followed is enclosed in Appendix J.

The purpose of the interview sessions is twofold. At first, the interviews aim is to support the description of the current working methods. Second purpose of the interviews is to gather suggestions for improvement from the field. The most important findings of the interviews are combined with the findings of the case studies, and clustered in the next chapter of this report.

6.3 Chapter summary

This chapter described that two projects will be studied in order to gain insight into the current practice: N31 (DBFM) and Capacity Expansion Johan Frisosluis (DBM). In addition, experts will be interviewed to find out to what extent the findings in the case studies can be generalized to the Dutch civil engineering industry as a whole. The project analyses itself are enclosed in the appendix. The following chapter contains a description of the most important findings of the case studies and the interviews.

7 EMPIRICAL ANALYSIS

This chapter combines the analyses of both case studies and the external interviews. Per role structure element, the most important findings will be presented. These findings and the literature study together form the input for the role structure design that will be presented in the final part of this report.

7.1 General findings

Each of the interviewees has been asked to give his/her opinion on how maintenance is dealt with by the Dutch civil engineering industry. In addition, the interviews have been asked to describe what developments they have observed in this approach. The most widely held opinions are summarized below.

7.1.1 Civil engineering maintenance is still in its infancy

The field of civil infrastructure maintenance is still in its infancy. Other industries, like for instance the process – and shipbuilding industry, are much more professionalized in this field. Several reasons have surfaced during empirical study. The most plausible reason is that both public and private organisations have never been judged on the performance of an infrastructure system throughout its life cycle. Traditionally, decision makers have only been criticized on a project its initial investment. No-one was judged if the performance in terms of value and costs during the operational life were disappointing. More or less the same applies for the private parties involved. Contractors were only judged on how the system performed right after completion. There has never been a real incentive to consider and optimise the life cycle performance. The incentive was rather the opposite: the more maintenance was required, the more work was put on the market, and the money could be made.

7.1.2 From awareness towards specific actions

Subjects like life cycle costing and maintenance engineering have already been introduced in the civil engineering industry a few decades ago. The interviewees explain that it has taken till a few years ago before some actual progress was made. The introduction of integrated contract seems to have stimulated the recent developments. Most interviewees indicate that the majority of the private parties are now aware of the fact that they cannot any longer ignore maintenance in the early project phases if they want to remain competitive. Others however tend to question whether this awareness is also spread among the operational workforce of the contractors.

Furthermore, it seems to be generally accepted that the civil engineering industry is rather conventional, and that the process of translating this awareness into concrete actions proceeds very slowly. The prevailing opinion is that there is still a very long way to go for both the public and private parties before maintenance is on the same level as in other industries.

7.2 Formal role structure analysis

This part of the role structure analysis answers the question mentioned below. The analysis is structured by means of the framework presented in chapter 5. The elements that will be dealt with are responsibilities, position, tasks and authority.

> *2.1 What formal role structure is currently applied in DBM and DBFM projects, and how does it affect the incorporation of maintenance?*

7.2.1 Responsibilities

The empirical study and interviews have been used to provide insight into what maintenance engineering responsibilities are assigned throughout an asset's life cycle, and how this affects the incorporation of maintenance. The following conclusions can be drawn.

7.2.1.1 Approach towards maintenance engineering responsibilities

The findings in this research confirm the statement of van Aken, that generally not much attention is paid to the role structure (see paragraph 5.3.1). Most of the interviewees find it difficult to describe his or her specific responsibilities in a design process. Formal aspects like responsibility and authority have rather negative connotations in the construction industry. Only a few seem to be aware of the fact that a formal role structure cannot only be used to avoid legal conflicts, but also to support a design process.

7.2.1.2 Maintenance planning responsibility in a design process

The responsibility of maintenance planning is usually clear and understood for all the actors involved, probably because it deals with the development of tangible products like a maintenance plan and a cost estimate. Most interviewees are aware of the importance of maintenance planning in the early project phases. First reason for this awareness is that client organisations often require private parties to already submit a maintenance plan in the tender phase. Another reason is that in a DBFM project, the maintenance cost estimate provides very important input for the financial models. A reliable bid requires an accurate maintenance cost estimate.

7.2.1.3 Maintainability engineering responsibility in a design process

Most interviewees have difficulties with the responsibility of a maintenance engineer in terms of maintainability engineering. The views differ on what this responsibility shall exactly comprise. A plausible explanation for this ambiguity is that many are not very familiar yet with the application of tools like LCC, FMECA and RAMS.

The opinions about the importance of maintainability engineering vary. Some believe that maintainability engineering is important, and that the current practice leaves a lot of room for improvement. Others think that the importance of maintainability engineering shall not be overemphasized. They have the opinion that life cycle and maintainability aspects are to a large extent incorporated in the standard design practices, norms and guidelines. There is also no consensus on whether it is possible and useful to make the maintainability engineering responsibility explicit and assign it to one actor.

7.2.1.4 Maintenance engineering responsibility throughout a construction phase

The scope of the initial research was restricted to the tender and design phase. Some of the interviewees however believe that a sort of maintenance engineering function shall be assigned during the construction phase as well. Three suggestions have surfaced, which shall be ideally assigned to the actor that finally bears responsibility for the actual maintenance phase. First is to let the maintenance contractor act as a quality supervisor, who makes sure that the construction company provides the quality agreed on, and that no undesired last-minute changes are processed. At the same time, it can keep track of abnormalities within the construction process that are useful to know for the maintenance phase[41]. Finally, it can try to search for last-minute optimisations that have been overlooked during preparatory phases.

7.2.1.5 Distribution of responsibilities

A lot of the above mentioned maintenance engineering responsibilities are already (partly) fulfilled in the current practice. But how do these relate to each other? At first, everyone agrees that maintenance responsibilities can’t be considered separately. An integrated approach is required. In addition, it is generally considered to be important that operational experiences are used to improve the performance of new to be developed systems. This is only possible of the organisational structure of a contractor facilitates this process. The general belief is that this is poorly arranged (see also 7.2.2.1).

The performance within a project is influenced by the way the maintenance responsibilities are organised within the project. In the Dutch construction industry, there is not really a universal approach. What responsibilities are addressed, and how they are divided, depends on the organisational structure of the companies involved and the project characteristics. In some occasions, maintenance engineering is included in the overall design

[41] One of the interviewees gave the following example. A cooled down asphalt mixture leads to a less durable road construction. A contractor however will be urged to use it anyway because of the huge costs that go along with returning it. The maintenance contractor will not (try to) forbid the use of the mixture. It however wants to be informed on where it is applied so that it knows what part of the system has to be monitored more carefully during the maintenance phase.

process. It is than assigned as a whole to an external engineering consultant. The opposite is to involve the maintenance contractor early in the process. The maintenance contractor than takes care of the total maintenance engineering process. Also several variants in between have been brought up during the interviews. The role structure design will be used to further elaborate on this subject.

7.2.2 Position

The extent to which a party is able to properly fulfil its responsibilities, among other things depends on its position within its parent company and the project organisation. Regarding the organisational structure and its influence on the incorporation of maintenance, the following conclusions can be drawn.

7.2.2.1 Organisational structure of a contractor

The purpose of Rijkswaterstaat is to enable an integrated construction process by combining design, build and maintenance in one contract. Many of the interviewees however believe that there is still a long way to go before one could speak of a truly integrated project. This is mainly the result of the organisational structure of the large contractors. The contractors all consist of numerous independent subsidiaries, which are primarily judged on its individual financial performance. When a contractor executes a DB(F)M contract, often different subsidiaries are involved. The fact that the interests of these subsidiaries are rarely aligned, makes a DB(F)M contract much less integrated than desired.

Another interesting subject is the position of maintenance within a contractor's organisation. Each large contractor contains an in-house engineering consultant, a construction contractor and a maintenance contractor. It differs per organisation whether these units are combined, categorized in different departments, or even organised as separate subsidiaries. The interviewees all agree on the fact that all of the abovementioned units have to make a contribution to the maintenance engineering process. It is also known that cooperation outside projects is needed to realise a process of continuous improvement. Many of the larger contractors are still looking for the best way to structure these disciplines, and manage the exchange of knowledge. The general opinion is that the above is rather poorly arranged in the current practice.

7.2.2.2 DBFM triangle: SPC, EPC, MTC,

In a DBFM project, legal and financial reasons often make the parties decide to establish different legal entities. Most often applied is the DBFM triangle, elaborately described in subparagraph 3.3.1. It can be concluded that this setting causes fragmentation, which harms the integration of maintenance.

In the tender phase, the EPC is stimulated by the fact that a more life cycle cost effective design will increase the chance of winning the contract. After contract awarding, there is generally no direct financial incentive for the EPC to optimise the total life cycle, since its remuneration is not dependent on the system performance throughout the maintenance phase. Engineering consultants are not stimulated to develop a life cycle cost effective design, whereas contractors are not stimulated to optimise the quality of its' construction processes. They have tried to fix the above by means introducing warrant clauses. The problem is, however, that concise warrant clauses don't hold stand in practice. On the other hand, elaborate clauses cost (too) much time and effort.

The abovementioned results in a disadvantageous position for the MTC: it needs to be involved in the design and construction process in order to defend its interests, but has no formal position to do so. Some indicate that, especially when the maintenance costs are substantial, a more dominant role for the MTC would be appropriate. The MTC shall than act as an influential asset manager, which is formally involved in every project phase. Others however stick to the more conventional approach, in which every party directs its traditional speciality.

A few of the interviewees put all these disadvantages in perspective. They believe that this is all just theoretical, and that the negative effects can be avoided if the project directors present the image of a collaborative team. If they set a good example, the rest will follow suit.

7.2.2.3 EPCM structure

The interviewees that have been involved in the N31 project are very positive about the EPCM structure. There are however several reasons for why it is not considered to be perfect either. A company that enters into an EPCM bears responsibility for the design, build and maintenance aspect. Most companies (or subsidiaries) are however specialized in only one or two of these aspects. Entering in an EPCM means that the company has to bear responsibilities beyond its (traditional) field of expertise[42].

7.2.2.4 Position of an engineering firm

Engineering consultants are generally involved on the basis of a cost reimbursement contract. As a result, they are not (financially) motivated to aim for life cycle optimizations. This can be solved by letting the engineering firms participate in the consortium, and letting it contribute equity. This strategy is carried out by the Coentunnel Company, in which Arcadis participates. It is the question though, how willing the smaller engineering firms are to carry these kind of financial risks.

7.2.2.5 Partnering and learning

Most interviewees indicate that they are best able to manage a DB(F)M if they execute it individually. Most contractors however do take part in a partnership to reduce competition and minimize the financial risks. Several disadvantages of partnering can be found in literature. One potential disadvantage in particular surfaced during this study. One of the interviewees mentioned that he experienced that evaluations are less easily initiated when a partnership consists of competitors. A plausible explanation seems to be that none of the partners is very willing to invest in an elaborate evaluation if the learning experiences are shared with competitors. This makes the competitive advantage that can be achieved relatively small.

7.2.2.6 The involvement of subcontractors

Involving (maintenance) subcontractors has both its advantages and disadvantages. Potential disadvantage is that the early involvement restricts the solution space. Consider, for instance, a lock project. If lock gates are generally made of steel, than its a logical choice to involve a steel contractor from the start. Potential risk is that other (innovative) materials, which are possibly much more suitable, are not any longer considered.

If dealt with strategically, an early involvement of subcontractors can also have its advantages. One of the cases showed that a steel supplier immediately lowered its price after taking notice of a life cycle cost analysis in which it didn’t score well. As a result of the lower steel price, the steel alternative ranked best again.

In some projects, part of the maintenance obligations is subcontracted by means of long term maintenance contracts. Several interviews mention the risk of a fragmented maintenance process. Additional effort is required to treat this risk, and ensure that the individual maintenance strategies are geared towards each other (e.g. clustering inspections and interventions).

7.2.3 Tasks

This section addresses the conclusions that can be drawn regarding the maintenance engineering tasks that are executed. Addressed will be both the tasks itself, and the way they are structured and coordinated.

7.2.3.1 Maintenance planning

The following main tasks can be distinguished within the maintenance planning process:

- Performing a technical / functional analysis;
- Deciding on the maintenance strategy / policies;
- Planning the maintenance activities;
- Budgeting the maintenance phase;

[42] An interviewee gave the following example. A construction contractor is unfamiliar with accident management in a maintenance phase, and will therefore be not very willing to assume liability for it. Similarly, a maintenance contractor has only expertise in controlling system parts that are maintainable. It will therefore be not very willing assume liability for a foundation.

- Developing a quality control plan.

Files like the maintenance policy description, schedule, and quality plan are usually combined in a maintenance plan. Client organisation increasingly require contractors to develop an elaborated maintenance plan within the tender phase. One of the interviewed client organisations had the experience that the plans always look very promising, but that the execution during the maintenance phase often leaves a great deal to be desired. Especially, the regularly promised evaluation and development process is often ignored in practice.

7.2.3.2 Maintainability engineering

In general, much less emphasis is laid on maintainability engineering tasks. Some have mentioned the application of Failure Modes, Effects and Criticality Analyses (FMECA) and life cycle costing analyses (LCCA). These analyses typically dealt with subsystems like hydraulic structures, pavement constructions, lock gates, driving mechanisms and expansion joints. Other interviewees explained that they generally try to improve the system performance by indicating the most expensive system elements in terms of maintenance costs. These subjects are than discussed in the engineering meetings. If found to be useful, further effort is put in extending the intervention interval (by means of a different material, coating, etc.), or optimising the maintenance intervention itself.

7.2.3.3 Supportive tools and concepts

The abovementioned activities are barely supported with tools or methodologies. A lot of engineers also have the opinion that typical maintenance engineering tools are way too complex for civil engineering, and only suitable for fields electrical engineering. Only the experienced maintenance experts know how tools and concepts from other industries (RCM, FMECA, FTA/ETA), can be useful in civil engineering projects.

If analyses are performed, it is often done because it is required by the client organisation. As a result, the analyses often tend to become an end instead of a means. First reason is that the client organisations often lack knowledge about the applicability of the analyses. Another reason is that private parties don't yet have a concept or working method in which the analyses can be properly incorporated.

7.2.3.4 Maintenance engineering concept

Another interesting finding is that the civil engineering industry is not used to deal with continuous, cyclical processes. This is especially observed by the interviewees with a different background (e.g. shipbuilding and manufacturing industry). The current working methods are still based upon the traditional role of a contractor. The general belief is that there is an urgent need for a more industrial approach, which enables a more prominent, and integrated approach of the maintenance engineering activities. This considered to be the only way to realise substantial improvements.

Only very little of the interviewees make use of a maintenance concept to structure the maintenance engineering tasks. Some complain that, especially in most tenders, not enough time is available to apply a fully structured engineering approach. Many are looking for a much more simplified concept, that is geared towards civil engineering practices in specific. It should roughly describe and support the steps that have to be passed through in order to arrive at a maintainable system and maintenance plan.

7.2.4 Authority

Subparagraph 5.3.5 described that four sources of authority can be distinguished. The following can be concluded with regard to division of authority, and its effect on the integration of maintenance.

7.2.4.1 Network centrality

In a perfectly managed collaborative design process, each actor can derive certain authority from network centrality. To what extent is this the case in practice? The tender phase and contract phase will be addressed separately.

Besides evaluating the maintenance costs, clients now often also evaluate the maintenance plan when awarding a contract. A proper maintenance plan and a life cycle cost effective bid design is required in order to win the contract. This makes the actors involved (contractor, engineering firm, subcontractors) to a certain extent dependent on the actor responsible for maintenance engineering. The fact that the other users need the actor that is responsible for maintenance engineering, provides this actor a source of authority.

This source of authority disappears after contract awarding. Network centrality only remains intact if the perfect collaborative organisation is established. It has been described already (see 'position'), that this is barely the case in practice, especially when different entities like a SPC, EPC and MTC is established. The interviewees experience that the MTC is highly dependent on the performance and willingness on EPC, but not the other way around. Some experience that this lack of authority puts the MTC on the sideline in the early project phases.

7.2.4.2 Availability of means

The lack of network centrality can be compensated by assigning specific means of authority. What means have been noticed in practice? In a design process, usually several parties have to grant approval before a design is accepted, and the process can continue. A few of the interviewees mention that the maintenance contractor can be made one of the approval authorities. In theory, the other parties will then minimize the risk of disapproval by involving the maintenance contractor, and ensuring its input is incorporated. Unfortunately, the empirical study did not provide insight in whether, and how, this kind of authority is exactly applied in practice.

What also can be considered as a means of authority, is the warrant clause between the EPC and MTC in a DBFM project. The warrant clause gives the MTC the means to force the EPC to deliver quality, by indicating that it will have to pay the maintenance costs that are the result of insufficient construction quality. Many of the interviewees however indicate that the warrant clauses are often only a formality. If a contractor wants to, it will always find a way to dodge the claims.

7.2.4.3 Expert power and personal characteristics

Most of the interviewees that are employed by maintenance contractors indicate that their expertise is still based upon a very limited number of projects. Some have the experience that this limited experience makes it hard to impose its requirements[43]. They however expect that this will improve when more experience is gathered, and more solid information becomes available to underpin arguments.

No specific examples surfaced in which authority has been derived from personal characteristics in terms of attitude. One of the interviewees mentioned that the importance of maintenance can be emphasized by assigning it to a person with a very high position. In the HSL-Zuid project (High-Speed Line South), one of the directors of one the contractors was involved to make sure that maintenance was considered in every important design decision. Also in the N31 project, one of the directors took care of maintenance during the tender phase.

7.3 Informal role structure analysis

This part of the analysis answers the question mentioned below. The analysis is structured by means of the framework presented in chapter 5. The elements that will be dealt with are knowledge, skills and attitude.

> *2.2 What informal role structure is currently applied in DBM and DBFM projects, and how does it affect the incorporation of maintenance?*

7.3.1 General findings

Before addressing the specific informal role structure elements, some more general findings will be discussed regarding the current situation of the field of maintenance engineering.

[43] One of the interviewees illustrated this with the following example. A project that has already been in the maintenance phase for a few years now, shows that a roadside has to be mowed two times per year. In tender of another project, several actors were from the start, very biased towards the idea that one time per year is sufficient. They justified their belief by coming up with all kind of reasons why the reference project was not comparable (e.g. different soil type, different water levels, etc.)

7.3.1.1 Development of competencies

Paragraph 7.1 described that practically all interviewees are convinced that the civil engineering industry lags behind other industries with regard to maintenance engineering. The competencies that have been developed are mainly the result of practical experiences. None of the interviewed with a civil engineering background got specific education in maintenance. Also in educational programs, not much attention is paid to maintenance (engineering). It is only since a few years that a subject like asset management is included in the study programs. Most experts however think that also more attention should be paid to the maintenance engineering methodologies, like done in for instance the study programs of mechanical – and aerospace engineering.

As a result of the above, there is a lack of maintenance engineering experts. One of the possible reasons for why so few people invest in developing these competencies, is that maintenance has a rather negative image. People want to be involved in engineering because they want to create something. The art of maintenance engineering is to ensure that the situation remains unchanged, and this is by many considered to be much less challenging and satisfying.

7.3.1.2 Electrical engineering vs. Civil engineering

The availability of an infrastructure systems is often largely determined by the performance of the mechanical – and electrical (M&E) systems[44]. The key positions in a project organisation are however almost always fulfilled by people with a civil engineering background. Some of the interviewees wonder whether this is wise. It is understandable from the point of view that in the construction phase, most money is spend on civil engineering systems. It is much less logical when considering that the M&E systems are more critical, and often consume most of the maintenance budget. This is why some of the interviewees believe that substantial savings can be realised if in the design and construction phase, more emphasis is put on the M&E systems and its maintenance need.

7.3.2 Knowledge

7.3.2.1 Theoretical maintenance knowledge

The general belief is that the civil engineering industry lacks maintenance engineering knowledge. At first, there is a lack of theoretical knowledge about for instance failure mode, life spans, maintenance policies and maintenance costs. In other industries, suppliers have developed huge databases with historical data. In the civil engineering industry, no such thing is available yet. Where this lack of knowledge stems from will be elaborately discussed in the final piece of this chapter, see subparagraph 7.5.4.

Many of interviewees who work in the private sector, indicate that they find it especially difficult to estimate the maintenance costs in the earliest design phases. They simply lack the historical data to analyse trends and maker proper predictions. In addition, there is a lack of knowledge about construction materials. Substantial savings can often be realised by simply applying different materials or coatings. Problem is that not many engineers have close relationships with suppliers and that, consequently, most are not aware of recent innovations.

7.3.2.2 Practical maintenance knowledge

Everybody agrees that operational maintenance experiences shall be used to give feedback on the maintenance engineering process. The engineers on site can tell how a certain material deteriorates in practice, whether it is easy to maintain, et cetera. The operational workers also possess practical knowledge that can be directly used to improve the maintainability of future systems[45]. The prevailing opinion is that in the current practice, only a very small part of the operational knowledge is made use of. One of the reasons is that most organisations lack

[44] Several recent examples can be given of movable bridges (e.g. Merwedebrug, Hefbrug Waddinxveen) and tunnels (e.g. Roertunnel) in which problems with the M&E systems have led to non-availability.

[45] For instance, mowing costs can be easily reduced by gearing the width of a strip of grass towards the range of a mower. Another example is that the duration of maintenance tasks (e.g. inspections) can often be reduced by improving the accessibility, and making sure that, for instance, parking space is available nearby.

an exchange of knowledge outside projects. Most are aware that substantial savings can be realised if this is improved.

7.3.2.3 Knowledge resources of public organisations

Many of the interviewees working in the private sector are convinced that the public client organisations (especially Rijkswaterstaat) possess a lot of valuable data, information and knowledge. Many wonder why this information isn't made publicly available. The contractors are convinced that this will result in less uncertainties in a tender phase, and thus lower bids of the private parties.

The interviewees who are directly or indirectly employed by Rijkswaterstaat confirm that Rijkswaterstaat has a lot of data. The interviewees however indicate that the data is not organised in a way that valuable information can be easily derived. The Difficulty is that the data is not stored in a central database, but scattered throughout all the region - and district offices. Rijkswaterstaat is currently busy to solve this issue, among other things by the implementation of a universal maintenance system[46].

Currently, a lot of Rijkswaterstaat its knowledge is stored within the workers' heads. Some private parties intend to hire people from Rijkswaterstaat to benefit from this knowledge. The private parties however face the issue that most employees of Rijkswaterstaat only have a narrow speciality (e.g. barriers or road marking), while they are looking for employees with a broader field of knowledge. One of the interviewees also indicated that it is very difficult to find people with the proactive, assertive and knowledge-sharing attitude that is required to be of real added value.

7.3.3 Skills

Tools and methodologies like, for instance, LCC, RCM, RAMS, FMECA, are barely applied. One of the reasons is that there is a lack of engineers that posses these skills. The engineers that currently deal with maintenance can be broadly divided into three categories.

The first category consists of engineers with a traditional civil engineering background. These engineers have no specific maintenance engineering skills, but can compensate this with an extensive experience in, for instance, designing or construction management. The second category are engineers with specific maintenance engineering skills, but a different background than civil engineering. They are very skilled in the tools and methodologies, but lack the civil engineering background that is needed to optimally apply them. The last category consist of engineers that posses both the civil engineering competencies and the specific maintenance engineering skills. Going by the interviewees, these engineers are very rare.

Because only limited attention is paid to maintenance at the universities, most of the skills have to be developed in practice. Some of the interviewees prefer to teach a civil engineer the maintenance engineering skills. Others are convinced that it is much easier to instruct a maintenance engineer the basic civil engineering knowledge. They belief that it is much more about the way of thinking, concepts and tools. Knowledge regarding the objects itself is of less importance, and considered to be much easier to instruct.

7.3.4 Attitude

The concept of colours described in the literature study will be used to draw a picture of the attitude that is generally assumed by the actors that deal with maintenance, and how this affects the performance.

7.3.4.1 Blue-print thinking

At the large contractors, many of the engineers that deal with maintenance have a background as site manager, project leader, or cost estimator. Broadly speaking, these functions typically require a blue attitude: usually, clear and specific goals are imposed and a structured project management type of attitude is required to ensure the goals are met. Going by the interviews, it seems that this attitude is perfectly suitable for maintenance planning, because of its focus on specific tasks and goals.

[46] The program is in Dutch referred to as 'Areaal op orde'. The maintenance system is OBS (Onderhouds-BeheerSysteem).

The performance of course also depends on how the attitude is put in practice. A maintenance engineer can be someone who is mainly reactive, and only monitors and checks the design process. The other extreme is a proactive maintenance engineer, who brings in creativity and stimulates the design team to search for optimisations. The proactive attitude is required to be of added value in a design process.

7.3.4.2 White-print thinking

The involvement of a white-print thinker can have a very positive effect. It stimulates the creativity that is required to develop innovative maintenance solutions. The empirical study has shown that this attitude doesn't necessarily have to be assumed by the maintenance engineer itself. A conceptual designer or architect can perfectly fulfil this role as well.

7.3.4.3 Green-print thinking

The prevailing opinion is that within the civil engineering industry, not much attention is paid to the process of learning and improvement. This can be explained by a lack of a green-print thinker: someone who focuses on collecting instructive experiences to improve the future performance. Some of the interviewees indicate that for every project, one person shall be assigned that primarily deals with performance measurement and evaluations. Most are however afraid that such a role will be never created in practice, since many consider it to be an optional, long term investment with uncertain returns.

7.3.4.4 Red-print thinking

Many also assign a very important role to the project manager/project director. One of the case studies showed that a manager can have a very important role in motivating the actors to take account of maintenance by focussing on the soft organisational aspects. This is especially valuable when the interests are not perfectly aligned and maintenance is formally put on the sideline.

7.4 Role of the client organisation

The final part of the analysis of the empirical study deals with the following question:

> *2.3 How is the market's approach towards the incorporation of maintenance in DB(F)M projects affected by the procurement strategy of client organisations?*

7.4.1 In general

All interviewees agree on the fact that the market still has difficulties with integrating design, build and maintenance. Some however indicate that Rijkswaterstaat must take some blame for this too. They think that the implementation of integrated contracts was way too sudden. One of the interviewees explained that most contractors still have difficulties with integrating the design and build aspect in a D&C contract, let alone DBM, or even DBFM. Some think that a more gradual implementation would have better facilitated the learning process. There are however also interviewees who call this into a question. They belief that a more gradual introduction would have only resulted in an ever longer learning process.

The interviewees broadly agree on the fact that Rijkswaterstaat is still not totally used to the new division of roles. It is still looking for how to optimally fulfil its role as a network manager. The market experiences that Rijkswaterstaat finds it difficult to keep to its strategy role and apply a more hands-off approach. For instance, during a maintenance phase, Rijkswaterstaat is sometimes still inclined to inspect the physical status of objects. Instead, Rijkswaterstaat should be much more focussed on assessing how the private party manages the system.

7.4.2 Contract awarding criteria

All interviewees point out that the design of the contract awarding criteria largely determine the contractor's approach in the tender phase. Most of the interviewees that are working in the private sector, indicate that client organisations generally attach too much weight to price. A contract that is mainly (e.g. 90%) awarded to the bidder with the lowest price is undesirable, because of two reasons. First, because optimisations which turn out to be value increasing (instead of costs reducing) are not valued by the client organisation. This decreases the incentive for a private party to pursue optimisations. Second, because it stimulates private parties to cut costs in order to win the contract. Because of the time value of money, private parties are tended to cut costs in the construction phase. An optimal value/cost ratio throughout the life cycle however often requires the opposite approach: make an additional investment in the construction phase that is recovered throughout the maintenance phase.

It is considered to be a positive development that client organisations increasingly ask the private parties to develop a maintenance plan in the tender phase. The empirical study showed that one client organisation even asked the private parties to consider not only maintenance for the contract period, but also for the thirty years thereafter. All the interviewees are convinced that such incentives stimulate the private party to improve its approach towards maintenance.

7.4.3 Payment mechanism

It can be concluded that the private party's approach towards maintenance is also influenced by the payment mechanism that is applied. From a finance point of view, it is beneficial to include a large payment upon completing the construction phase. The advantage of including a large payment early in the process, is that it has a risk-reducing effect. This cuts down the financing costs, which on its turn results into cheaper tender bids.

However, the conclusion can be drawn that such an early payment tends to shift the attention of the contractors and investors towards the short term performance. The reason is that the private party is rewarded for completing the construction phase as soon as possible. This is likely to harm the quality of the construction process, and thus the value that is provided by the infrastructure system throughout its life cycle.

7.4.4 Requirement specifications

Many interviewees indicate that the requirement specifications provide substantial room for improvement. Complaints mainly regard the level of detail, and the fact that specifications often contain conflicting requirements. Some maintenance engineers complain that often requirements[47] and methodologies[48] are prescribed which totally miss the point. The general belief is that the client organisations lack the maintenance engineering competencies that are needed to formulate its question and verify the solutions that are developed by the market.

7.4.5 Division of maintenance responsibilities

In a DB(F)M project, client organisations make the private party responsible for maintenance. The scope of this maintenance obligation differs per project. In some projects, a client organisation decides to manage part of the maintenance activities itself. The case project showed that the client organisation included no incentive for the private party to consider these activities in its maintenance engineering process.

The sequential interface such as traditionally present (between construction and maintenance & operate) is then replaced by a parallel interface: two parties are simultaneously responsible for ensuring the system's performance. The result is a fragmented maintenance approach and a decreased optimisation potential. The comment must be made that this subject has been mainly studied from the contractor's point of view. The fact that the client organisation has to manage the value of the infrastructure network as a whole, can give several reasons that justify its approach.

[47] One of the interviewees gave the following example. A requirement specification for a tunnel, described that it should provide the fire department a supply of 120 m^3/h with a 100% reliability. Further into the text, the client however prescribed two pumps, each with a capacity of 60 m^3/h. The latter requirement conflicts with the first, knowing that pumps with a 100% reliability don't exist.

[48] One of the interviewees gave the following example. In a lock project, the client organisation required the private party to execute a very detailed RAMS analyses on the hydraulic driving mechanism of the lock gates. The interviewee was convinced that this analysis was way too detailed, and that it was of no use to any of the parties involved.

7.4.6 The role of permit authorities

The final conclusions does not specifically deal with the role of the client organisation. The study showed the optimisation potential that is created by client organisations can be affected by permit authorities. Some permit authorities are very risk avoiding, and therefore unwilling to issue permits for innovative solutions. Most contractors are not willing to risk problems with permit procedures, and therefore decide to go for a traditional solution. The result is a less optimal solution for both the contractor and client organisation.

7.5 Chapter summary

The previous chapter explained the empirical study approach. This chapter contained an overview of the most important outcomes. The role structure framework has been used to organise the conclusions, addressing both the formal- and informal elements. Each of the analysis parts will be shortly summarised, followed by a short reflection on the effect of the formal elements on the development of knowledge.

The overall conclusion of the empirical study is that civil infrastructure maintenance is still in its infancy compared to other industries. One of the reasons is that there has never been an incentive for the industry to consider the total life cycle of infrastructure. Fortunately, some progress has been made in the last few years.

7.5.1 Summary of the formal role structure analysis

Looking at the formal role structure design that is currently applied in DBM and DBFM projects, the following conclusions can be drawn. In maintenance engineering, generally most emphasis is laid on the responsibility of maintenance planning. Maintainability engineering receives only limited attention. On top, both responsibilities are only rarely combined into an integrated, cyclical approach.

An optimal incorporation of maintenance typically requires a contribution of the engineering consultant, construction contractor and maintenance contractor. A good result can only be achieved if every actor benefits from a life cycle cost effective system. This condition is not satisfied in project organisations in which a separate entity is created for the design & construct activities (EPC) and the maintenance activities (MTC).

The maintenance engineering tasks that are generally executed, mainly focus on the development of a maintenance plan. After deciding on the maintenance policies, a planning, cost estimate and quality plan are developed. In general, much less emphasis is laid on the tasks that aim to optimise the system design. Besides, engineers rarely make use of supportive tools and/or methodologies.

The fulfilment of the maintenance engineering responsibilities can be jeopardized if an actor lacks authority. During the tender phase, maintenance can derive some authority from the fact that everybody wants to win the contract. After contract awarding, it depends on the project organisational structure whether a collaborative process occurs. A lack of network centrality can be only partly compensated by other sources of authority (i.e. specific means of authority, expert power and personal characteristics).

7.5.2 Summary of the informal role structure analysis

The general opinion is that the civil engineering industry lags behind other industries with regard to maintenance engineering competencies. Most striking is the lack of knowledge. In contrast to other industries, there is only a limited amount of historical data available. Another issue is the lack of typical maintenance engineering skills. Civil engineers that know how to properly apply concepts and analysis techniques are very rare. As a result, tools and methodologies like, for instance, LCC, RCM, RAMS and FMECA are barely applied in practice.

Final competency element that is considered, is the attitude of the actors involved. In the current practice, the maintenance engineering positions at contractors are mainly held by people who focus on the hard project management aspects. As a result, only very limited attention is paid to learning and improving. Another conclusion that can be drawn, is that involving someone with a creative attitude has a positive effect on the incorporation of maintenance. It turns out that it is also beneficial to involve someone who pays attention to the soft organisational aspects, especially if maintenance is formally sidelined.

7.5.3 Role of the client organisation

Just as the market, Rijkswaterstaat is still not totally used to the division of roles in a DB(F)M project. It is still looking for how to optimally fulfil its role as a network manager. The market experiences that Rijkswaterstaat finds it difficult to stick to its strategic role, and apply a more hands-off approach.

The private parties believe that client organisations have an important role to play in facilitating the market to develop a life cycle cost effective system. The current fulfilment of this role leaves quite some room for improvement. Several interviewees indicate that the current requirement specifications, contract awarding criteria permit procedures and payment mechanism not always facilitate and stimulate an optimal incorporation of maintenance.

Another conclusion that can be drawn, is that client organisations create a fragmented maintenance approach if a DB(F)M contract includes only part of the maintenance activities. The sequential interface, as traditionally present, is then replaced by a parallel interface: two parties are simultaneously responsible for ensuring the system's performance. The result is a fragmented, inefficient maintenance approach.

7.5.4 Key conclusions

In order to structure the analysis, a clear distinction has been made between the formal aspects, informal aspects and the role of the client organisation. The empirical study showed that these three subjects are closely related. The final part of this chapter will elaborate on the relation between the formal elements on the one hand, and the application and development of knowledge on the other hand.

To begin with, the formal structure determines what skills and knowledge are applied, for instance, by indicating which actors are involved per project phase. The formal structure is however also of influence on the quality of the learning process. A totally fragmented process makes it, for example, more difficult to transfer knowledge from one project (phase) to another.

Based upon the empirical study, it can be concluded that the current formal role structure does not optimally facilitate a learning process. It turns out that informal aspects play a role too. Most essential in this regard is the attitude of the actors involved. Finally, also the role of the client is of influence. The quality of the learning process is, among others, dependent on the process requirements that are enforced by the client.

The abovementioned findings are visualised in Figure 26. The findings have important implications for the role structure design that will be developed throughout this research. Aiming for sustainable improvements in the field of maintenance, it is important that the formal role structure design, informal role structure design and the role of the client organisation facilitate the development of knowledge. Only then, a continuous and sustainable process of improvement can be realised.

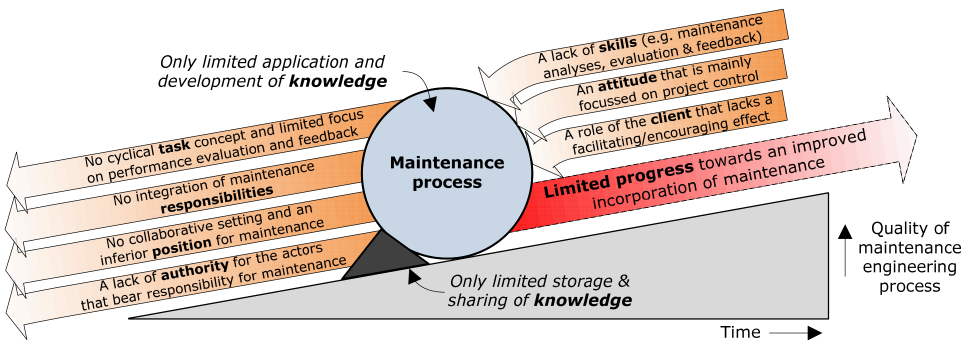

Figure 26: A visualisation of the key conclusions regarding the current situation

Part 3

Solution design

8 FORMAL ROLE STRUCTURE DESIGN

The previous part of the report described the most important findings of the empirical analysis. These findings will be combined with the output of the literature study into a prescriptive role structure design, thereby achieving the first objective of this research. The following question will be answered:

3.1 What formal role structure enables an improved incorporation of maintenance in the tender -, design - and construction process of DBM and DBFM projects?

The framework that will be used to structure the formal role has been elaborately described in chapter 5. After the introduction, the following elements will be dealt with: responsibility, position, tasks and authority.

8.1 Introduction

Every design process is based upon certain requirements that the final design has to meet. The first requirement stems from the main objective of this research: the formal role structure must enable an improved incorporation of maintenance. On top, some additional requirements have surfaced during the literature – and empirical study.

To begin with, the roles structure design should facilitate a process of solution-finding, and provide the flexibility that is required to be geared towards a specific situation. Reason for why a design process cannot be strictly determined up-front, is that a design process is a human action system that is typically faced with a dynamic environment. For more information about this subject will be referred to subparagraph 5.3.4 and Appendix B.

Secondly, the task concept of the role structure design should provide a certain degree of scalability. It should ensure that a structured, cyclical process can be passed through, independent of the time constraints that have to be dealt with. This means that the task concept should contain tools that provide a quick insight into the maintenance related design issues (e.g. for in a tender phase), but also the more complex analysis methods that can be necessary to further optimise the design.

Finally, the empirical study concluded that the field of infrastructure maintenance leaves quite some room for improvement. The role structure should therefore facilitate and stimulate the private party to increase its level of knowledge. Taking a lead on the development of knowledge will mean a competitive advantage in the long run.

8.2 Responsibilities

The first element that will be addressed in the role structure design is responsibilities. What approach to maintenance engineering responsibilities does best facilitate the incorporation of maintenance? Based upon the empirical study, it can be said that explicitly labelling the maintenance planning and maintainability engineering responsibility facilitates the maintenance process. The reason is that it makes all the actors aware of the importance of maintenance. Special attention should be paid to maintainability engineering, which gets easily ignored or sidelined compared to maintenance planning. The reason is that maintainability engineering is less tangible and, for many engineers, a more unknown territory.

The following subparagraphs describe the nature of the maintenance engineering responsibilities throughout the tender -, design – and construction phase. A summary of the content of these responsibilities can be found in Table 5. It is important to keep in mind that the different responsibilities are closely related. As a result, only an integrated approach will lead to an optimal performance. A concept that supports an integrated approach will be introduced in the task section, see paragraph 8.4.

In addition, it is important that the maintenance process as a whole is integrated in the overall design and construction process. This integration is, amongst other things, determined by how the responsibilities are divided between the parties involved. The last subparagraph will therefore address some alternative divisions of responsibilities, suitable for DB(F)M projects.

8.2.1 Responsibilities throughout the project phases

8.2.1.1 Tender phase

The maintenance planning responsibility comes down to developing a maintenance plan and a maintenance cost estimate. The purpose of this responsibility is twofold. On the one hand, it aims to support the development of a reliable and effective bid, by trying to optimally satisfy all maintenance related EMAT criteria. On the other hand, it aims to pave the way for a successful performance throughout the rest of the project, for instance, by providing insight into the resources that have to be reserved for subsequent phases. The latter purpose indicates that the maintenance planning approach should not only be geared towards the demands of the client, but also towards the maintenance strategy of the companies involved. This is the only way to ensure that the maintenance plan becomes a means instead of an end.

The maintainability engineering responsibility is to support the development of a life cycle cost effective bid design, by incorporating maintenance related aspects into the design process. Ideally, maintenance is considered from the start of the design process, when the principal decisions (system or subsystem level) still have to be made and the optimisation potential is still maximal. The concept that will be introduced later on will further elaborate on how this responsibility can be fulfilled in practice.

During a typical tender process, several (sub)contractors and engineering consultants are involved. If maintenance engineering responsibilities are divided between several parties, one party must bear the responsibility of coordinating the maintenance process[49].

8.2.1.2 Design phase

The design process continues after contract awarding, so does the maintenance engineering process. During the design phase, the system design will be optimised and worked out more in detail. It is the responsibility of the maintenance engineer to regularly update the maintenance plan so that it remains geared towards the system design. Since more information becomes available as the design process progresses, the maintenance plan can be worked out more in detail as well.

Despites that most principal design decision have already been fixed in the bid design, there is still room for optimisations. The scope of the maintainability engineering process depends, among other, on the level of detail of the bid design, and the room for adjustment left by the client organisation. As the design process progresses, the focus will gradually shift from a subsystem – to an element level. Design decisions that will be dealt with typically concern construction materials, coatings, aid constructions, etc.

Just as in the tender phase, often several parties are involved in the design phase. Again, it is important that one party is made responsible for coordinating the maintenance activities, so that integration is ensured.

8.2.1.3 Construction phase

Maintenance engineering is a continuous process, meaning that also during the construction phase responsibilities have to be borne[50]. In fact, the previously described efforts are largely a waste of time if maintenance is ignored during the construction phase.

To be able to continue the maintenance engineering process, it is necessary to be closely involved in the construction process. The emphasis in maintenance planning shifts from developing a maintenance plan, to monitoring the construction process and keeping track of abnormalities. It is recommended to process this

[49] At first, the coordination between maintainability engineering and maintenance planning must be ensured. It is however also important that the subprocesses itself are coordinated properly. With regard to maintainability engineering, it should be ensured that, for instance, the maintainability of individual subsystems is geared towards each other. An integrated maintenance planning approach on the other hand, requires that for instance maintenance policies and inspection intervals are attuned.

[50] Usually in DB(F)M projects, the private party is already responsible for maintaining (or actually preserving) the existing systems from the start of the construction activities. This 'maintenance management' responsibility will not be further addressed since the scope of this research is limited to the preparatory stages.

information in the maintenance approach. For instance, if it turns out that the intended construction quality has not been realised, the decision can be made to increase the inspection frequency throughout the maintenance phase.

Considering maintainability engineering, the construction phase can be used to realise optimisations that have been overlooked earlier. Because only a minimal optimisation potential is left, the maintainability engineering effort will mainly have to deal with easily adjustable system elements.

Finally, the system performance of some types of systems is heavily dependent on the quality of the construction process. For that reason, it can be beneficial to closely supervise the realisation of these parts. The maintenance engineer than acts as a kind of quality guard. Additional advantage is that a more active involvement in the construction phase, provides a better insight into the course of the construction process. This enables an optimal fulfilment of the previously mentioned maintenance engineering responsibilities.

8.2.1.4 Summary

Responsibility	Tender phase	Design phase	Construction phase	Maintenance phase
Maintainability engineering	Realising optimisations on a system and subsystem level (e.g. object type, plot lay-out etc.)	Realising optimisations on a subsystem and element level (e.g. materials, finishings, detailing etc.)	Realising 'last-minute' optimisations, focussing on an element level (detailing)	Not applicable anymore (optimisation potential is minimal now the design has been realised)
Maintenance planning	Ensuring a maintenance plan and maintenance cost estimate is developed (as part of the bid offer)	Ensuring a detailed maintenance plan is completed, and resources are secured before the start of maintenance phase	Ensuring an up-to-date maintenance plan, by incorporating construction flaws/ adjustments	Ensuring an up-to-date maintenance plan by processing the actual deterioration and operational experiences
Others	Coordination of maintenance process	Coordination of maintenance process	Coordination of maintenance process; Supervising the critical parts of the construction process	Maintenance management

Table 5: An overview of the maintenance responsibilities throughout a DB(F)M project

8.2.2 Division of responsibilities

8.2.2.1 Introduction

The previous subparagraphs described the maintenance engineering responsibilities that can be distinguished throughout the tender -, design – and construction phase. These responsibilities have to be organised in a way that facilitates:

- A vertical and horizontal integration of maintenance. Vertical integration applies to the different maintenance engineering activities, but also to the design process as a whole[51]. The horizontal integration deals with the continuity of the maintenance process throughout the project phases;
- A process of continuous improvement. A setting has to be created in which knowledge that is gathered within one project (e.g. during a maintenance phase), is used to improve the maintenance performance (e.g. the system maintainability) for future projects.

The extent to which the above two goals are realised is, among other things, determined by the division of responsibilities within a contractor its organisation and the way this is translated into a project organisation. With regard to maintenance, it is especially important to consider the division of responsibilities between the maintenance contractor and the engineering consultant, and the degree to which these parties exchange knowledge in,- and/or outside projects.

[51] Integration of the maintenance engineering activities deals with, for instance, the integration of maintenance planning and maintainability engineering. The integration of the overall design process mainly refers to the integration of the maintenance process with the other engineering disciplines.

Not every contractor has the same organisational structure. Since the division within a project is dependent on the organisational structure, it is impossible to prescribe one 'ideal' setting. Therefore, three kind of contractors will be introduced, each having assigned a different position to maintenance within its organisation. For each type of organisation will be introduced what the most suitable project setting looks like. The three variants are presented in Figure 27.

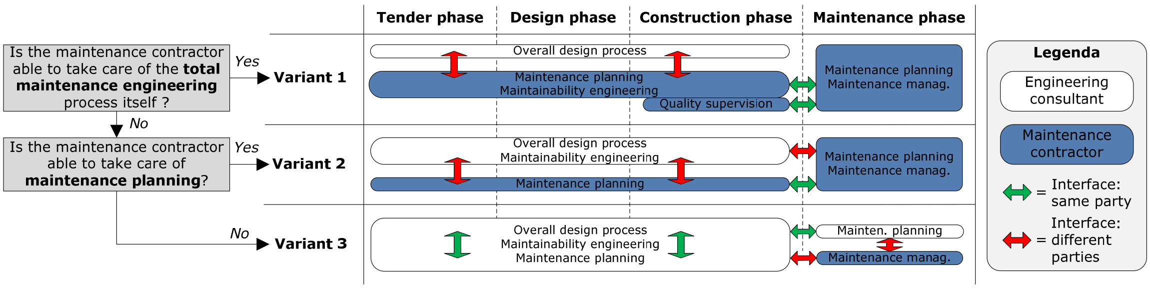

Figure 27: Overview of the three variants and its applicability

8.2.2.2 Variant 1

The first type of contractor that will be considered has established a maintenance contractor that can execute the total maintenance process: it provides maintenance engineering consultancy; is able to watch over the quality of the construction phase; and can manage the maintenance phase.

The project setting that best fits this organisation, is presented on top of Figure 27. As can be seen, the maintenance contractor is involved from the beginning of a DB(F)M process. It bears the responsibility of both maintenance planning and maintainability engineering. The other engineering disciplines are taken care of by the engineering consultant. During the construction phase, the maintenance contractor is involved to watch over the quality of the quality of the critical system parts. After finalising the construction phase, it takes over the system responsibility and manages the maintenance phase.

To what extent does this division of responsibilities facilitate the vertical and horizontal integration of maintenance within a project? Actually, the only interface that has to be managed, is between maintainability engineering and the other engineering disciplines. The vertical and horizontal integration of the maintenance process itself, is facilitated by the fact that is taken care of by one party. The result is that the maintenance contractor is optimally prepared for the maintenance phase, because it is fully familiar with both the system design and maintenance plan.

8.2.2.3 Variant 2

The second type of contractor introduced, has established a maintenance contractor that only takes care of maintenance planning. Maintainability engineering, which often requires more complex analyses, is joined with the other engineering disciplines at the in-house engineering consultant.

The setting that best fits this organisation is presented in the middle of Figure 27. The maintenance contractor is involved from the start, but only to develop a maintenance plan. Maintainability engineering is, just as the overall design process, taken care of by the engineering consultant.

To what extent does this division of responsibilities facilitate the vertical and horizontal integration of maintenance within a project? The vertical integration is harmed by the fact that maintainability engineering and maintenance planning are taken care of by different parties. Additional effort will be required to ensure an integrated maintenance engineering approach. The early involvement of the maintenance contractor in terms of maintenance planning, has a positive effect on the horizontal integration of maintenance. Disadvantage compared to variant 1, is that the maintenance contractor will be less familiar with the system design, because it is less actively involved in the design process.

8.2.2.4 Variant 3

The last type of organisation introduced, is a contractor which has joined the total maintenance engineering process with the other engineering disciplines at the in-house engineering consultant. The only responsibility of the maintenance contractor is to manage the maintenance phase itself.

The setting that best fits this organisation is presented at the bottom of Figure 27. The total design process, including maintenance engineering, is taken care of by the engineering consultant. The maintenance contractor is not involved till the start of the maintenance phase. When the maintenance contractor needs engineering capacity during the maintenance phase, it simply hires the engineering consultant.

To what extent does this division of responsibilities facilitate the vertical and horizontal integration of maintenance within a project? The fact that all the engineering responsibilities are taken care of by the engineering consultant, facilitates an integrated design process. The fact that the maintenance contractor is not involved in the preparatory phases, harms the continuity of the maintenance process. Potential risk is that the maintenance plan is not geared towards the requirements of the maintenance contractor. Combined with the fact that it less familiar with the system design itself, increases the risk of start-up problems in the maintenance phase.

8.2.2.5 Process of continuous improvement

The other criterion mentioned in 8.2.2.1, is that the division of responsibilities should facilitate a process of continuous improvement. How do the three variants do in this area? Variant 1 has the advantage that the total maintenance process is taken care of by the maintenance contractor. This means that all maintenance knowledge is managed by one party, and no exchange of knowledge with other units, subsidiaries, or companies is needed. This enables the maintenance contractor to realise improvements, independent of which engineering consultant is worked with.

In that respect is variant 2 less ideal, since the maintenance engineering process is dealt with by separate parts of the organisation. A process of continuous improvements requires the maintenance contractor and the engineering consultant to exchange knowledge. Only then, knowledge gathered in a maintenance phase (by the maintenance contractor) can be used to improve the maintenance engineering process (executed by the engineering consultant). No long term improvements will be realised if a sustainable relationship between the engineering consultant and the maintenance contractor is lacking.

The same disadvantage applies to variant 3. The maintenance process during the design process is dealt with by a different party than the management of the actual maintenance phase. Even more than in variant 2, an exchange of knowledge outside projects is required to ensure that the maintenance engineering process improves. Again, the learning process is dependent on the sustainability of the relationship between the engineering consultant and the maintenance contractor.

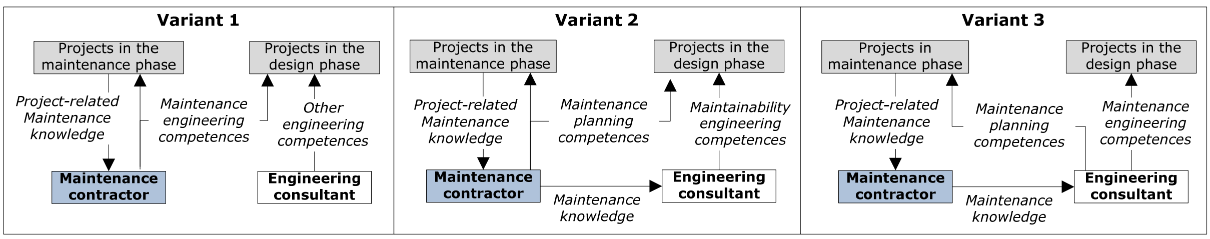

Figure 28: The flows of knowledge required to facilitate continuous improvement

8.2.2.6 Overview

The properties of the three variants are summarized in Table 6.

Var.	Integration of disciplines (vertically) and project phases (horizontally)	Process of continuous improvement	Additional pros & cons
1	- Both the horizontal and vertical integration of the maintenance process itself are optimally facilitated. - The integration of maintenance engineering within the overall design process requires attention.	- Optimal, since all maintenance knowledge is managed by one party.	+ The risk of start-up problems in the maintenance phase is minimal. + The performance of the maintenance process is largely independent of the EC involved.
2	- The integration of maintainability engineering within the overall design process is facilitated. - The integration of maintainability engineering and maintenance planning requires attention. - Horizontal integration is only facilitated with regard to maintenance planning.	- A process of continuous improvement regarding maintainability engineering requires a sustainable relationship between the MC and EC.	+ The risk of start-up problems in the maintenance phase are larger than in variant 1, but not as large as in variant 3. – Maintenance planning performance is dependent on the cooperation with a specific EC.
3	- An integrated design process (vertically) is facilitated because it is dealt with by the EC. - The horizontal integration requires attention, and is heavily dependent on the relationship between the EC and the MC	- A process of continuous improvement regarding maintenance engineering requires a sustainable relationship between the MC and EC.	– Large risk of start-up problems in the maintenance phase. – Maintenance planning performance is largely dependent on the cooperation with a specific EC.

Table 6: An overview of the properties of the three variants
Abbreviations: EC = Engineering consultant, MC = Maintenance contractor

8.3 Position

The previous section described what responsibilities are important, and how they can be distributed amongst the actors typically involved in DB(F)M project. This paragraph will further expand on the division of responsibilities by addressing the organisational structure and the contractual relationships. The research has not led to an 'ideal' contractual structure that can be applied to every DBM, or DBFM project. The role structure design will therefore limit itself to an explanation of the aspects that should be considered when aiming for an optimal incorporation of maintenance.

8.3.1 Integrated approach

An optimal incorporation of maintenance requires a collaborative process, in which also the parties that are responsible for the design- and construction phase are confronted with the actual system performance. This is the only way to ensure that all parties make the desired contribution.

In some occasions, a contractor decides to execute a project individually. The project organisation then consists of several subsidiaries, which all make its contribution. The fact that these subsidiaries are part of the same company, does not automatically create an integrated, collaborative process. The reason is that each subsidiary is typically judged on its own financial performance. An integrated approach therefore requires an alignment of the interests. This can be facilitated in two ways:

- Within the project organisation, by ensuring that every subsidiary has an interest in a life cycle cost effective system. A contractual structure that supports this, will be addressed in the next recommendation (8.3.2);
- Outside the project organisation, by ensuring that subsidiary A is not judged on a negative result (-), if its contribution has substantially increased the result of subsidiary B (++), and thus increased the result of the company as a whole (+).

The latter option is not possible if a project is executed by a consortium of different companies. The only possibility left is then to align the interests within the project organisation. How this can be done will be explained in the following recommendation.

8.3.2 EPCM instead of EPC-MTC

The empirical study elaborately described that the DBFM triangle (SPC-EPC-MTC) is not desirable from a maintenance point of view. Especially when a consortium consists of different companies, it is recommended to apply the EPCM structure, illustrated in Figure 29. The same principle applies to a DBM project: ensure that the parties that are responsible for the design and construction phase, remain involved during the maintenance phase.

The EPCM should not only include the contractors, but also the leading engineering consultant[52]. The reason is that the engineering consultant plays an important role in the optimisation process. It will only optimally fulfil this role if its remuneration is related to the life cycle cost effectiveness of its design. This makes the involvement on the basis of a cost reimbursement kind of contract undesirable.

An optimal application of the EPCM structure requires some further study. This study should, among others, aim to find a solution for the following two issues.

- An EPCM structure requires the parties to be involved in fields or project stages which are beyond their (traditional) scope of work. Problem is that no party is very willing to bear risks it is unfamiliar with and/or unable to manage. A setting shall therefore be created in which each party is (at least) made responsible for its individual contribution to the life cycle cost effectiveness of the system. How this can be put in practices requires further study;
- An EPCM structure requires all the parties to be committed to a project for a very long period (e.g. 20 years). The long term commitment affects the flexibility of a contractor's business strategy, since part of its capital can't be touched. This can be undesired, especially if the number of DBFM projects increase. Additional study is therefore required into what this long term commitment should look like, and what exit possibilities should be included.

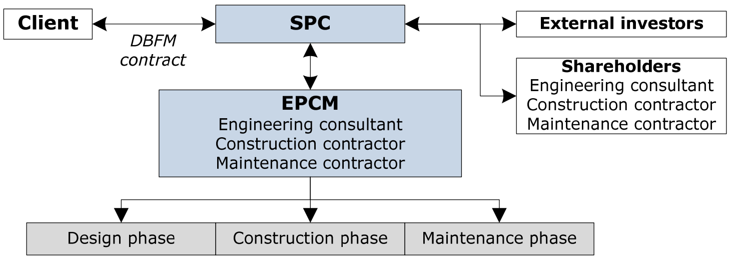

Figure 29: Recommended EPCM structure from a maintenance point of view

8.3.3 The involvement of partners and/or subcontractors

In DBM and DBFM projects, there can be a variety of reasons that make a contractor decide to execute a project in cooperation with other companies like, for instance, the need of specific competences or capacity. These companies can be involved as partners or as subcontractors.

In some occasions, a subcontractor is only involved to take care of a specific design, construction or maintenance task. In other situations, the decision can be made to enter in a more lengthy relationship. An example is a subcontractor that is hired to deal with the design, construction and maintenance of a part of the system. The subcontractor is than involved by means of a DBM contract. Regularly, these agreements are set up so that penalties due to defaults of the subcontractor are passed on one-on-one.

As mentioned already, there are a variety of reasons that justify the cooperation with other companies as a partner or subcontractor. When aiming for an optimal incorporation of maintenance, it is however important to take the following aspects into consideration:

- The risk of a fragmentised the maintenance process.
  For instance, if company A becomes responsible for designing, constructing and maintaining subsystem 1, than company A is motivated to develop a maintenance plan that is optimal for subsystem 1, not taking into account whether it results in the optimal maintenance approach for the total system. As a result, additional effort is required to ensure an integrated approach;

[52] This need is smaller in case the in-house engineering firm is involved, assuming that the engineering consultant is motivated by the fact that a more optimal design results in a better performance of the maintenance contractor, and thus the overall firm.

- Early involvement of partners/subcontractors limits the design freedom.
  An optimal design in terms of life cycle costs, sometimes requires an innovative approach. The early involvement of a supplier of 'traditional' materials (e.g. steel, concrete), can limit the view of the designers. As a result, innovative materials are not taken into consideration (e.g. composite, carbon etc.);
- The risk of a difficult (maintenance) performance evaluation process.
  Performance evaluation during the maintenance phase is essential to improve the system performance during the maintenance phase, and improve the long-term maintenance performance of the company as a whole. A partnership with different companies can hamper the overall evaluation process. The only limited competitive advantage that can be realised de-motivates the individual partners to evaluate.
- The risk of conflicts during the maintenance phase.
  The agreement can be made that the penalty as a result of the malfunction of a subsystem are passed on to the responsible subcontractor. But what if the non-availability is caused by a defect on the interface of two, or even three subsystems? Solid agreements, but especially good relationships are needed to avoid conflicts.

8.4 Tasks

8.4.1 Introduction

The previous paragraphs have addressed the maintenance engineering responsibilities that have to be fulfilled in a DB(F)M-project. But what tasks have to be executed in order to successfully fulfil these responsibilities? One of the most important conclusions of the empirical study is, that only a small part of the civil engineering industry is familiar with the variety of maintenance engineering tasks, - methodologies and - tools that can be applied. In addition, only a limited part knows how the individual tasks should be integrated into an overall, cyclical maintenance process.

In order to improve the current situation, this role structure design will present a maintenance concept that can be used to guide and structure the maintenance engineering tasks. The concept is an expansion of the flexible maintenance framework of Waeyenbergh and Pintelon (2009, p. 635), introduced already in the literature study (see subparagraph 4.5.4). This framework is chosen as a point of departure for the following reasons:

- It is complete, in the sense that it facilitates an integrated approach of maintainability engineering and maintenance planning. See chapter 4 for why this integration is so important. In addition, it facilitates an approach that meets the four conditions for successful system control of De Leeuw, described in Appendix C. An additional step (2) is inserted to better satisfy the condition that a model is required to monitor the current status and the presumable effect of control measures[53];
- The concept facilitates a cyclical approach, which is so important because it enables a learning process. This is particularly valuable for the civil engineering industry, since the current approach to maintenance leaves quite some room for improvement;
- The main steps of the framework are concise and straightforward. That is important because it makes the concept easy accessible, also for engineers that lack specific maintenance engineering competencies. This enables a maintenance engineer to instruct other engineers the basics of the field, thereby facilitating the integration of maintenance into the overall design process;
- The framework provides the flexibility that is required to gear it towards different kind of infrastructure design processes. Each of the main steps can be geared towards the type of system that is considered, the design stage, the amount of time that is available et cetera.

[53] Condition one (be familiar with the system objectives) is met by step one. The second condition (availability of a model) is satisfied by step two. Condition three (information & data) is dealt with by the description of the input that is required per step. The cyclical approach further ensures that the availability of knowledge and data is improved. Step four covers condition four (control variety).

8.4.2 Flexible maintenance concept

The maintenance concept that is prescribed to structure the maintenance tasks is illustrated in Figure 30. The following subparagraphs contain an explanation of the six main steps. Addressed will be the sub steps that have to be passed through, the input that is required, and the output that will be produced. Each step is summarised by means of an IDEFO activity model[54].

The content of each of the steps stems from several sources. Parts are borrowed from existing maintenance and design methodologies, like for instance Reliability Centred Maintenance and RAMS. The RAMS guideline of Rijkswaterstaat (2010b) was useful in particular, among others because of its overview of supportive tools and analyses. Confronting these theories with the findings of the empirical study has led to the concept that will be presented in the following subparagraphs.

How should the maintenance concept be applied in practice? As can be seen, the cyclical process consists of six steps. Each step is executed several times during a DB(F)M process. The specific tasks that are executed per step is determined by, among others, the input information available, the output required and time constraints that have to be dealt with. The level of detail of each of the steps gradually increases as the design process progresses.

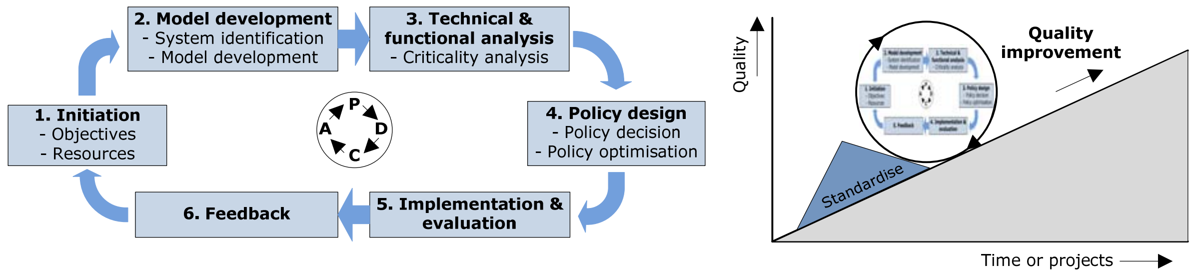

Figure 30: The maintenance concept (left) (elaboration on Waeyenbergh & Pintelon, 2009, p. 635), and its function in facilitating a process of continuous improvement (right)

8.4.3 Step 1 - Initiation

The initiation phase aims to pave the way for the subsequent steps. It consists of the following tasks:

1) Develop (or update) an understanding of the system (scope, context and purpose) and its environment;
2) Determine (or update) the maintenance process objectives. First group of objectives are in function of the learning process, and derived from the long term strategy. An example can be the gathering of specific data, or the implementation of a new tool. Second group of objectives describes the contributions of the maintenance process to this specific project, in terms of maintenance planning and maintainability engineering.
3) Determine (or update) the system objectives. Aspects that, amongst others, have to be addressed are reliability, availability, maintainability and life cycle costs. Project specific requirements are derived from the tender documents; general requirements from norms and standards[55];
4) Tailor the subsequent maintenance engineering process. Describe how the maintenance responsibilities are divided and how these are related to the overall design process. This description also contains an overview of important meetings, milestones and schedule dependencies;
5) Identify the resources that are required to execute the maintenance process. Resources have to be defined in terms of, among others, time, money and competencies[56].

[54]IDEFO stands for Integration DEFinition for Function. Each box represents an activity. Project specific input information enters from the left. Control information (e.g. engineering standards) enters from the top and control mechanisms (e.g. analysis tools) enter from the bottom. The produced output information leaves the box at the right.

[55] Useful in this regard is Appendix 4 of the RAMS guideline (Rijkswaterstaat, 2010b), which contains an overview of RAMS requirements that are included in norms and standards.

[56] The informal role structure design presented in the next chapter will provide a competency profile.

The results can be documented in the overall project plan, or as a separate kick of document. It is important that the assumptions and justifications are clearly described, so that the output can be updated easily if new information becomes available. As the cycle suggests, this step will be passed through several times during a project's life cycle. As the maintenance process progresses, the emphasis of this step will shift from designing and shaping, to executing and controlling the maintenance process. Not every substep has to be completed the first time the cycle is passed through. Substeps can be postponed to a subsequent cycle if, for instance, not enough information is available.

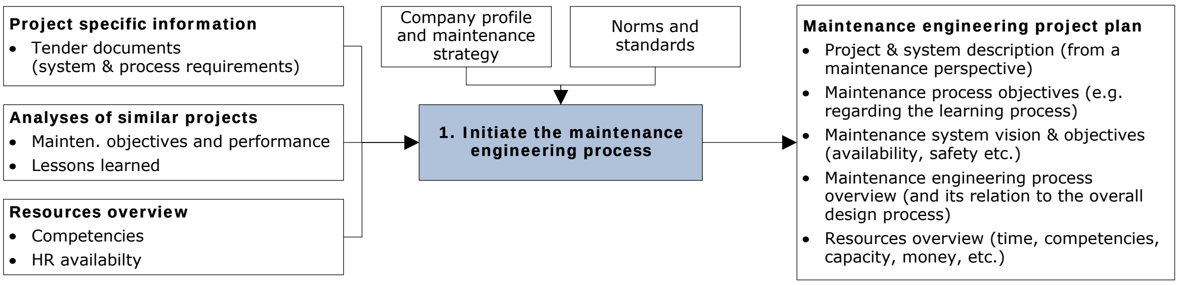

Figure 31: Step 1 - Initiation

8.4.4 Step 2 - Model development

The goal of this step is to develop a model in which the most important system characteristics are present. It is used throughout the rest of the maintenance engineering process to monitor the performance of the current design and the presumable effect of control measures. In addition, a performance measurement plan is being developed.

1) Develop a model that enables performance measurement and simulation. What kind of model is required is, among others, dependent on the system complexity and the availability of resources. It is essential that the model design is in balance with the data availability. A detailed model without the data available to determine the parameters and validate the results is useless. Appendix E gives an idea of the type of modelling techniques that can be applied.
2) Develop (or update) a performance measurement plan: define the performance indicators and the analysis technique that will be used to monitor the performance during the design-, construction and maintenance phase[57]. This decision is among others based upon the project stage, availability of resources, maintenance objectives and system complexity.

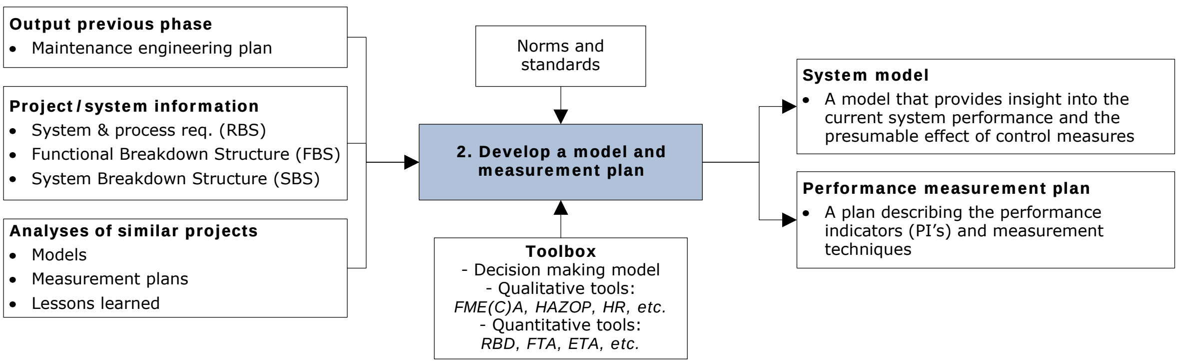

Figure 32: Step 2 – Model development

8.4.5 Step 3 - Criticality analysis

The prime intent of this step is to identify which specific failure consequences could have an impact on the system objectives previously defined. The following tasks have to be executed:

[57] A useful aid for performance measurement in the maintenance phase is the recently published NEN 2767, titled Condition assessment - Part 4: Infrastructure.

1) Perform the analyses to identify and asses the issues that can prevent the system from achieving the objectives. The analysis should not only consider physical issues only, but also organisational, environmental-, safety issues, et cetera. The result is an overview of the most critical systems, containing a description of its functions, failure modes, failure effects, and failure consequences.
2) Identify opportunities in terms of life cycle optimisations, for instance, by identifying the system parts with a high maintenance costs/investment costs ratio. In addition, the parts have to be identified which require expensive maintenance interventions at an interval that is around similar (or half, or even a third) of the duration of the maintenance obligation[58]. As part of the identification process, it can be helpful to split the system up into three categories:
   - System parts that already exist. The modification is prescribed by the client, or no modification is allowed at all. The optimisation potential for these parts is minimal;
   - System parts that exist, but allow for substantial modification or reconstruction. These parts usually provide a medium optimisation potential[59];
   - System parts that do not exist yet and have to be developed from scratch. These parts offer maximal optimisation potential and deserve most attention throughout the engineering process.

In sum, this phase determines what specific parts of the system design require attention during the next phases of the maintenance engineering process. If the analyses are initially set up well, than the rest of the design process can be used to update the analyses or work them out more in detail.

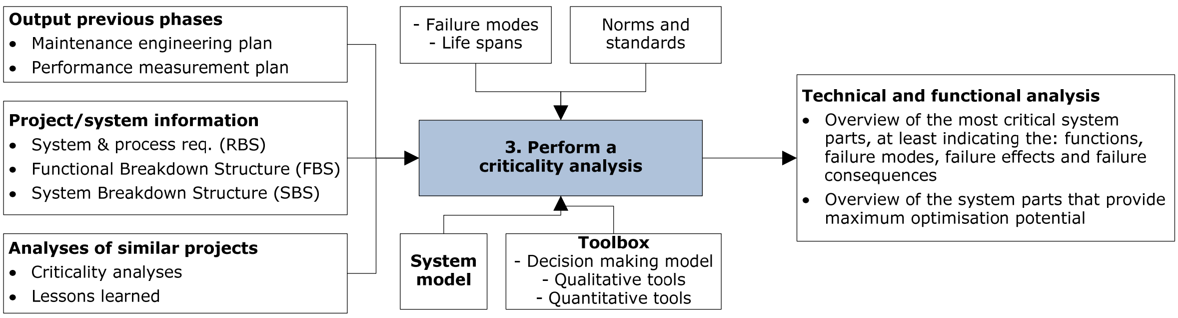

Figure 33: Step 3 - Criticality analysis

8.4.6 Step 4 - Policy design and optimisation

After performing a technical and functional analysis, an overall maintenance strategy can be developed. Key activity in step is defining the maintenance policies. The most well-known policies available, are failure based maintenance (FBM), condition based maintenance (CBM) and use based maintenance (UBM). For an explanation of each of these policies and its applicability, will be referred to Appendix F.

Several times in this research, it has been emphasized that successful maintenance engineering requires an integration of maintenance planning and maintainability engineering. This concept enables this integration, by providing an alternative policy: design out maintenance (DOM). DOM aims to eliminate, or at least reduce the need for maintenance by adjusting the system design. The first question should be asked, is whether it is technically feasible to design out the maintenance need. Second, it should be assessed whether is it is economically desirable to adjust the design, since it typically has a negative impact on other aspects (e.g. initial investment, aesthetic value, user comfort). A tool that is typically suitable for the economical assessment is the life cycle costing analysis.

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[58] A typical example can be a certain type of pavement construction, that requires a large maintenance intervention 9 years. It speaks for itself that this task interval is very unfortunate if the maintenance obligation is twenty years. Substantial savings can be realised by increasing the task interval to, for instance, 11 years. An early identification of these kind of opportunities makes it easier to seize them.

[59] Roughly two options are available. The first option is to keep the existing construction as it is, and accept high maintenance costs. Second option is to spend some money on reconstructions at the start, and make relatively low maintenance costs. A life cycle costing analysis can be used support the decision making process.

After deciding on the most suitable maintenance policies, each policy should be optimised. This process should aim to optimise the maintenance policy itself (e.g. optimal intervention intervals and levels), but also optimisation of the system design. For instance, the accessibility of a certain subsystem can be improved in order to shorten the (expected) duration of a planned maintenance task. Again, a life cycle costing analysis can support the typical trade-off between construction costs and maintenance costs.

In sum, step three consists of the following sub steps:

1) Identify the optimal maintenance policy for all critical system parts;
2) Specify and optimise the maintenance policies:
    a) Design out maintenance: write a design adjustment proposal;
    b) Failure based maintenance: develop contingency plan;
    c) Condition based maintenance: define inspection intervals, intervention levels, etc.;
    d) Use based maintenance: define intervals and maintenance tasks.
3) Plan response actions to risks that require a different type of response (e.g. financial, political, organisational etc.). The four generic responses to threats are to accept, avoid, transfer or reduce the risk;
4) Make a maintenance cost estimate;
5) Update the maintenance performance plan (as developed in step 1);
6) Process all the above in a maintenance plan.

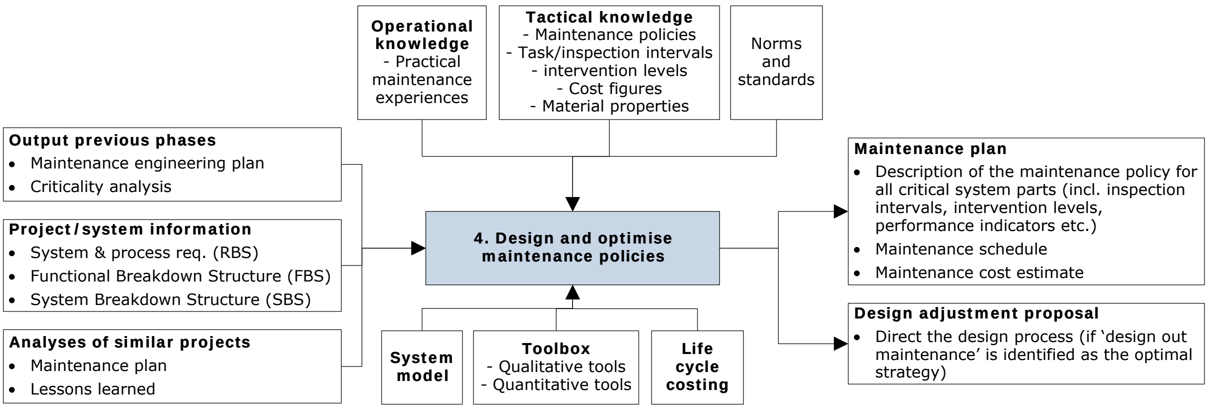

Figure 34: Step 4 - Policy design

8.4.7 Step 5 - Implementation & evaluation

The first objective of step four is to implement the maintenance policies. With regard to design out maintenance policy, this consists of presenting and processing the design adjustment proposals. Actual implementation of the other policies (e.g. condition based maintenance) is obviously waited for till the system is realised, and the maintenance phase has begun.

Second objective is to evaluate the performance of the maintenance process. The elevation should at least deal with the following two aspects. To begin with, it should address performance of the maintenance engineering process itself, in terms of both effectiveness and efficiency. Amongst others, the following questions should be answered: Is the maintenance engineering process still within time and budget? What is the quality of the maintenance engineering output? How is the linkage between the overall design process and the maintenance engineering process? What improvements are possible? Et cetera.

The second aspect that requires attention within the evaluation process, is the performance of the maintenance policies and other response actions. Again, the evaluation should both focus on effectiveness (e.g. has an intervention had the desired effect on the system performance?), and efficiency (e.g. how can the duration of a maintenance task be decreased?). Close interaction with the site personnel is required in order to gather the operational experiences and information that is required to further optimise the maintenance approach.

In sum, step four consists of the following sub steps:

1) Implement the maintenance policies (adjust the design, or execute the maintenance tasks);
2) Implement the actions that have been planned in response to other risk categories;
3) Evaluate the performance of the maintenance engineering process;
4) Evaluate the performance of the maintenance policies and other response actions.

Performance monitoring and evaluation should be a continuous process. The most important findings should be recorded into a maintenance process evaluation on a regular basis, and disseminated to other relevant parties.

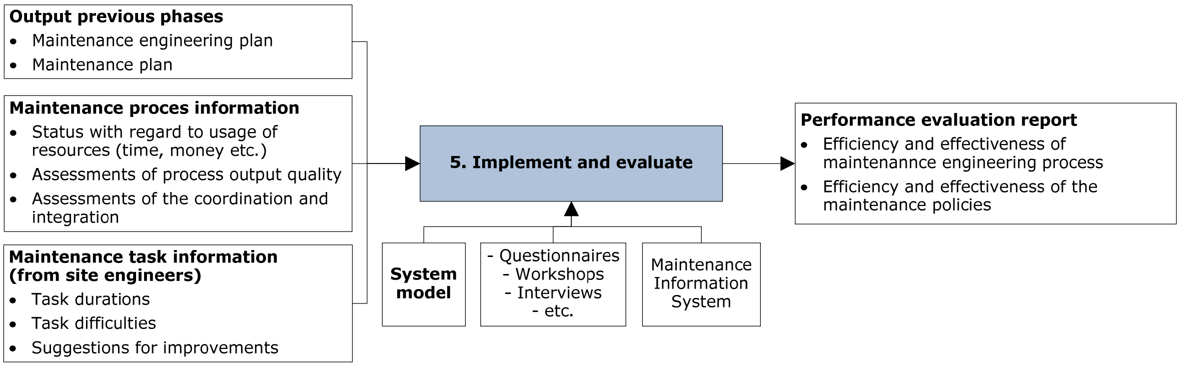

Figure 35: Step 5 - Implementation & evaluation

8.4.8 Step 6 - Feedback

The last step completes the feedback loop. It deals with spreading project created knowledge towards the project organisation, but also towards the companies involved (and possibly other subsidiaries). The part of the role structure design about responsibilities (subparagraph 8.2.2) already explained that the precise fulfilment of this step depends on the division of maintenance engineering responsibilities within the company and project. Broadly speaking, the following two steps can be distinguished:

1) Spread knowledge within the project organisation, in order to improve the maintenance engineering process, and thus the project performance. This deals with project related improvements;
2) Spread knowledge within the company, in order to improve the maintenance performance of the company as a whole. This deals with more general improvements that have a broader applicability.

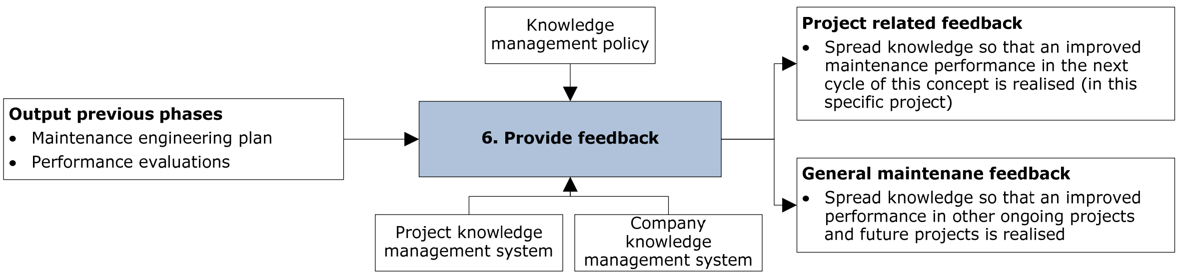

Figure 36: Step 6 - Feedback

8.5 Authority

The literature and empirical research described that the authority of an actor among others depends on network centrality, the availability of means, expert power and personal characteristics. How can each of these facilitate the incorporation of maintenance in the early phases of a DB(F)M project?

8.5.1 Network centrality

With regard to network centrality, a distinction has to be made between the tender phase and the contract phase. Within the tender phase, it largely depends on the contract awarding criteria whether authority can be derived from network centrality. The more value is attached to the maintenance plan and life cycle aspects, the stronger the position of the party responsible for maintenance engineering. The tender manager can play an important role in confirming this position, by making the other parties aware that the tender can only be won if everyone supports the maintenance engineering process.

The situation changes after a contract has been won. Network centrality then requires a project organisation that facilitates a collaborative design process. The paragraph that deal with the position of the maintenance actors (8.3), already indicated that from a maintenance point of view, an EPCM structure is recommendable. The reason is that an EPCM structure creates a setting in which all actors benefit from an optimal maintenance process. This network centrality provides the actors that are responsible for maintenance with a source of authority.

8.5.2 Availability of means

Ideally, a DB(F)M project is set up in a way that a collaborative process is facilitated. If this is somehow impossible, there can occur a situation in which the position of 'maintenance actors' can come under pressure. An example is the DBFM triangle, in which the MTC has a rather difficult position compared to the EPC. In this situation, specific means can be made available to (partly) compensate the lack of network centrality. Looking at the position of the parties that are responsible for maintenance engineering in specific, the following could be arranged:

- Assign approval authority within the design and construction process.
  In a design and construction process, usually several parties have to grant approval before a design is accepted and the process can move forward. The position of the party that deals with maintenance can be improved by making it an approval authority. The proposed effect is that the other parties will try to minimize the risk of disapproval, by taking the demands of the maintenance engineers into account throughout the design process;
- Enforce strict warrant clauses.
  The application of warrant clauses is normal practice when a project organisation with a separate EPC and MTC is established. The warrant clauses ensure that the EPC pays for maintenance costs that are caused by faults in the design and construction phase. The proposed effect is that the EPC also pays attention to the long term performance and aims for a high quality construction process. Such clauses only work if the scope and duration of the warrant clauses are thought out well. The empirical study already indicated that this is not as simple as it sounds, since the clauses become easily too concise, or too elaborated.

8.5.3 Expert power and personal characteristics

The authority of the party responsible for maintenance engineering is primarily determined by the previous two sources, which are fixed in the formal role structure design. This position can be enforced (or weakened) by means of two informal aspects: expert power and personal characteristics.

Expert power initially deals with the competences that are brought in. What competencies are suitable in this regard will be elaborately described in the informal role structure design, presented in the next chapter. The empirical study also indicated that the number of reference projects plays a role. Putting effort in the gathering of data is recommended, since it contributes to the performance of the maintenance engineering process, and thus to the informal authority of the maintenance engineer. Having more data makes it much easier for the maintenance engineer to underpin its arguments, and justify investment proposals that increase the life cycle cost effectiveness.

Second informal source of authority is the attitude of maintenance engineer involved, a subject that will also be dealt with in the next chapter. In addition, the management team can confirm the importance of maintenance by making one of the managers or directors primarily responsible for it. This gives a clear to all actors involved that maintenance should not be ignored.

8.5.4 Overview

The sources of authority referred to in the previous subparagraphs are summarised in Figure 37.

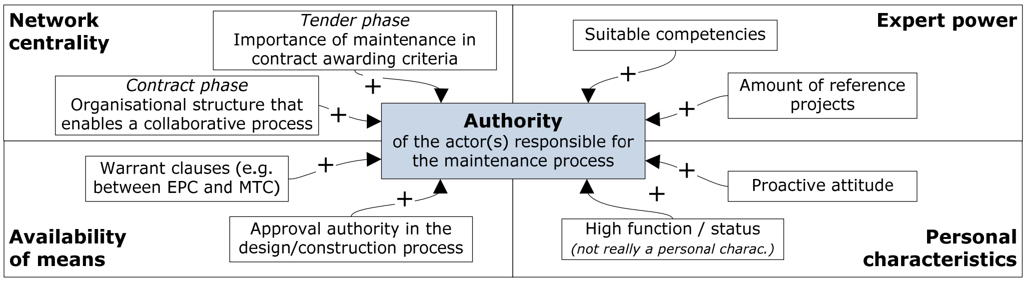

Figure 37: Overview of the sources authority that can be provided

8.6 Chapter summary

The previous part of this report presented the most important findings of the empirical study. It ended with the conclusion that the formal role structure plays an important role in the application and development of knowledge. The formal role structure design that has been presented in this chapter therefore not only aims to allow for an optimal incorporation of maintenance in the early phases of DB(F)M projects, but also tries to initiate a process of continuous improvement. Such as visualised in Figure 38, each part of the role structure aims to foster the development of knowledge in the field of infrastructure maintenance.

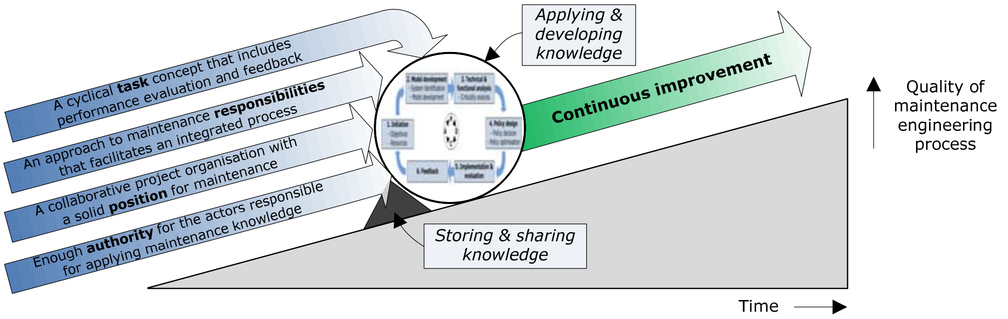

Figure 38: The contribution of the formal role structure to an improved maintenance field

The formal role structure design elaborates on the following elements: responsibilities, position, tasks and authority. The rest of this paragraph contains a summary of each of these four subjects. At first, it is important that the responsibilities of maintenance planning and maintainability engineering, and its role throughout the process, are clear for all the actors involved. Special attention should be paid to maintainability engineering, which gets easily ignored or sidelined compared to maintenance planning. Whether the responsibilities can be successfully fulfilled, depends among others on how they are divided in the project organisation. Prescribing a generally applicable setting is impossible, since the division responsibilities within a project is dependent on the organisational structure of the companies involved. Therefore, three variants have been presented, each based upon a different organisational structure.

Whether the actors are able to successfully fulfil its responsibilities, among others, depends on the organisational structure and the contractual relationships. It is recommendable that a setting is created in which all the actors benefit from a life cycle cost effective system. From this perspective, it is advisable to establish an EPCM: a partnership in which the engineering consultant, contractor and maintenance contractor are represented throughout the whole project. In addition, it is from a life cycle optimisation perspective very important that the pros and cons of partnering and subcontracting are properly taken into account.

A wide range of tasks have to be executed in order to successfully fulfil the maintenance engineering responsibilities. These tasks are combined into a cyclical maintenance concept, which enables a process of continuous improvement. It consists of six main steps: (1) initiate the process, (2) develop a model, (3) perform a criticality analysis, (4) design and optimise the maintenance policies, (5) implement and evaluate, and finally (6) feedback. The concept is passed through several times during a DB(F)M process. The level of detail of each of the step and sub steps gradually increases as the process progresses.

The actors responsible for maintenance engineering need some authority in order to successfully fulfil its responsibilities. It is recommended that the matter of authority is arranged by means of network centrality. Special attention needs to be paid to the project organisation after contract awarding, because maintenance gets easily sidelined if not every actor benefits from a life cycle cost effective design. A lack of network centrality can be compensated to some degree by assigning specific means of authority, but this should not be the starting point when deciding on the formal structure. To conclude, also informal sources of authority can be applied. These are however less powerful, and therefore primarily suitable for enforcing the formal authority.

The next chapter will elaborate on the informal aspects of the role structure. Addressed will be the knowledge, skills and attitude that enable a successful execution of the maintenance engineering process.

9 INFORMAL ROLE STRUCTURE DESIGN

The previous chapter described the new formal role structure design. This chapter will deal with the informal role structure, thereby achieving the second objective of this research. The following question will be answered:

> *3.2 What informal role structure enables an improved incorporation of maintenance in the tender -, design - and construction process of DBM and DBFM projects?*

The informal role structure is presented as a competency profile. The chapter will start with a short introduction, addressing the functions of the profile. Subsequently, each of the competency elements will be addressed: knowledge, skills and attitude.

9.1 Introduction

As explained in paragraph 5.4, the quality of a design process among others depends on how the actors understand the contents of the process design, and design, manage and execute their own activities according to it. The same can be said about the maintenance engineering process in specific. This is why the following paragraphs will present a competency profile for a maintenance engineer.

The profile can be used for several purposes. In the earliest phase of a project, the formal role is still negotiable. The competency profile can then be used to gear the formal and informal role towards each other. In case the this flexibility is not available and the formal structure is more or less fixed, the competency profile can be used to select the most suitable employees for a specific project. This allows for a more quality-driven approach, instead of a capacity-driven approach. Finally, it can be used to assess what competency elements are insufficiently represented within a specific project, department or company. The assessment can then be used to improve the personnel training and staff hiring policy.

9.2 Knowledge

The maintenance concept presented in paragraph 8.4 has been used as a starting point in determining what knowledge is required in the maintenance engineering process. Some of the knowledge that is required is stored in the heads of employees, while some of it will be provided by knowledge bases. Based upon this research, it can be said that there is a very important role to play for knowledge bases, especially in enabling a process of continuous improvement.

However, making recommendations with regard to the design of these bases requires a more in depth study into this specific subject. Since that is beyond the scope of this research, no recommendations will be made about whether specific knowledge should be brought in by an employee itself, or that the support of another kind of source is required. The following subparagraphs will describe the knowledge profile for a maintenance engineer. A distinction is made between two categories: maintenance process knowledge and maintenance engineering knowledge.

9.2.1 Maintenance process knowledge

- *Organisational structure & strategy*
  A good understanding of the organisations involved is of key importance. The engineers must be familiar with how the maintenance process is embedded within in the organisation. Only then will it be possible to create an integrated maintenance approach, in which each of the projects makes a contribution to the achievement of the long term objectives.

- *Competency resources*
  Having an overview of the maintenance engineering competencies that are present within the organisation is of value for several reasons. At first, it supports a better harmony between the maintenance process and the engineering competencies. It supports the engineer in assessing whether objectives have to be revised,

or additional competencies have to be obtained. Finally, an overview of the competencies supports the human resource department in optimising the staff training and hiring policy.

- *Knowledge management system*
  The maintenance engineer must be familiar with the knowledge management system and learning strategy. Regarding both the project knowledge bases and company knowledge base, the engineer must know what kind of knowledge should be stored, how it should be stored, and with who it should be shared. Examples of knowledge that is typically being stored, are cost figures, life spans, task durations, et cetera.

- *Risk management*
  The main steps of the maintenance concept presented in the previous chapter is to a large degree similar to most well-known risk management concepts. The concept also described that several kinds of issues can prevent the system from achieving the objectives. Some of these can be management by means of a maintenance policy, while others (e.g. political and environmental issues) require a different approach. Being familiar with well-known risk management methodologies supports the management of those issues.

- *Market knowledge*
  The maintenance engineering process can only be improved if there is up-to-date knowledge regarding the market. The engineer must be aware of the latest developments with regard to materials, ICT-tools, equipment etc. It is important that this knowledge is not limited to the civil engineering industry only, since the approach to maintenance in other industries is generally much further developed. A lot can be learned from the developments in, for instance, the manufacturing industry.

- *Sustainable design*
  There is a growing desire for sustainable practices and design. The maintenance engineer can make an important contribution, by including environmental knowledge into its considerations (e.g. in life cycle analyses). This requires knowledge about, for instance, carbon oxide dioxide emissions, environmentally-friendly maintenance techniques and recycling.

- *Norms and standards*
  A wide range of norms and standards are applied in the maintenance engineering process. In order to meet all requirements, it is important that the engineer has an up-to-date overview of the relevant norms and standards. This overview should contain object related - and process related norms and standards. An example of object related norms are the object maintenance regimes of Rijkswaterstaat, prescribing for instance the minimal availability of a canal. A process related norm or standard deals with subjects such as RAMS and Systems Engineering.

9.2.2 Maintenance engineering knowledge

- *General infrastructure maintenance knowledge*
  For the frequently occurring infrastructure systems, it must be known which parts typically require most attention in terms of maintenance engineering. Examples of parts that usually require focus, are the pavement construction, joints, green, mechanical items etc. The earlier the important parts are identified, the larger the size of the life cycle costing optimisation potential that can be realised.

- *Maintenance engineering tools*
  The engineer should have an understanding of what analyses can be performed and what ICT-tools can be used to support these analyses. An overview of the tools that are currently available is presented in appendix 5 of the RAMS-guideline, published by Rijkswaterstaat (2010b, p. 114).

- *Input information*

  The tools are useless if no accurate information is available to fill them with. Information is, among others, required about failure modes, -effects and – consequences. In many other industries, there are companies which combine such information into extensive databases. In the civil engineering industry, there is are no such kind of services available yet. As a result, currently much value is attached to the knowledge that is stored within the heads of the engineers.

- *Maintenance policy - and task knowledge*

  Knowledge is needed about performance indicators, maintenance policies, maintenance tasks, task intervals and task durations. Since condition based maintenance is the most frequently applied maintenance policy on infrastructure systems, it is also important to have proper knowledge regarding inspection techniques, inspection intervals, warning limits and action limits. Much value is attached to the knowledge of engineers, since only very limited knowledge is stored and shared by means of knowledge bases.

  The knowledge should be continuously improved, by making use of (theoretical) engineering analyses and (practical) site experience. The importance of the latter one should not be underestimated since it can provide valuable information for improving the future maintenance plans (e.g. more accurate schedules) and system designs (e.g. regarding the width of a green strip, for more efficient mowing).

- *Material knowledge*

  Material knowledge is of key importance. It must be known what functions a material can fulfil, its weaknesses, its technical lifespan, and the maintenance approach that is most suitable. In order to be able to realise improvements, the engineer should be kept up to date with the developments regarding new materials and new applications of existing materials (e.g. carbon, composite, etc.). It is for that reason recommendable to maintain close relationships with suppliers.

- *Maintenance cost figures*

  The engineer should have a wide range of cost figures available that supports the development of both global top-down estimates, and detailed bottom-up estimates. In particular in the field of maintenance, it is of major importance that the cost figures are provided with the right context information. Some examples of context information are: the base date, uncertainty range, object properties and the properties of the environment. Basically all information should be recorded that is of substantial influence on the maintenance costs. One could, for instance, think of usage intensity, weather circumstances, et cetera.

- *Economic factors*

  A maintenance cost estimate includes costs that (probably) are going to be made in the future. Dependent on the purpose of the analysis, the future costs have to be discounted in order to make the correct allowance for the time value of money. Discounting these costs requires knowledge about discount - and inflation rates.

9.3 Skills

What skills should a maintenance engineer posses to successfully fulfil the maintenance engineering process? The competency profile of the 'future civil engineer', published by the American Society of Civil Engineering (2008, p. 11), has been used as a point of departure. The set of skills, introduced already in subparagraph 5.4.4, has been geared towards the role of a maintenance engineer. Besides, some other skills have been added to complete the overview.

- *Manage*

  At first, basic project management skills are required in order to design the maintenance engineering process and control its performance. The engineer must, among others, be able to make and control a budget and schedule. In addition, coordination skills are needed to ensure that the individual contributions are combined into an integrated approach. These skills are especially important if the engineering responsibilities are divided between several parties. A lack of coordination skills can then result into a fragmented, inefficient maintenance approach.

- *Collaborate*
  An engineer that performs in a DB(F)M project most know how to collaborate on intra-disciplinary, cross-disciplinary, and multi-disciplinary teams. Intra-disciplinary means within the field of civil engineering, for instance, with site managers or clients. Cross-disciplinary means among engineering disciplines such as structural engineering, mechanical engineering, and architectural designing. Multi-disciplinary finally means combining engineering and other disciplines, like for instance, law and economics (ASCE, 2008, p. 11).

- *Perform analyses and apply tools*
  As presented in Appendix E, several tools are available to support the maintenance engineering process. The engineer must be able to choose the appropriate tool, and apply it in practice. The level of analytical skills that is needed is dependent on the kind of tool that is applied. The most complex tools, as usually applied to hydraulic structures, require the engineer to master complicated probabilistic techniques.

- *Estimate costs*
  The engineers should be able to estimate the maintenance costs in different project phases, on different levels of detail. Most rough is a global (top-down) technique[60]. More detailed is the operational (bottom-up) technique, which includes a detailed estimation of equipment, labour and materials. On both levels of detail, it is possible to apply a deterministic or a probabilistic approach. The latter one is generally considered to be more suitable when dealing with a lot of uncertainties. It is increasingly applied in the civil engineering industry. In some occasions, a probabilistic approach is even demanded by client organisations.

- *Learn about, assess, and master new technology*
  A process of continuous improvements requires the engineers to learn about, assess, and master new technology. This applies to construction materials, maintenance tasks, inspection techniques, analysis tools etc. It is important that the engineer looks further than the world of civil engineering only, since often much can be learned from other industries with regard to maintenance.

- *Evaluate and provide feedback*
  A process of continuous improvement requires the engineer to perform a maintenance process evaluation and deliver constructive, specific and timely feedback. Dependent on the project characteristics, analysis -, survey - and interview skills can be required to support these activities.

9.4 Attitude

The concept of colours, elaborately described in Appendix G, addressed the main types of attitude profiles that an actor can assume towards a process or situation. What attitude best suits a maintenance engineer? Unfortunately, there is no such thing as a one-size-fits-all attitude. At first, because of the diversity of the maintenance engineering process and the wide range of settings that has to be dealt with. Second, because it depends on the specific situation and the attitude of the other actors involved, what attitude is most suitable.

One of the conclusions of this research is, that each of the attitude profiles can somehow be of value in the maintenance engineering process. The following subparagraphs will be used to shortly introduce each kind of attitude and prescribe in what way it can make a contribution.

[60] The costs can be estimated per product unit (e.g. per m^2 of pavement), or indirectly as a percentage of the investment costs (e.g. every year 1,5% of the investment). The latter methodology should not be applied too far along the process, because it contradicts one of the most important ideas behind life cycle costing, namely that a higher investment can result in a cheaper maintenance phase (and thus a more life cycle effective system).

9.4.1 Blue-print thinking

What are the most important characteristics of blue-print thinking? A blue-print thinker has a very rational, project management approach. Clear goals are defined up front, just a as the step by step action plan that has to ensure that the goals become realised. The typical skills that support this attitude are analytical -, planning- and control skills.

Blue-print thinking is crucial in a maintenance engineering process in different ways. At first, it is suitable to ensure that the overall objectives are realised, without delays and budget overruns. Content-wise, blue-print thinking supports all the hard project management aspects of the process, in which goals can be clearly defined up-front. These parts mainly deal with maintenance planning and concern, for instance, the delivery of a maintenance plan and a cost estimate.

9.4.2 White-print thinking

A white-print thinker typically tries to realise improvements by challenging existing ideas and customs. It is someone who tries to enhance creativity and start a process of change, by tapping other people's its own will, desires and strengths. A white-print thinker is typically self steering and has the courage and ability to deal with insecurity.

How can white-print thinking be of value in maintenance engineering? The process – and output quality is very dependent on the amount of creativity. At first, it supports the development of innovative, life cycle cost effective design solutions. For instance, by applying new materials, or coming up with a new application for existing materials. Second, it supports an innovative maintenance approach, for instance, by bringing in innovative interventions or inspection techniques.

A white-print thinker is able to ensure this level of creativity by triggering the engineers to leave aside the traditional solutions and think outside the box. The white-print thinker does not especially have to be a maintenance engineer him- or herself. The role can also be fulfilled by, for instance, an architect. It is important that this attitude is used in moderation, so that its power remains intact.

9.4.3 Green-print thinking

A green-print thinker is a facilitator who supports people to develop themselves, by letting them gain new insights and skills. It is someone who is able to design and facilitate learning situations, has knowledge of organisational development and feedback skills.

A green-print thinker is of key importance. Its first function is to stimulate the engineers to be open to new maintenance engineering methodologies and develop the necessary skills. Second, the green-print thinker enables the maintenance process to continuously improve itself, by emphasizing the importance of evaluations and feedback. This is especially important during the maintenance phase, when much can be learned for the benefit of future designs and maintenance plans. In sum, the green-print thinker facilitates an integrated, cyclical process, in which each of the opportunities is seized that improves the working methods and provides a competitive advantage.

9.4.4 Yellow-print thinking

A yellow-print thinker considers a process of change as a power game. It is someone who aims to search for common interest so that coalitions can be formed. Besides having a wide knowledge of the sector and strategy issues, a yellow-print thinker is typically very sensitive to power-relations.

The yellow attitude is suitable for the earliest strategic project phases, when the formal structure is still open for discussion. It can be supportive in the decision making process about the project organisational structure, the position of maintenance and the division of authorities between the actors involved. By defending the interests of maintenance in the earliest project phase, the yellow-print thinker is able to ensure that its role is optimally geared towards its business strategy, project portfolio and the project characteristics. It thereby paves the way for an optimal incorporation and execution of the maintenance process.

9.4.5 Red-print thinking

A red-print thinker is a kind of process manager, who especially focuses on the soft organisational aspects such as teamwork and communication. It is someone who always tries to realise a fit between organisational – and individual goals. Motivated, interested and comfortable people are considered to be the key to success.

In what way can the red attitude be of value to the maintenance engineering process? As in every engineering process in which people cooperate, it is important that someone takes care of the soft aspects. In DB(F)M projects, these soft aspect become even more important when the individual interests are not perfectly aligned. In such a situation, a red-print thinker can enable an atmosphere in which the formal aspects are left aside and everyone is willing to collaborate. It can, for instance, enable an engineering consultant to put additional effort in maintainability, independent of whether it actually benefits from a more maintainable design.

9.4.6 Overview

The previous subparagraphs described how each of the attitude profiles can make a positive contribution to the quality of the maintenance process. The essential points have been summarised in Figure 39.

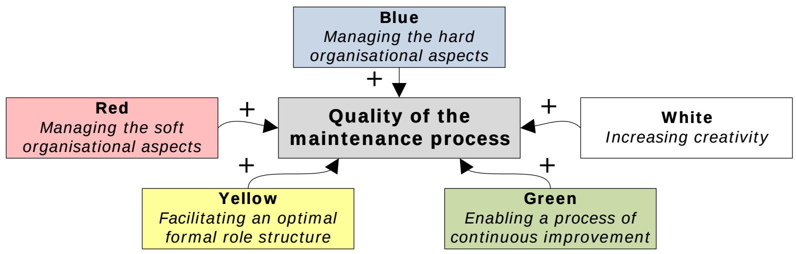

Figure 39: Overview of the value of each attitude in a maintenance process

9.5 Chapter summary

The previous chapter presented the formal role structure design. This chapter has elaborated on the informal aspects of the role structure. Addressed have been the knowledge, skills and attitude that enable a successful execution of the maintenance engineering process. A summary of the competency profile is given in Figure 40.

Knowledge	Skills	Attitude
Maintenance process knowledge • Organisational structure & strategy • Competency resources • Knowledge management system • Risk management • Market knowledge • Sustainable design Maintenance engineering knowledge • General infrastructure maintenance • Maintenance engineering tools • Input information • Maintenance policies - and tasks • Material knowledge • Maintenance cost figures • Economic factors	• Manage • Collaborate • Perform analyses and apply tools • Estimate costs • Learn new technology • Evaluate and provide feedback	Blue-print thinking *Managing the hard organisational aspects* Red-print thinking *Managing the soft organisational aspects* White-print thinking *Increasing creativity* Green-print thinking *Enabling a process of continuous improvement* Yellow-print thinking *Facilitating an optimal formal role structure*

Figure 40: Maintenance engineering competency profile

The empirical study ended with the conclusion that, besides the formal aspects, also informal aspects influence the application and development of knowledge. The informal role structure design that has been presented in this chapter therefore not only aims to allow for an optimal incorporation of maintenance in the early phases of DB(F)M projects, but also tries to initiate a process of continuous improvement. What aspects of the informal role structure foster the development of maintenance knowledge is shown in Figure 41.

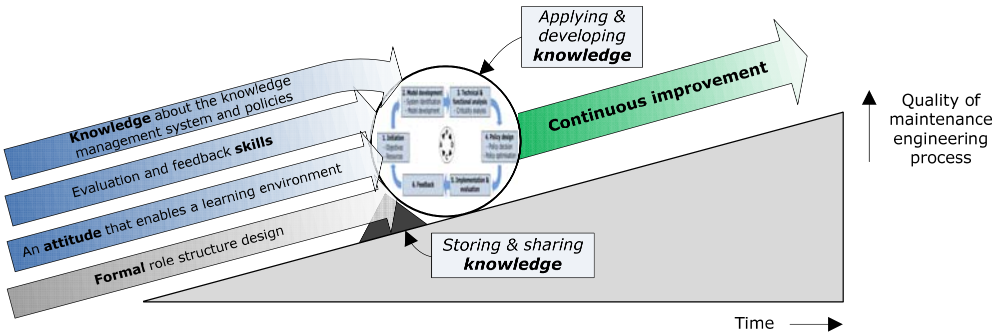

Figure 41: The contribution of the informal role structure to an improved maintenance field

10 CONCLUSIONS AND RECOMMENDATIONS

The previous two chapters presented the recommended role structure design. This chapter presents an overview of the main points of interest of this research, by referring back to the initially presented research questions and –objectives. First, the most important conclusions will be described by means of a step-by-step treatment of the subquestions that have been answered in the literature – and empirical study. Second, the last set of subquestions will be dealt with, resulting into a set of recommendations for the contractors. Subsequently, the role of the client organisation will be addressed by recommending on how the client can facilitate the market to realise a better incorporation of maintenance. This is followed by a discussion about infrastructure management on a more strategic level. Finally, some recommendations for further research will be presented.

10.1 Conclusions

10.1.1 Part 1 - Literature study

This subparagraph treats the reader with the most important conclusions of the literature study. The first question that will be answered, has been dealt with in chapter 2:

> *1.1 What is the current status of the road infrastructure development and -maintenance industry?*

The coming years, a lot of maintenance needs to be done to ensure the functionality of the existing Dutch road infrastructure system. On top, the requirements of the stakeholders in terms of availability, safety and life cycle costs become increasingly demanding. Satisfying these requirements in the long run requires the new infrastructure systems to be more life cycle cost effective than the current systems. This requires, among others, an improved approach towards maintenance. Dutch client organisations try to facilitate a more life cycle cost effective approach by applying integrated project delivery methods. Two of these methods will be addressed by answering the following subquestion:

> *1.2 What do DBM and DBFM comprise, and what are the potential advantages?*

Design, Build & Maintain (DBM), and Design, Build, Maintain & Finance (DBFM) are project delivery methods that aim to encourage life cycle optimisations early in the construction process by combining the aspects design, build and maintenance into one contract. Optimally realising this life cycle optimisation potential requires the contractor to incorporate maintenance early in the process. Already in the tender- and design phase, the contractor should think about how performance is going to be ensured during the operational life. The following subquestion elaborates on this subject:

> *1.3 In what way can maintenance engineering contribute to the performance of infrastructure?*

The functionability of an infrastructure system depends on its inherent characteristics and the way it is maintained and operated. The field of maintenance engineering concentrates on both aspects. Managing the maintenance related aspects throughout the design process is referred to as maintainability engineering; preparing the maintenance phase is called maintenance planning. Several concepts, tools and methodologies are available that support the maintenance engineering process. The theory further emphasises that a system can only be optimally maintained if the responsible organisation recognizes the importance of maintenance on every managerial level. The quality of the maintenance process can only be managed (and improved) if a cyclical process is realised. It is further important that knowledge is exchanged, especially between the tactical and operational level. The final subquestion that will be addressed forms the stepping stone to the empirical study:

> *1.4 What framework can be used to study the current practice, and prescribe an improved approach?*

The selected framework stems from design management literature, that describes that a design process can be designed by means of a process design. This research will concentrate on the role structure of a process design, which specifies the actors and their roles within the process. It can be further split up in a formal and an informal role structure. The formal structure describes the responsibilities, position, tasks and authority of the actor. The informal structure describes the knowledge, skills and attitude an actor needs to posses in order to successfully fulfil its role.

10.1.2 Part 2 - Empirical study

The second part of this research aimed to provide insight into the current practice. Two projects have been studied and several interviews have been conducted. The overall conclusion that can be drawn is that, compared to other industries, civil infrastructure maintenance is still in its infancy. However, the last years some progress has been made. Among others due to the introduction of DB(F)M contracts, private parties become increasingly aware that they cannot any longer ignore maintenance if they want to remain competitive.

> *2.1 What formal role structure is currently applied in DBM and DBFM projects, and how does it affect the incorporation of maintenance?*

In DB(F)M projects, generally most emphasis is laid on the responsibility of maintenance planning. The job of optimising the system design in terms of maintainability and life cycle costs, receives only limited attention. In addition, both responsibilities are rarely combined into an integrated, cyclical maintenance engineering approach. This flaw is, among others, caused by the way maintenance is positioned within the organisational structure of the companies and projects. Many struggle with the exchange of knowledge, in- and outside projects, between the departments, subsidiaries and/or companies involved.

The incorporation of maintenance is also harmed by the fact that the parties which are finally responsible for the maintenance phase, often experience a lack of authority. This can be solved by establishing a project organisation in which all parties involved in the primary process are paid for its contribution to the system its long term performance (instead of its effort). Unfortunately, such a collaborative setting is rarely established in practice. Compensating a lack of network centrality with other sources of authority is only effective to a limited extent. The second subquestion deals with the informal part of the role structure:

> *2.2 What informal role structure is currently applied in DBM and DBFM projects, and how does it affect the incorporation of maintenance?*

The general opinion is that the civil engineering industry lags behind other industries with regard to maintenance engineering competencies. At first, there is a lack of knowledge. In contrast to other industries, there is no large supply of database with historical data. Another issue is the lack of typical maintenance engineering skills. Civil engineers that know how to properly apply concepts and analysis techniques are rare.

The final competency element that is considered, is the attitude of the actors involved. In the current practice, the maintenance engineering positions at contractors are mainly held by people who focus on the hard project management aspects. As a result, only very limited attention is paid to learning and improving. Another conclusion that can be drawn, is that involving someone with a creative attitude has a positive effect on the incorporation of maintenance. The same can be said about the involvement of someone who pays attention to the soft organisational aspects. The last subquestion that is answered by means of the empirical study is:

> 2.3 *How is the market's approach towards the incorporation of maintenance in DB(F)M projects affected by the procurement strategy of client organisations?*

All the private parties that have been involved in this research believe that client organisations have an important role to play in facilitating the market to optimally incorporate maintenance. The current fulfilment of this role leaves quite some room for improvement, for instance concerning the contract awarding criteria, procurement procedures, payment mechanism and the requirement specifications.

Another conclusion that can be drawn, is that client organisations create a fragmented maintenance approach if a DB(F)M contract includes only part of the maintenance activities. The sequential interface, as traditionally present, is then replaced by a parallel interface: both the client organisation and the private party are simultaneously responsible for ensuring the system's performance.

10.1.3 Key conclusion

The key conclusions of the empirical study are combined and visualised in Figure 42. The conclusion can be drawn that there is quite some room for improvement in the field of maintenance. In addition, it turns out that the formal role structure that is applied by the contractor, has a considerable influence on what knowledge is applied and developed. The same applies for the role of the client organisation and the attitude of the actors involved. The empirical study will therefore be finalised with the conclusion that a continuous and sustainable process of improvement will only emerge if the application and development of knowledge is in the heart of role structure design.

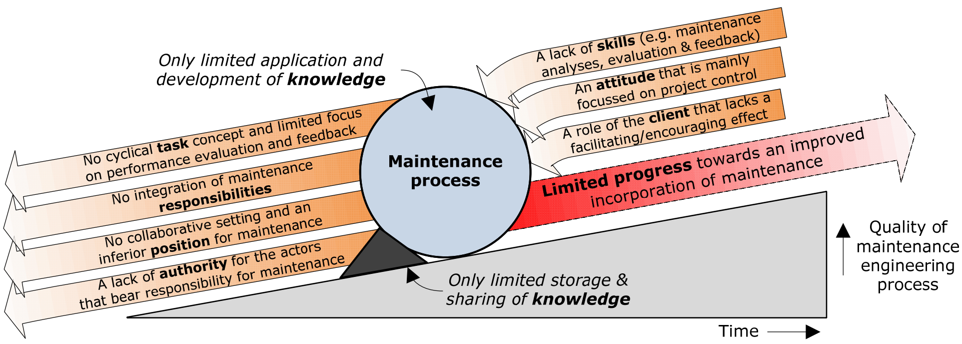

Figure 42: The current situation: a visualisation of the key conclusions

10.2 Recommendations for contractors

The literature study has presented a whole range of principles, tools and methodologies that can contribute to the maintenance engineering performance. Subsequently, the empirical study has shown what can be improved in the current practice. The findings of the literature - and empirical study have formed the basis of the role structure design, presented in part 3.

The subquestions 3.1 and 3.2 correspond with research objective 1 and 2, respectively. By answering these questions, the first two objectives are realised automatically:

> 3.1 *What formal role structure enables an improved incorporation of maintenance in the tender -, design - and construction process of DBM and DBFM projects?*

The recommended formal role structure has been presented in 8 of this report. The desired contribution of the formal role structure to the development of knowledge runs like a common thread to the design. In sum, attention should be paid to the (division of) maintenance engineering responsibilities, the position of the actors that deal with maintenance, and the tasks that have to be executed in order to successfully fulfil the maintenance engineering responsibilities. Finally, the responsible actors should have the authority that is required to achieve its objectives. The next subquestion deals with the informal role structure elements:

3.2	*What informal role structure enables an improved incorporation of maintenance in the tender -, design - and construction process of DBM and DBFM projects?*

The recommended informal role structure design has been described in chapter 9 of this report. The competency profile that is presented describes the knowledge, skills and attitude that support the formal role structure and enables an optimal incorporation of maintenance. Again, the development of knowledge runs as a consistent thread to the design. An example is the prescription of feedback and evaluation skills. In addition, actors should be involved with the type of attitude that enables a learning environment.

10.3 Recommendations for client organisations

Throughout the research, most emphasis has been laid on the approach of the contractors. Along the process, it became obvious that the client organisations can play a very important role in facilitating and stimulating the contractor to move forwards. This has resulted into the following research question:

3.3	*How can client organisations facilitate and stimulate the contractors to improve the incorporation of maintenance in DBM and DBFM projects?*

10.3.1 Value based procurement

A better incorporation of maintenance does not happen automatically. It requires the contractor to make an additional effort, especially since it is a fairly new area for most contractors. A contractor will only make this additional effort if it is rewarded, for instance, in terms of a sustainable competitive advantage.

Whether a competitive advantage can be achieved by means of a better incorporation of maintenance is largely determined by the client organisations. They can stimulate contractors to move forwards by rewarding those contractors that have optimally incorporated maintenance into its processes. Properly rewarding the benefits of a better incorporation of maintenance requires an appreciation of both the additional value that has been created (e.g. in terms of higher system availability), and the savings that have been realised in terms of life cycle costs. Ignoring one of these two benefits will highly demotivate a contractor to address maintenance, because it limits the competitive advantage that can be achieved.

It is for the reasons mentioned above that value based procurement is advised. It is important that significant value is attached to the system performance in terms of availability and life cycle costs. Also the quality of the maintenance plan should be considered. From a life cycle point of view, it is further recommendable that contractors are motivated to consider a longer period than the contract duration only. This can be done in several ways. For example, by evaluating not only the maintenance costs estimate of the first 20 years, but also of the 30 years thereafter. This will enlarge the scope of the life cycle optimisation process, and increase the value of the infrastructure throughout its life.

10.3.2 Payment mechanism

One of the conclusions of the empirical study is that the payment mechanism plays an important role as well. When deciding on the payment mechanism, several variants are possible. One strategy is to reward the contractor for completing the milestones early in the process (e.g. the construction phase). This is favourable from a finance point of view, but unfavourable when aiming for a system that provides maximal value throughout its life cycle.

The opposite is to relate all payments to the system performance that is actually realised during the maintenance phase. This payment mechanism is obviously much more in line with the original intent of a DBFM contract, since it creates a maximal incentive for the contractor to consider the long-term performance. From this point of view, it is even advisable to let the performance based rewarding gradually increase as the maintenance phase progresses. An inevitable downside of this approach are relatively high financing costs.

Deciding on a suitable payment mechanism requires insight into this trade-off. The financing costs can be expressed and quantified in terms of financing costs. The other side, namely the effect on the motivation of the contractor to focus on the long term, is much more difficult to measure and quantify. Based upon this research, it can only be recommended that one should be careful not to underestimate this effect. It seems valuable to do further research into this issue, concentrating on how the payment mechanism exactly affects the approach of the contractor in practice.

10.3.3 Requirement specifications

The literature study showed that the optimisation potential is largely determined by the requirement specifications that are drawn up by the client organisation. One of the conclusions is that the current requirement specifications often harm the maintenance engineering process. In specific, it is recommended that the following aspects are improved.

The first aspect is rather obvious, and regards the level of detail and the consistency of the requirements. It speaks for itself that, from a life cycle optimisation potential point of view, abstract requirements are recommendable. The more abstract the requirements, the larger the optimisation potential and the more the contractor is stimulated to distinguish itself. Obviously, maintenance engineering competencies are required in order to properly formulate the functional requirements. This will also enable the client to evaluate the output of the maintenance engineering process.

Second aspect deals with the prescription of specific analysis methodologies, as is occasionally done in the current practice. It goes without saying that this is not in line with the nature of a DB(F)M contract. The client organisation should give up its old habits and give the contractor the freedom to design its engineering process. No tools or analysis methodologies should be prescribed, so that the contractor is able to gear its approach towards internal procedures, long-term strategies, availability of competencies et cetera.

10.3.4 In addition: the role of permit authorities

The final recommendation that will be given is not specifically directed towards client organisations. The empirical study showed that the life cycle optimisation potential is influenced by the demands of permit authorities. In order to avoid problems with permit procedures, contractors can feel inclined to apply traditional design solutions, instead of applying a more innovative, life cycle effective approach. This an undesired situation for all the parties involved. The contractor can treat the risk by taking the permit authorities along in the process. It is however questionable to what extent this really improves the current situation. In order to come up with a more solid solution that really terminates the risk, it is therefore advised to execute an in depth research into this issue. This research should focus on the relationships between the client organisation, permit authority and contractor.

10.4 Summary of recommendations

The empirical study concluded with the finding that there is quite some room for improvement in the field of infrastructure maintenance. The recommended role structure design therefore aims to stimulate a sustainable and continuous process of improvement. How each part of the solution design contributes to this process is summarised and visualised in Figure 43.

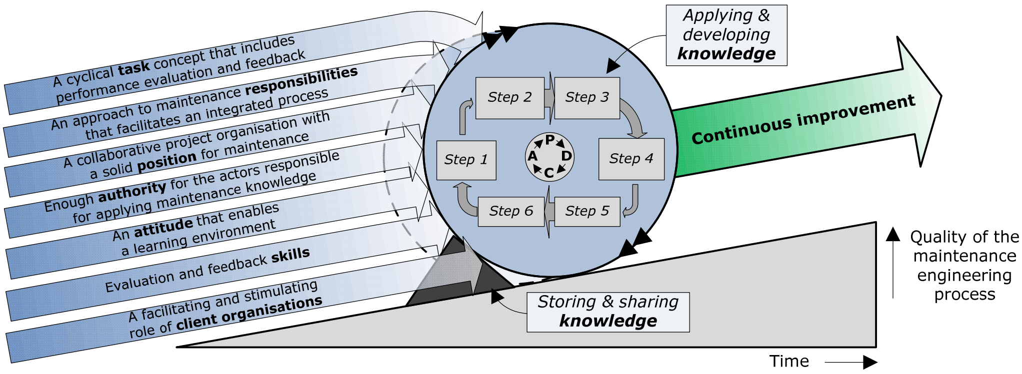

Figure 43: Towards a continuously improving incorporation of maintenance

10.5 Final discussion

This paragraph will be used to elaborate on the subject of research on a more strategic level. The discussion will reflect on the road that is followed by the public infrastructure management organisations. Given the findings of this research, is it wise and justified to continue the current course and increasingly apply DB(F)M?

This research has mainly dealt with the optimisation of an individual DB(F)M project. A client organisation is however expected to take care of a total infrastructure network, consisting of several systems. The value the total network is not simply the sum of the individual systems. The coordination between the individual systems plays an important role. Considering the scope of the maintenance obligation that is included in DB(F)M contracts, the network manager has to deal with the following trade-off.

The one extreme is to incorporate all maintenance activities into different DB(F)M contracts. Advantage is that it creates a maximum life cycle optimisation potential for the market (on a system level). Disadvantage is that it becomes very difficult for the client to coordinate the different maintenance approaches. Handing over part of the control makes it difficult to optimise the network as a whole. The other extreme is to go for a more traditional approach, and totally abandon long term maintenance obligations. Disadvantage is that there is no life cycle optimisation potential for the market. Advantage is that the client is free to coordinate the maintenance process. This provides the client with the flexibility to optimise the value of the network.

A well-founded decision regarding the abovementioned trade-off is of mayor importance for the performance of the network as a whole. It requires a proper consideration of the costs and benefits of the alternative approaches. Rijkswaterstaat has developed some tools that can support in deciding on the most beneficial contracting method. The most important is the Public Private Comparator[61]. The output quality of the decision making tools is determined by the quality of the knowledge that is put in, for instance about maintenance (costs). As concluded earlier in this research, only limited knowledge is available. It is therefore questionable whether such tools provide a sound basis for decision making.

This brings us to the heart of the matter. Is it responsible to increasingly apply DB(F)M and relinquish part of the network control to the market if none of the parties involved has in depth knowledge about infrastructure maintenance? Based upon this research, I am tempted to believe that the current level of competencies is not solid enough to justify the continuation of the current course. The lack of competencies hinders an accurate consideration of the strategy and its consequences. This is problematic because the long duration of the DB(F)M contracts makes it difficult, or even impossible, to reverse part of the consequences. The same applies to the organisational changes that are processed at the client organisations and contractors.

I would therefore suggest to insert a phase of consideration and reflection. This period should be used to (further) assess the current level of maintenance competencies at both client organisations and private

[61] The Public Private Comparator (PPC) is a tool that supports Rijkswaterstaat in deciding what type of contract to apply. A public reference variant (D&C) is compared with a private variant (DBFM). The Public Sector Comparator (PSC) is subsequently used during the tender phase of a DBFM contract to compare the DBFM bids with a D&C approach.

organisations. Based upon this assessment, decisions can be made about what specific competencies have to be further developed and how this can be achieved. Only if the right level of competencies is achieved, a well founded, long term strategy can be developed regarding the management of the infrastructure network and the desired division of responsibilities between the public and private parties involved.

10.6 Further research

Several recommendations for further research have already been mentioned throughout this report. In sum, research is recommended into:

- An optimal application of the EPCM structure. First aspect that should be studied is the design of the long term partnership arrangement itself (e.g. inclusion of exit strategies). Second aspect is the optimal division of risks between the EPCM partners. See for more information also section 7.2.2.3;
- The design of the payment mechanism that is applied in DB(F)M, concentrating on the trade-off between the financing costs and the desired long-term focus of the private party. See also subparagraph 10.3.2;
- The role of permit authorities in the size and realisation of the life cycle optimisation potential. The research should focus on the relationships between the client organisation, permit authority and contractor. See also subparagraph 10.3.4;
- The competencies currently available at client organisations and private parties. This research should aim to identify gaps in knowledge (e.g. in terms of cost figures and failure data) and develop an improvement plan. Based upon that research, a contracting strategy can be developed that facilitates the industry to continuously improve its approach towards maintenance.

11 REFLECTION

The final chapter will be used to take a critical look at the work and point out its weaknesses and limitations. The first two concepts that will be addressed are the reliability and validity. Third aspect stems from the practical nature of this research and deals with its usability in practice. Finally, a brief personal reflection will be given on the graduation process itself.

11.1 Reliability

Reliability is the extent to which a study yields the same result on repeated trials. The empirical study has been based on two projects: one DBM- and one DBFM project. More projects would have definitely increased the reliability of the outcome. Unfortunately, this was not feasible because Ballast Nedam was not able to supply more case studies. Involving another contractor was not an option, since contractors are generally not willing to provide insight into its working methods if this knowledge is shared with competitors.

The reliability of the empirical study has been increased by conducting additional interviews with external experts. These interviews have been used to verify the findings of the case studies and, as will be explained in the next paragraph, to increase the external validity. The reliability of the interviews is ensured by following the interview protocol, described in Appendix J. The way the answers are finally interpreted is of course highly dependent on the competencies of the researcher and the ambience during the interview.

Only limitation that can be raised regards the empirical study into the role of the client organisation. This role has mainly been studied from the perspective of the contractors involved. On the one hand this is not really an issue, because the purpose was primarily to study how the contractor can be facilitated. On the other hand, a more complete picture could have been drawn if more attention had been paid to the client’s perspective.

11.2 Validity

The external validity deals with the extent to which the outcome of the research can be used, or applied in a broader perspective. The validity has been, among others, ensured by the selection of interviewees. Experts have been interviewed from several contractors, client organisations and (engineering) consultants. The fact that each of these experts is involved in different companies and projects, has resulted in a wide variety of experiences that cover most of the civil engineering field. The external validity also determines the value of this research for the organisations involved. Since Brink Groep is mainly active in the real estate industry, it would be useful to know to what extent the results can be applied to this sector as well. This subject is left for future graduate students.

11.3 Usability

11.3.1 Brink Groep

Final aspect that will be considered, is the usability for the companies that have facilitated the research. Brink Groep was willing to contribute because it believed that the observed problems offer an interesting opportunity to expand its services in the civil engineering industry. The empirical study has indeed confirmed that the current situation leaves room for improvement. Especially the large contractors are still struggling with the question how to incorporate maintenance into its organisation and projects. Brink Groep can take advantage of this situation by helping the contractors to analyse its current working methods and come up with recommendations. The empirical study that is included in this report can be supportive in analysing the current working methods. The role structure design can be subsequently used to translate the analysis into suitable recommendations.

11.3.2 Ballast Nedam Beheer

Requirements with regard to the external validity of this research made it impossible to fully gear the role structure design to Ballast Nedam. Nevertheless, there are more than enough parts of the role structure design that can be directly applied. An example is the maintenance concept that is presented in the task section of the formal role structure design.

Maybe even more valuable is that this research can help Ballast Nedam Beheer in planning its future course. The role structure design can, for instance, support in deciding on what responsibilities Ballast Nedam Beheer wants to assume in future DB(F)M projects, and what competencies have to be developed or collected to properly fulfil these responsibilities. As the research has shown, these are not questions that should be answered by Ballast Nedam Beheer alone, because the coordination with other subsidiaries (e.g. Ballast Nedam Engineering and Ballast Nedam Infra) is crucial for a process of continuous improvement.

11.4 Personal reflection

Finally some brief personal reflection on the research process itself. With hindsight, the start-up of this research has been the most difficult part. I found it very difficult to come up with a solid research design that satisfied the wishes of the University, Brink Groep and - last but not least - myself. Despites all the warnings and advice, I was torn between several research objectives, - questions and approaches. The most important lesson I have learned is to attach much more value to my own wishes and believe.

The difficult start-up phase definitely led to some delays. With hindsight, I think it would have been helpful to split my interview sessions into two rounds. Some explorative interviews in the last phase of my literature study would have helped in determining the scope and focus of my literature study. Something I now had to repair afterwards. The interviews itself were much more valuable than I had expected. They not only provided me an insight into the current practice, but also helped me to improve my interview skills. In addition, they gave me a better insight into the construction industry, which helped me in planning my future career.

Finally some words on the internship at Brink Groep. Up-front, I made the decision to solely focus on my thesis. As a result, I didn’t really get involved in the company’s daily activities. The most important reason for making this decision was that I didn’t want to end up in an never-ending graduation process. From that point of view, I still support my decision. On the other hand, I find it a shame that I didn’t gain a better insight into the activities of my close colleagues and the company as a whole. The fact that I was only busy with my research made it a rather solitary journey. Once again, it made me aware of how gratifying it is to be part of a team and face a challenge together.

DEFINITIONS & ABBREVIATIONS

- **Attitude**
  Reflects an individual's values and determines how he or she perceives, interprets and approaches the world.
- **Authority**
  The power or right to control, judge, or prohibit the actions of others.
- **BV** *(besloten vennootschap)*
  Legal form equal to the Limited Company.
- **DBM (Design, Build & Maintain)**
  An integrated contract that includes the aspects Design, Build and Maintenance.
- **DBFM (Design, Build, Finance & Maintenance)**
  A PPP kind of contract that includes the aspects Design, Build, Finance and Maintenance.
- **EPC (Engineer, Procure, Construct)**
  An entity that enters into an agreement with the SPC and takes care of the design and construct activities within a DBFM contract.
- **EMAT (Economically Most Advantageous Tender)**
  Tender that is awarded on other criteria than just price.
- **EPCM (Engineer, Procure, Construct, Maintain)**
  One entity that bears the responsibility for the design-, construction- and maintenance activities.
- **Formal role structure**
  Part of the process design that describes the patterns within an organisation that develop according formally established instructions.
- **Informal role structure**
  Part of the process design that describes the competencies an actor should possess to successfully fulfil its role.
- **Maintainability**
  The inherent characteristic of an engineering system related to its ability to be maintained in the state of functioning by performing the required maintenance tasks as specified.
- **Knowledge**
  Information in a personalised context.
- **LCCA (Life Cycle Costing Analysis)**
  Cost-centred engineering economic analysis whose object is to systematically determine the costs attributable to each of one or more alternative courses of action over a specified period of time.
- **Maintenance**
  The combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function.
- **Maintenance contractor**
  Contracting party that agrees to undertake responsibility for providing a given maintenance (consultancy) service.
- **Maintainability engineering**
  Incorporation of maintenance related aspects in the design process to support the development of a life-cycle cost effective system.
- **Maintenance engineering**
  The combination maintainability engineering and maintenance planning.
- **Maintenance planning**
  Development of an optimal maintenance plan in order to be well prepared for managing the maintenance phase.
- **MTC**
  Contracting party (e.g organisation, joint venture, etc.) that has agreed to undertake responsibility for providing a given maintenance service. This may include the provision of a consultancy service.
- **Network centrality**
  Authority that is derived from the fact that actor A makes an essential contribution to something that B is a part of.
- **NV** *(naamloze vennootschap)*
  Legal form equal to a Public Limited Company.

- **PPP (Public Private Partnership)**
  Public Private Partnership. Private and public sectors are brought together in long-term contracts (e.g. DBFM) to produce and provide for instance an infrastructure system.
- **Process design**
  Describes at what moment in time a step in a process has to be executed, and which actor(s) has to carry out that step.
- **Process structure**
  The planning part of a process design.
- **RAMS**
  A methodology that supports the description, determination and monitoring of the aspects Reliability, Availability, Maintainability and Safety for practically every function.
- **Reliability**
  The probability that an item can perform a required function under given conditions for a given time interval.
- **RCM (Reliability Centred Maintenance)**
  A maintenance concept that aims to ensure that assets continue to fulfil its functions.
- **Responsibility**
  A duty to deal with or take care of something, so that you may be blamed if something goes wrong.
- **Role structure design**
  The organising part of a process design that specifies the actors and their roles.
- **RWS (Rijkswaterstaat)**
  The organisation responsible for managing the Dutch national infrastructure networks.
- **Skills**
  The ability to perform a certain physical or mental task.
- **SPC (Special Purpose Company)**
  The entity that enters into a DBFM agreement with the public party.

LIST OF FIGURES AND TABLES

Figures

Tables

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Interviewee	Function	Company	Date
Mr. O. Beuving	Operational maintenance manager	BAM	20-06-2011
Ms. J. Harskamp	Project leader maintenance phase	Ballast Nedam Beheer	23-06-2011
Mr. J.W. Bruining	Project director Wâldwei.com	BAM PPP	15-07-2011
Mr. M.H. Verwoerd	Design leader Aquaduct Langedeel	Ballast Nedam Engineering	16-08-2011

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- Tender plan Ballast Nedam Beheer, Ballast Nedam Beheer
- Onderhoudsplan (maintenance plan, part of bid offer), Ballast Nedam Beheer
- Project management plan (part of bid offer), several authors

Interviewee	Function	Company	Date
Mr. P. van der Pijl	Senior cost consultant	Ballast Nedam Beheer	23-06-2011
Mr. W.J. Attema	Project leader	Ballast Nedam Infra	30-06-2011
Mr. H. Doornbos	Design manager	Royal Haskoning	07-07-2011
Mr. E. Schrauwen	Designer (spatial quality)	Interra	18-07-2011
Mr. K.M. Schipper	Advisor operate and maintenance	Royal Haskoning	20-07-2011

Additional interviews

Interviewee	Function	Company	Date
Mr. P. van der Pijl	Senior cost engineer	Ballast Nedam Beheer	07-06-2011
Mr. R. van der Tol	Legal advisor	Ballast Nedam Beheer	15-06-2011
Mr. C. Uijl	Project manager / maintenance engineer	NedMobiel	21-06-2011
Mr. N. Reuten	Project manager / maintenance engineer	NedMobiel	21-06-2011
Mr. R. Bongers	Project manager SAA	Rijkswaterstaat	28-06-2011
Mr. D. Eikelenboom	Consultant maintenance and operations	Breijn (Heijmans)	29-06-2011
Mr. B. Hogendonk	Senior cost engineer	BAM Civiel	01-07-2011
Mr. H. Abing	Teamleader Asset Management	Grontmij	04-07-2011
Mr. T. Maas	Manager contracting & construction Rail	BAM Rail	06-07-2011
Mr. M. Akkerman	Contract advisor integrated contracts	Movares	07-07-2011
Mr. R. van Dongen	Tender manager / cost engineer	Heijmans (HTM)	11-07-2011
Mr. D. Vlassenrood	Advisor Asset Management	Grontmij	09-08-2011

Appendices

APPENDIX A COMPETITIVE DIALOGUE PROCEDURE

In a traditional contract, a cut is made between the development and the construction phase. As a result, the contract contains a design with technical specifications and a bill of quantities. These documents form the basis of the contractors' bidding stage. In an integrated contract, the contractor is involved much earlier in the process. As a result, a different tender approach is required. Mostly applied is the competitive dialogue procedure, illustrated in Figure 44. The three main stages will be briefly explained in the following paragraphs.

A.1 Pre-qualification stage

The procedure starts with the pre-qualification stage. Pre-qualification is based upon exclusion grounds and minimum requirements. The prima objective is to make a selection of parties which are, in principle, able to execute the project. The candidates, among others, have to present its financial bearing power and (technical) expertise.

A.2 Dialogue stage

The dialogue consists of three phases: the plan of action phase, consultation phase and the dialogue phase. At first, the participants are asked to submit a plan of action, which among others contains a project vision and management plan. Based upon these documents, are first selection is made.

Important characteristic of the competitive dialogue procedure is that the Economically Most Advantageous Tender (EMAT) award mechanism is applied. This means that the every product is evaluated on several aspects, concerning both the quality and the financial-economic properties.

The candidates that are left after the plan of action phase are invited to participate in the consultation phase. This phase aims to provide the client organisation with the opportunity to improve its procurement documents. Participants can discuss the admissibility of their design proposals and suggest adjustments in the procurement documents. This stage contains no selection moment.

Finally, the actual dialogue takes place. The main purpose of this phase is to provide the client organisation with the possibility to decide which participants will be invited to submit a final bid. Secondly, the client organisation aims to agree with the participants on the content of the procurement documents.

A.3 Bid submission and contract awarding stage

After the dialogue phase is ended, the remained parties are asked to submit a bid design and a price offer. Finally, the best bid is selected and the contract is awarded. The financial close confirms the agreement.

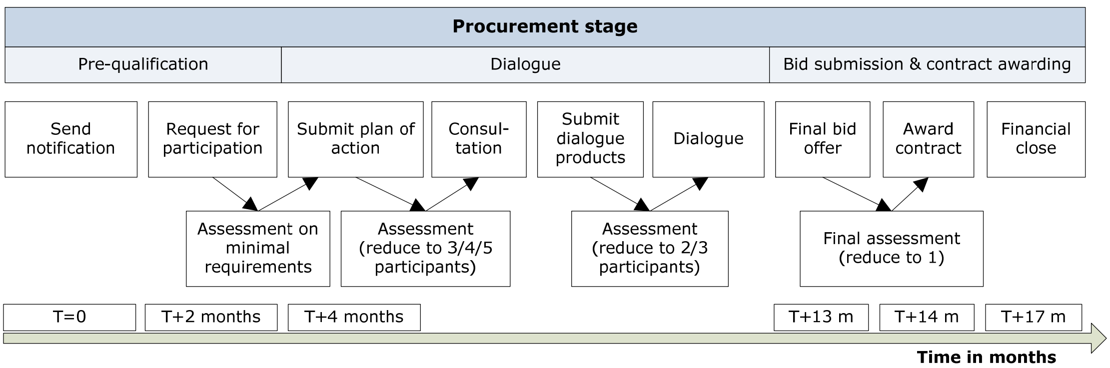


Figure 44: Process scheme & timeline competitive dialogue procedure (adapted from Rijkswaterstaat, 2005, p. 15)

APPENDIX B DESIGN PROCESS CHARACTERISTICS

B.1 Design phases

It is difficult to define a strict demarcation for the design phase. It can be characterized as the phase in between the establishment of the need for a certain type of asset, and the start of the actual construction activities. The process that has to be passed through in order to arrive at this finalised design can again be split up in several phases, shown in Figure 45.

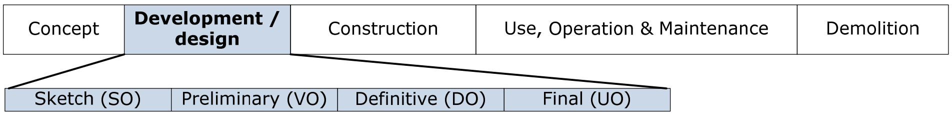


Figure 45: The design phases

B.2 Complex

The design team of large civil engineering projects are faced with several challenges. At first, the process can be characterized as complex, meaning that “the properties or aspects of the system are interrelated and determined by the combined action of the interconnected parts of the system in its environment” (Gelderloos, 2010, p. ii). For instance, if designers choose to apply another type of wearing course to reduce the noise levels, the decision also affects the needed maintenance, costs, safety and constructability.

B.3 Dynamics

Because of the size of a typical infrastructure design project and the limited amount of time available, usually large design teams are required. In order to meet the deadlines, designers have to work on different parts of the system in parallel. Besides that the design itself is constantly changed, also the environment in which the system has to be realised is faced with constant change. What changes will occur, and to what extent the changes affect the (perception of the) quality of the design is however unpredictable. Both the changes and the uncertainly regarding the effects of the changes are captured with the term dynamics of the design process (Gelderloos, 2010, p. ii).

B.4 Information gap

Another key characteristic of the design process is that there is a discrepancy between influence and information. In paragraph 3.1, it has already been described that the course of a construction project can be most easily influenced in the early life cycle stages. The same applies within the design process. A difficulty that usually has to be dealt with, is that there is a discrepancy between amount of information available to base the decisions on, and the influence that can be exerted on the actual design (van Doorn, 2004).

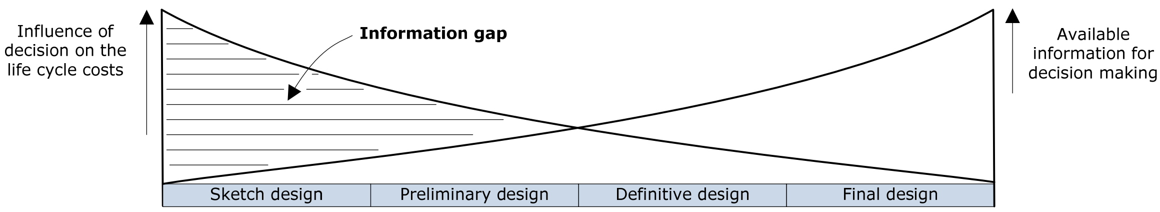


Figure 46: The typical discrepancy between information and influence

B.5 The design cycle

The design process can be characterised as an iterative process. As the process progresses, the initial design question and its relationship with the environment becomes more clear. As a result, it is sometimes necessary to set one step back in the process in order to set two steps forward. The design process can be split up in three elements (van Doorn, 2004), such as illustrated in Figure 48 (left).

- The input, consisting out of both design related, and process design related information;

- The process itself, in which the requirements are translated into a spatial design;
- The output, consisting of the final design result, the technical - and financial specifications.

These moments not only represent the design process as a whole, but also the design cycles that has to be gone through repeatedly within the design process itself. The design processes comprises more activities than determining what the construction is going to look like. In order to arrive at a construction-ready design, several other activities have to be executed such as exploring, designing, research, specifying, scheduling and cost estimating. To what extent these activities are present in the design process differs per stage. Figure 48 (right) illustrates the variation in accent that typically takes place throughout the design process.

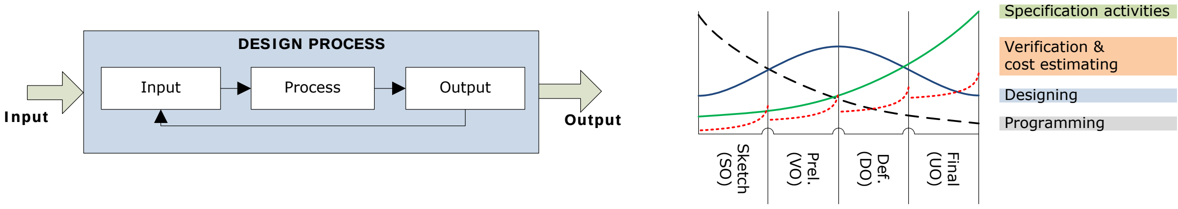
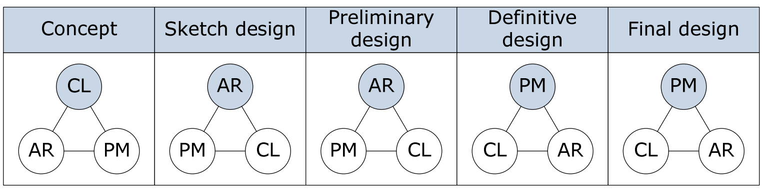


Figure 47: Design process cycle (left), the varying accent of activities (right) (adapted from van Doorn, 2004)

B.6 Wheel of dominance

Another important characteristic of the design process is the way the process is led. The design leader plays an important role in the decision making processes. The leader typically takes care of the coordination and integration of activities. Formally, this role is often appointed to one specific actor, called the design- or project manager. Each design phase however has different characteristics. In accordance, often an formal or informal shift takes place within the division tasks and the responsibilities that go along. This so called dynamic leadership is often referred to with the Wheel of Dominance, illustrated in Figure 48.



CL = Client; AR = Architect; PM = Project Manager

Figure 48: The Wheel of Dominance (adapted from van Doorn, 2004)

APPENDIX C SYSTEM CONTROL CONDITIONS

The performance of a system design can be controlled by controlling the aspect systems. The control paradigm of de Leeuw, shown in Figure 49, illustrates the principles of system control. The controller its aim is to achieve a certain goal that is defined in terms of a certain output. The function of the system (or aspect) manager is to control the system and the environment in a way that the goals are met. Control measures are based upon information about the system and the environment. The following paragraphs describe the four conditions that have to be satisfied for successful system control (de Leeuw, 1976, p. 97).

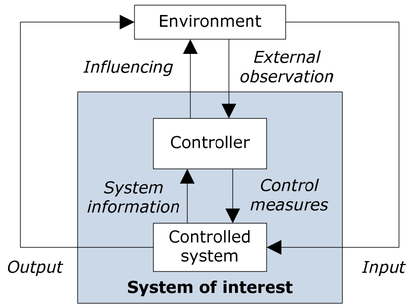


Figure 49: De Leeuw's system control paradigm (adapted from Kok, 2010)

C.1 Goal

First condition is that the manager should be familiar with the system objectives. This knowledge makes it possible to compare the actual performance with the desired performance. Based upon this comparison, the manager can determine if, and what kind of measures are necessary to (re)direct the process. It is important to realise that the goals can change during the process, for instance as a result of changing client requirements. It is not always feasible to specify the objectives as specific target value. Such difficulties should not be a reason to ignore an aspect. Most important is that the manager is able to assess the control measures and determine if measures have led to improvements or not (Kok, 2010).

C.2 Model

A model is a simplified representation of part of the reality, where the most essential characteristics are present. The manager needs a model to get insight into the current status and the presumable effect of control measures. The type of model required depends on the situation and the nature of the aspect system under control. Examples are planning models (e.g. by means of MS Project) to model the aspect construction time and Building Information Models (e.g. by means of Revit) to model the aspect geometry.

C.3 Information & data

The system should be developed so that the manager is able to retrieve information about the status of the system and its environment. It is important that the model and the data supply are geared towards each other. This applies to project specific data (in terms of what information can be retrieved with regard to the current status) and more general data (e.g. cost figures).

C.4 Control variety

Finally, the manager needs to have alternative measures at its disposal, so that it can react on the possible scenarios and direct the process in the right course. As the design process progresses, the solution space decreases while the cost to implement changes increase. The consequence is that the steering variety typically decreases throughout the design process. Two types of control measures can be distinguished:

- Feed-forward control: measures in advance of deviations. A pro-active form of control which is based upon information regarding the input and the knowledge about the functioning of the system;
- Feed-back control: measures after deviations occur. This is a reactive form of control, solely based upon output information.

APPENDIX D RELIABILITY CENTRED MAINTENANCE (RCM)

D.1 Introduction

Reliability Centred Maintenance (RCM) is a concept that was originally developed for the aeroplane industry. Later, adjustments have been made to make it more suitable for other industries as well. The RCM process seeks to answer seven questions, of which the first five together form the Failure Modes Effects and Criticality Analysis (FMECA).

D.2 Process steps

Several criteria have to be satisfied for every step. The majority of the description below overview below is directly borrowed from a Maintenance Engineering Handbook (Mobley, et al., 2008, p. 2.35).

1) What are the functions and the associated desired standards of performance of the asset in its present or intended operating context? (functions)
   - The operating context of the assed shall be defined;
   - All functions of the asset or system shall be identified (primary and secondary functions);
   - All function statements contain a verb, an object and a performance standard (preferably quantified).

2) In what way can it fail to fulfil its functions? (functional failure)
   - The only criterion is that all failed states associated with each function shall be identified.

3) What causes each functional failure? (failure mode or functional failure)
   - All failure modes that are realistically possible to cause functional failure must be identified;
   - Failure modes shall be indentified at a level of causation that enables the identification of an appropriate failure management policy;
   - The list shall include failure modes that have occurred, failure modes that are currently being prevented by maintenance programs and failure modes that have not yet occurred;
   - The list of failure modes include any event or process that is likely to cause a functional failure, including deterioration, design defects and human errors.

4) What happens when failure occurs? (failure effects)
   - Effects describe what would happen if nothing were done to anticipate, prevent or detect the failure. Effects can be described at an element level, subsystem, or system level;
   - Effects include all the information that is required to support the evaluation of failure consequences:
     - What is the evidence (if any) that the failure has occurred?
     - What it does to kill or injure someone, or to have a negative effect on the environment?
     - What it does to have an adverse effect on operations? (production, capacity, etc.)
     - What physical damage is caused by the failure?
     - What must be done to restore the function of the system after failure?

5) In what way does each failure matter? (failure consequences)
   - The assessment of failure consequences shall be carried out as if nothing were done to anticipate, prevent or detect the failure. Effects can be described at an element level, subsystem, or system level;
   - The consequences of every failure mode shall be formally categorized as follows:

- The consequences categorisation shall distinguish hidden – from evident failure modes;
- The consequences categorisation shall distinguish events (modes & failures) that have safety and/or environmental consequences from those that only have economic consequences.

6) What should be done and by who, to predict, or prevent each failure? (proactive tasks and task intervals)
   - The selection of failure management policies shall be carried out as if nothing were done to anticipate, prevent or detect the failure. Effects can be described at an element level, subsystem, or system level;
   - The failure management selection process shall take in consideration that the conditional probability of failure modes can increase, decrease or do not change with age;
   - All scheduled tasks shall be technically feasible and worth doing (applicable and effective), and the means by which this requirement will be satisfied are set out under scheduled tasks;
   - If two or more proposed failure management policies are technically feasible and worth doing (applicable and effective), the most cost-effective policy shall be selected;
   - Scheduled tasks are tasks that are performed at fixed, predetermined intervals, including continuous monitoring (interval of effectively zero). The following criterion have to be met:
     - In the case of an evident failure mode has safety or environmental consequences, the task shall reduce the probability of the failure mode to a level that is tolerable to the owner/user of the asset. In the case of a hidden failure mode where the associated multiple failure has safety or environmental consequences, the task shall reduce the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner/user;
     - In the case of an evident failure mode that does not have safety or environmental consequences, the direct and indirect costs of doing the tasks shall be less than the direct and indirect costs of the failure mode when measured over comparable periods of time. In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, the direct and indirect costs of doing the task shall be less than the direct and indirect costs of the multiple failure plus the costs of repairing the hidden failure mode when measured over comparable periods of time;
   - RCM makes a distinction between the following three proactive categories of tasks:
     - On-condition Task: a scheduled task to detect a potential failure (other names used in maintenance theory are predictive tasks, condition-based tasks, condition-monitoring tasks);
     - Scheduled Discard Task: a scheduled task that entails discarding an item at or before a specified age limit regardless of its condition at the time. Such tasks can only be accepted if there is a clearly defined age at which there is an increase in the probability of failure;
     - Scheduled Restoration Tasks: a scheduled task that restores the capability of an item at or before a specified interval(age limit) regardless of its condition at the time, to a level that provides a tolerable probability of survival to the end of another specified interval. Again, there needs to be a clearly defined age at which there is an increase in the probability of failure.

7) What should be done if a suitable proactive task cannot be found? (default actions)
   - The first option is to let the asset run to failure. In general, this approach is only accepted if the associated failure has no safety or environmental consequences;
   - Second option is to change something about the asset's operating context. This can be done by changing the design or the way it is operated.

APPENDIX E MAINTENANCE ENGINEERING TOOLBOX

E.1 Introduction

This appendix provides an overview of the tools that can be applied in the maintenance engineering process. If not explicitly mentioned otherwise, the content is borrowed (and translated) from the RAMS guideline of Rijkswaterstaat. At first, the decision model will be presented that can be used to select the most suitable analysis method. Subsequently, the different kind of analyses will be introduced. For a more elaborated description will be referred to the RAMS guideline itself (Rijkswaterstaat, 2010b). Appendix 5 of the guideline also contains an overview of the ICT-tools that can be used to support the analyses.

E.2 Decision making model

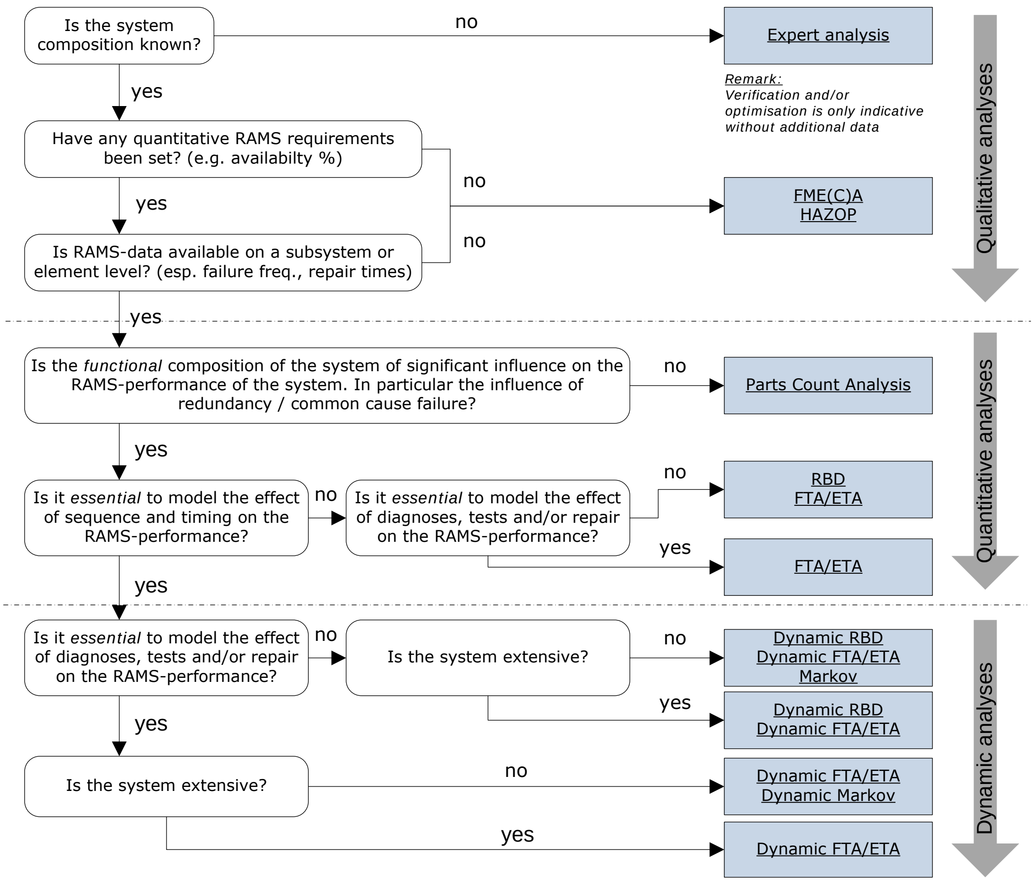


Figure 50: Decision-making model RAMS methods (adapted from Rijkswaterstaat, 2010b, p. 75)

The decision-making model supports the engineer in selecting the most suitable analysis. If only limited time is available, it is very tempting to go for the least complex analysis method. There are however more ways to save time. One could for instance cluster a number of (sub)systems. The first step in this approach is to divide the different (sub)systems into categories (e.g. small, medium, and large viaducts). Second, an in-depth analysis has to be performed for one object out of each category. These detailed analyses can be used to derive unit figures per system category. Finally, the unit figures (e.g. in terms of maintenance costs) can be used to say something about the other systems in a category.

E.3 Qualitative tools

E.3.1 System analysis

This tool is not included in the RAMS guideline, but mentioned by Kuijper (2006, pp. 6-12). He proposes to start the maintenance analysis with a description of the functions and the components of a system. The physical components can comprise elements of different functional subsystems. A matrix can help to provide insight into the relations between the different subsystems and the functional requirements. An example is illustrated in Table 7:

	Functional subsystems			
Physical subsystems	Stopping water	Letting water pass	Letting ships pass	Letting fish pass
Superstructure of the dam	X			
Lock gates	X		X	
Lock chamber	X		X	
Fish ladder	X	X		X

Table 7: Relations between functional and physical subsystems of a lock complex (Kuijper, 2006, pp. 6-12)

E.3.2 Expert analysis (checklists, expertise, benchmarking)

The second qualitative analysis technique that can be applied is the expert analysis. Experts with elaborate design competencies give their opinion about the design, its strengths and weaknesses.

Advantages:

+ Utilisation of experiences from both inside and outside the organisation.

Disadvantages:

- The completeness of the analysis is impossible to underpin;
- Quantification of the analysis is impossible (only ranking);
- Different experts can give significantly different rankings;
- Experiences can be insufficient, or even inapplicable in case of new systems.

E.3.3 FME(C)A

E.3.3.1 FMEA (Kuijper, 2006)

FMEA entails systematically drawing up the failure modes of the subsystems and the consequences for the function of the system. Figure 51 illustrates a general flowchart for the FMEA. An example of a FMEA result table is shown in Table 8.

The analysis can be executed bottom-up by beginning at a subsystems level (or lower) and by expanding the analysis to system level. The level that is supposed to be reasonable for starting the analysis can be determined by, for instance, the availability of data concerning failure modes. Disadvantage of the bottom-up approach is that the analysis almost always includes some components or subsystems that are not, or hardly of importance to the overall system functioning.

Time and effort can be saved by applying a top-down approach, requiring the analysis to be carried out in two or more phases. The system first has to be divided into function blocks: a set of subsystems/components which together have one function. For every block, an inventory can be made of the failure modes. By determining the effects of possible unwanted functioning of a block on the total system performance, the decision can be made whether or not to further analyse a function block more in detail. Disadvantage of this method is that failure modes can be easily overlooked (Kuijper, 2006).

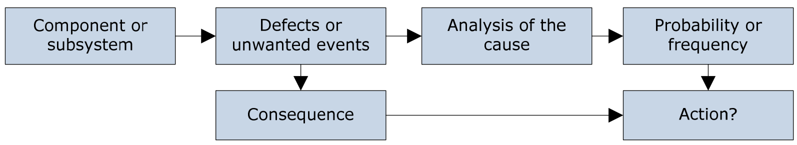


Figure 51: Flowchart FMEA (Kuijper, 2006, pp. 6-13)

Subsystem: water pipe **Function:** supply of water			
Defect	**Possible cause**	**Consequence**	**Action**
No water	Pump does not work Pipe is broken Valve does not work	Stagnation of production	Installing a second pump Construction a backup pipe
Too much water	Pump doesn't turn off Valve does not work	Water problems and waste of water	Safety system for pump operation Constructing a double valve

Table 8: FMEA example registration (Kuijper, 2006, pp. 6-14)

E.3.3.2 SFMECA (Waeyenbergh & Pintelon, 2002)

Waeyenbergh & Pintelon (2002) propose a Simplified Failure Modes, Effects and Criticality Analysis (SFMECA). The difference with the FMEA is that also a criticality matrix is included, relating the different failures modes and consequences to each other. It thereby classifies the consequences according to gravity. Score tables are used to define evaluation criteria such as the severity of impact, the probability that a specific failure mode will occur, and the probability that the failure will be detected. A multiplication of scores finally leads to a priority number. Table 9 shows an example of a SFMECA analysis for a sub subsystem of a car. As can be seen, borders have been defined to indicate each of the criteria. These borders are derived from the system characteristics and project objectives. A simple calculation finally leads to a risk priority number.

Sub subsystem	**Tire**
Function:	Support the car (and thereby enable safe and comfortable driving)
Failure mode:	Flat tire
Failure cause	Sharp object on the road (e.g. glass)

	Severity factor			
	0	**1**	**2**	**3**
Failure risk				
Probability of failure	< 1/270.000 km	**< 1/90.000 km**	<1/30.000 km	< 1/10.000 km
Hidden failure	**No**			Yes
Redundancy	Yes			**No**
Failure effect				
Safety problems	No			**Yes**
Cost of materials	< €50,-	€50,- <x< €100,-	**€100,- <x< €200,-**	> €200,-
System unavailability	< 1 h	**1 h < x < 4 h**	4 < x < 24 h	> 24 h
Secondary damage	**None**	Small (scratches)	Medium	Large (total loss)
Priority number	**(*2* x 0) + (*2* x 1) +(*1* x 2) + (*2* x 3) = *10***			

Table 9: Example SFMECA for a tire of a car (the format is borrowed from Waeyenbergh & Pintelon, 2002)

E.3.3.3 Advantages and disadvantages

The RAMS guidelines mentions the following advantages:

- \+ Utilisation of experiences from both inside and outside the organisation;
- \+ Provides insight into, and documentation of, the way the system functions (and can be improved);
- \+ An FME(C)A provides a proper basis for a quantitative analysis (e.g. an FTA which concentrates on reliability and availability).

Disadvantages:

- Quantification of the analysis is impossible (only ranking);
- Different experts can give significantly different rankings;
- The method is difficult to apply for complex systems, due to the large amount of data required;
- Multiple failures, and common cause failures are generally not included.

E.3.4 HAZard & OPerability (HAZOP)

HAZOP analyses the effects of all possible failure modes. The approach is almost similar to the FMECA.

Advantages:

- \+ Utilisation of experiences from both inside and outside the organisation;
- \+ Provides insight into, and documentation of, the way the system functions (and can be improved);
- \+ The HAZOP provides a proper basis for a quantitative analysis (e.g. FTA, focussed on safety).

Disadvantages:

- The completeness of the analysis is impossible to underpin;
- Quantification of the analysis is impossible (only ranking);
- Different experts can give significantly different rankings;
- The method is difficult to apply for complex systems, due to the large amount of data required;
- Multiple failures, and common cause failures are generally not included.

E.3.5 Human Reliability Analysis (HR)

This method can be used to analyse the possible failure modes (and its effects) in which a human factor is included.

Advantages:

+ Utilisation of experiences from both inside and outside the organisation;
+ Provides insight into, and documentation of, the way the system functions (and can be improved);
+ Provides the possibility to consider human failure as a failure mechanism.

Disadvantages:

- The completeness of the analysis can only be underpinned by means of supporting techniques, as a Task analysis and RASCI-tables;
- Quantification of the analysis is very difficult, and dependent on expert opinion;
- Human failure is not a constant factor.

E.4 Quantitative tools (hardware-failure)

E.4.1 Parts Count Analysis

This method determines the failure frequency per subsystem or component, and adds them up. The result is an indication of the failure probability of the system as a whole.

Advantages:

+ The analysis is very straightforward and does not require much system knowledge;
+ Software tools are available.

Disadvantages:

- Redundancy is not taken into account;
- There is no specification of failure mechanisms of system components;
- The use of data from handbooks is disputable, and does not always lead to the desired results;
- Test and repair measures are not taking into account.

E.4.2 Reliability Block Diagram (RBD)

A RBD gives a chain description of the system. It provides insight into the dependencies and redundancies.

Advantages:

+ The analysis is rather straightforward;
+ The visualisation simplifies the insight into the system behaviour;
+ Software tools are available.

Disadvantages:

- A block can only contain one failure mechanism (positive or negative);
- Test and repair measures (and its effect) are not included in the analysis;
- Common cause failures can only be executed by introducing additional blocks;
- There is no modelling of deteriorating system conditions;
- Time-dependent, or sequential, failure modes cannot be modelled;
- Different models are required for analysing ‘safe failures’ and ‘dangerous failures’;
- The method is mainly suitable for modelling reliability.

E.4.3 Fault-Tree Analysis (FTA)

The fault-tree can be used to analyse the system elements and events that lead to one particular undesired event. Such an event is defined as a “dynamic change of state that occurs in a system element [...]. A fault event is an abnormal system state. A normal event is expected to occur” (Mobley, et al., 2008, p. 3.137). An overview of the steps involved and an example FTA are illustrated in Figure 52. ‘Motor overheats’ is the event. The node above the base events (‘primary motor failure’ and ‘excessive current to motor’) shows the condition that has to be satisfied for the compound event to take place. This condition is referred to as a gate. See

'Probability in Civil Engineering' (Kuijper, 2006, pp. 6-16) for a more elaborate description of the fault-tree analysis and an overview of the symbols:

Advantages:

+ Suitable for dealing with complex systems (e.g. water defence system), by splitting up the system into subsystems (control, energy supply, etc.) with separate fault-trees.
+ Not only hardware- and software failure, but also other failure modes and causes can be considered;
+ Tools are available for evaluating, quantifying and even automatic generation of fault-trees;
+ Models are also understandable for non-experts;
+ The Method is suitable for systems with redundancy.

Disadvantages:

- In general, the analysis concentrates on one top event. As a result, several models are required for different top events (like, for instance, 'safe' and 'dangerous' system failure);
- The output is often a probability of a top event on a specific moment (often 'steady-state');
- Sequential events cannot be modelled with traditional fault-trees (only with dynamic FTA's);
- Aspects regarding the repair of failed components cannot be included adequately;
- Interaction between events cannot be modelled.

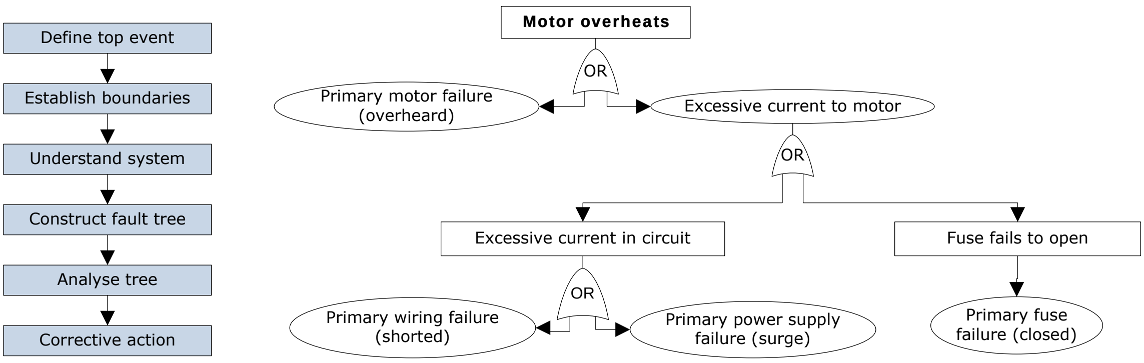


Figure 52: Typical fault-tree process (left) and a fault-tree example (right) (adapted from Mobley, et al., 2008, p. 3.137)

E.4.4 Event-Tree Analysis (ETA)

The event-tree can be used to support the analysis of the reaction of a system to one event. The event-tree relates one 'initial event' to all possible consequences, by analysing all the possible events that can follow the initial event. Figure 53 illustrates an example of an event-tree. 'Failure' is usually indicated in the bottom branch, and 'functioning' in the top branch. The advantage of this method is that parallel and serial systems can be recognized easily.

Advantages:

+ Provides a quantitative indication of the probability of a failure mode;
+ In combination with FTA's, it provides a full picture of the cause and effect;
+ Aspects regarding the repair of failed components can be included in the analysis;
+ Tools are available for evaluating, quantifying event-trees, and linking it to FTA's;
+ Models are also understandable for non-experts.

Disadvantages:

- In general, the analysis focuses on one specific start event. As a result, several trees are necessary for different events;
- The point of departure usually is a certain event on a specific moment in time ('stead-state');
- Dynamic behaviour cannot be modelled.

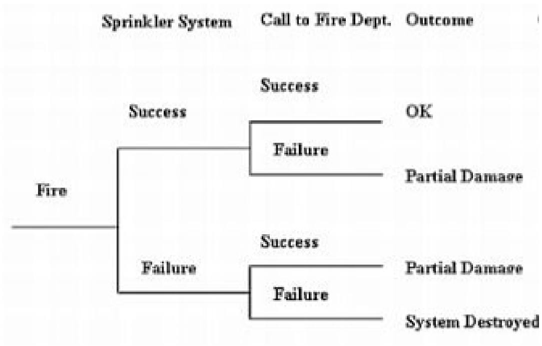


Figure 53: Example of an event-tree (fire event) (Wikipedia.org)

E.4.5 Markov Analysis

A Markov process has no memory, meaning that the probability distribution of the deterioration process is only determined by the state at that point in time, and not by the manner in which the states has been reached. This means that a repaired component is considered equivalent to a new one.

A Markov model assumes that the condition of a component can be described in terms of a limited number of condition states. Transition probabilities describe the probability that a component will move from one state to another. The transition from failure to function is the repair speed. The transition from function to failure is the failure rate. A simple Markov diagram (containing the states A, B & C) is illustrated in Figure 54. Several infrastructure management systems are based upon Markov models (e.g. for pavements and bridges) (van Noortwijk & Frangopol, 2004).

The advantages mentioned in the RAMS guidelines are as follows:

- + Very detailed analysis;
- + Provides a complete system description in one model;
- + Provides the possibility of modelling several repair scenarios;
- + The method provides the possibility to model sequential dependency.

Disadvantages:

- The analysis is complex;
- Models are very difficult to build and verify, especially for non-experts;
- Models can become very extensive (especially in terms of condition states);
- Every change in the system design requires the creation of a new model;
- The use of constant failure frequencies means that effects like fatigue and wear & tear require a different analysis method (semi-Markov-processes).

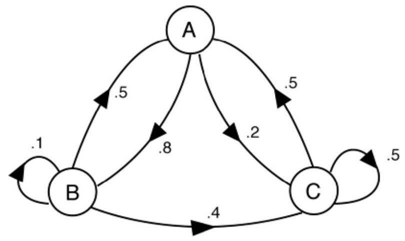


Figure 54: Markov diagram (3 states, 7 transition probabilities)

E.5 Quantitative tools (software- and human failure)

For a description of the quantitative tools that support the analysis of software – and human failure, will be referred to Chapter 5 of the RAMS guideline (Rijkswaterstaat, 2010b). The guidelines introduces the Software Reliability Growth Modelling, TDT-model, TOPAAS-model and OPSCHEP-model.

APPENDIX F MAINTENANCE POLICIES

F.1 Introduction

The choice of which maintenance policy to apply, among others depends on (Kuijper, 2006, pp. 7-9):

- Predictability of the life span of the object;
- Consequence of the failure of the object;
- Costs of inspection, replacement or repairs;
- Perceptibility of the condition of the structure (damage or deterioration).

F.2 Maintenance policies

F.2.1 Operational scenario adjustment (OSA)[62]

The criticality of a system among others depends on the operational characteristics. Revising the operational scenario therefore can be a way to decrease the criticality of a system. This can of course only be done in consultation with the client and/or operator.

An example provided by one of the interviewees will clarify the approach. Suppose, a tunnel design contains two firewater pumps, each with a capacity of 60 m^3/h. The fire department requires a supply of 120 m^3/h with a 100% reliability. The current design cannot meet this requirement: a failure in one pump would immediately lead to an insufficient supply and a dangerous situation in case a fire breaks out. A solution however can be that the fire department is contacted the moment one pump is out of service. If during this period of failure a fire breaks out, the fire department is aware that it has to bring in additional pump capacity.

F.2.2 Design out maintenance (DOM)

Design out maintenance (DOM) aims to eliminate the cause of failure or the negative impact of failure by adjusting the system characteristics. This policy, already referred to as maintainability engineering, is especially worth considering during the design process. Maintainability theory can be applied to study the feasibility of this policy and realise further optimisation.

DOM aims to eliminate, or at least reduce the need for maintenance. First question is whether it is technically feasible to design out the maintenance need. Second, it is the question whether is it is economically desirable because a design adjustment typically affects other aspects as well (e.g. initial investment, aesthetic value, user comfort) (Waeyenbergh & Pintelon, 2002, p. 309).

F.2.3 Failure based maintenance (FBM)

It is called failure based maintenance, or corrective maintenance if an intervention is done in response to the report of actual failure. Important characteristic of corrective maintenance is that (part of) the system is temporarily unable to provide service. As a result of the maintenance intervention, the service is recovered. Advantage of this strategy is that the life of the construction is optimally utilised. Usually, this strategy is not acceptable if the impact of failure is large (e.g. in terms of lethal casualties).

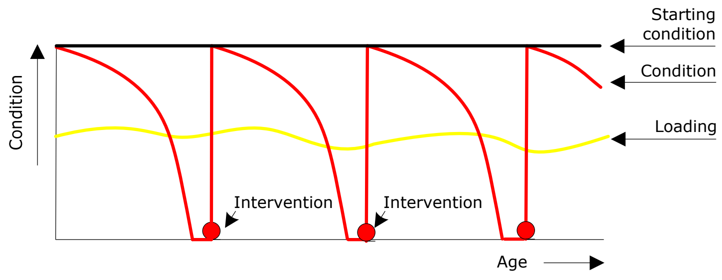


Figure 55: Performance development with a corrective based approach

[62] Some of the interviews brought this approach up. In literature, it is not explicitly mentioned as a typical maintenance strategy.

F.2.4 Condition based maintenance (CBM)

Condition based maintenance (CBM) belongs to the category of planned, proactive maintenance policies. These aim to reduce the probability of asset failure to an acceptable level of risk (Dekker & van Noortwijk, 2002, p. 4). CBM is the most applied maintenance approach for the critical elements in infrastructure systems since it offers the possibility to exploit the total life of the construction with a minimal probability of failure (and thus dangerous situations). Inspections are done in order to determine the state of the construction. This type of maintenance requires setting norms:

- A limit state that leads to the decision to increase the inspection frequency (warning limit);
- A limit state that leads to the decision to carry out repairs (action limit).

Intervention levels are chosen so that enough time is available to schedule and prepare the required intervention. Inspections can be planned with a fixed interval or based upon the observed deterioration process.

Another maintenance policy mentioned in literature is detective based maintenance (DBM). This policy, often referred to as failure-finding, aims to detect hidden or unrevealed failures. In the construction industry, the DBM and CBM often belong to the same policy category (Waeyenbergh & Pintelon, 2002, p. 310).

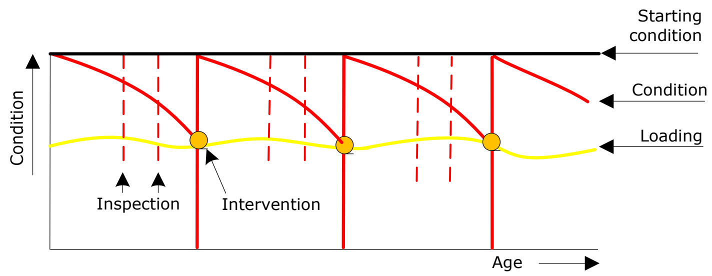


Figure 56: Performance development with a condition based approach

F.2.5 Use based maintenance (UBM)

Use based maintenance (UBM) also belongs to the category of planned, proactive policies. This strategy typically concerns fixed amounts of work (such as quantity of work in m^2/km) initiated after a certain amount of time (e.g. every 2 months) or usage (e.g. every 50.000 cars passed).

This approach is particularly suitable if the deterioration rate is stable. Infrastructure specific examples of this type of maintenance are grass cutting, culvert cleaning and drain cleaning. The frequency of scheduling depends on the required performance levels. Advantage of this type of maintenance category is that the activities can be planned far in advance. In order to make a proper schedule, reliable information is required about the deterioration rates (Robinson, Danielson, & Snaith, 1998, p. 162).

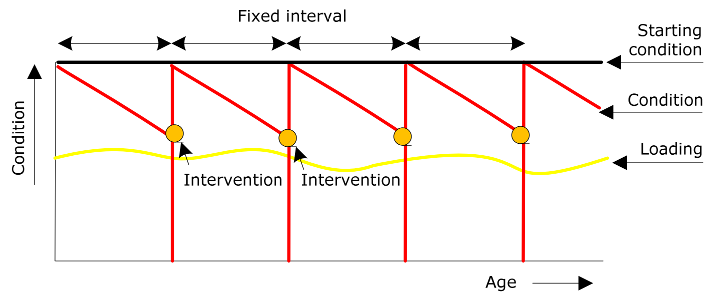


Figure 57: Performance development with a use based approach

APPENDIX G CONCEPT OF COLOURS

G.1 Introduction

The concept of colours is an instrument developed by Léon de Caluwé. It can be used to (de Caluwé, 2008b):

- Determine the best approach for a specific change that has to be processed;
- Identify personal strengths and weaknesses within an organisational process;
- Analyse how an organisational process has developed;
- Make the values and beliefs of individuals explicit, and thereby discussable. This increases the manageability of a process of change.

The underlying principle is that each kind of process of change needs a different approach. In the ideal organisation, each colour is represented so that every situation can be dealt with. De Caluwé explains the concept by projecting it on a football match. Red-print thinkers come as visitors to the match, hoping that the perfect wave will originate within the crowd. Blue-print thinkers however tell the red-print thinkers that they have to sit down instead, because the wave blocks the view on the pitch. They simply come to the stadium to see the match. Yellow-print thinkers just sit in their skybox, doing their own thing. The brilliant left-winger is a white-print thinker, using his intuiting and creativity to achieve well. The coach, being a green-print thinker, makes notes in order to ensure that the team performance improves as the competition progresses.

G.2 Attitude profiles

Each of the attitude profiles is explained in the following sections by addressing the key characteristics. The descriptions are copied one-on-one from a presentation of Twynstra Gudde (de Caluwé, 2008a).

G.2.1 Yellow-print thinking

Assumptions
"Changing = a power game" Something changes when you: • Search for common interests • Compel people to take certain positions • Form coalitions • Formulate new policies

Ideals
• Create common interests/win-win situations • To safeguard the feasibility of solutions
Pitfalls
• Building castles in the air • Power struggles (loose-loose)

Route
Result: unknown & changing along the way Interventions e.g.: • Alliance building • Arbitration/mediation • Creating/changing top structures • Favouring protégés, promoting people to the fringes Safeguarding progress: policy documents, power balance

Change agent
Role: facilitator who guards and uses his own power base Competencies e.g.: • Independence and self-control • Sensitive to power relations • Knowledge of the sector, strategy issues and structuring issues Focus: positions and context

G.2.2 Blue-print thinking

Assumptions
"Changing = rational process" Something changes when you: • Define a clear result on beforehand • Formulate a step by step action plan • Monitor progress and take corrective measures • Foster stability and reduce complexity

Ideals
• Progress can be planned; a better world can be 'built' • The 'best' solution (tangible aspects of organisations)
Pitfalls
• To steamroller over people and their feelings • To ignore irrational and external factors

Route
Result: delineated and guaranteed in advance Interventions e.g.: • Project management • Meeting procedures • Time management • Strategic analysis Safeguarding progress: monitoring, benchmarking, ISO

Change agent
Role: expert who formulates and implements plans if mandated to do so Competencies e.g.: • Analytical skills • Planning and control • Expertise crucial to the project content • Presentation skills Focus: expertise and results

G.2.3 Red-print thinking

Assumptions	Ideals
"Changing = trading exercise" Something changes when you: • Use the right incentives to motivate people • Make it comfortable and interesting for people • Award and punish people • Exercise care and safeguard fairness	• The optimal fit between organisational goals and individual goals • A solution that motivates people (soft organisational aspects) **Pitfalls** • Sparing the rod, avoiding conflicts, ignoring power struggles • Smothering brilliance

Route	Change agent
Result: outlined on beforehand but not guaranteed Interventions e.g.: • Appraisal and remuneration • Management of mobility and diversity • Social gatherings • Soap box Safeguarding progress: HRM systems	Role: systems expert who occasionally makes suggestions with regard to the content Competencies e.g.: • HRM methods • Organising proper communication • Working in teams • Exercising care Focus: Procedures and atmosphere

G.2.4 Green-print thinking

Assumptions	Ideals
"Changing = learning" Something changes when you: • Make people aware of their incompetencies • People gain new insights and new skills • Create settings for collective learning • Change people	• Learning organisations: with everybody, about everything, always • A solution that people help develop themselves **Pitfalls** • To ignore that not everybody is willing or capable of learning everything • Overabundance of safety and reflection, lack of decisiveness

Route	Change agent
Result: envisaged beforehand, but not guaranteed Interventions e.g.: • Training, management development • Gaming • Coaching / intervision • Open systems planning Safeguarding progress: permanently learning organisation	Role: facilitator who supports people Competencies e.g.: • Designing and facilitating learning situations • Knowledge of organisational development • Feedback skills • Empathy and creativity Focus: Setting and communication

G.2.5 White-print thinking

Assumptions	Ideals
"Changing = releasing energy" Something changes when you: • Tap people's own will, desire and strength • Remove obstacles to entrepreneurship and optimise conflicts • Discern underlying patterns and make meaning • Create new heroes and rituals	• Spontaneous evolution • Self-steering • Taoist (goal driven) **Pitfalls** • insufficient insight into underlying forces and patterns • Laissez faire, 'self-steering' as an excuse for management apathy

Route	Change agent
Result: hard to predict (the road = the destination) Interventions e.g.: • Self-steering teams • Open space meetings • Personal growth/empowerment • Challenge sacredly held ideas and customs Safeguarding progress: self steering	Role: personality who uses his being as instrument Competencies e.g.: • Pattern recognition and creation of (new) meaning • Challenging the status quo • Courage, and ability to deal with insecurity • Authenticity and self-awareness Focus: patterns and persons

APPENDIX H PROJECT ANALYSIS: N31

The first case project studied is a DBFM project that is currently in the maintenance phase: N31. The key findings of this analysis are included in the conclusions of the empirical analysis, described in chapter 7.

The analysis starts with a description of the general project characteristics. Secondly, the most important contract characteristics will be discussed, followed by an analysis of the formal and informal role structure. Finally, the role of the client organisation will be discussed. For an explanation of the framework that is used for the analysis will be referred to chapter 5.

H.1 Introduction

H.1.1 Project introduction

In the beginning of the nineties, the government decided that the road safety of the N31 had to improve. Around 1999, the Dutch knowledge centre for public private partnerships (PPP) drew up a list with projects that were considered to be suitable for a PPP. The Ministry of Transport, Public Works and Water Management (V&W) finally decided to go for a DBFM contract and use the N31 as a pilot project. Because it was the first DBFM project ever for Rijkswaterstaat (RWS), it was made one of the prime objectives to gain practical experience and knowledge. A map of the project is presented in Figure 58. The key characteristics of the project are (Buck Consultants & John Cooper Consulting, 2004):

- Contract:
  - Client: Ministry of V&W and RWS Noord-Holland;
  - Contractor: Consortium Wâldwei.com (Ballast Nedam, BAM, Dura Vermeer);
  - Value: ± € 80 mln (construction costs: € 60 mln, maintenance costs: € 20 mln).
- Scope:
  - Design and reconstruction of the motorway between the exit Leeuwarden and Nijega;
  - Design and construct of the aquaduct 'Langedeel' and the moveable bridge 'Fonejachtbrug';
  - Finance, maintain, and partly operate the above mentioned objects and the existing double lanes motorway between Nijega and Drachten (ca. 22 km) for around 20 years.
- Timeline :
  - Tender: March 2002 – December 2003;
  - Design and construct: January 2004 – October 2007;
  - Maintenance: January 2004 – December 2022.

Figure 58: Overview of the N31 DBFM project

H.1.2 Analysis approach

The tender, design and construction phase have already been completed for several years now. For that reason, it is difficult to perform an in depth study into these early project phases. Above all, it is questionable whether such an analysis would give a proper reflection of the current practice. The reason is that the N31 was the first time RWS applied a DBFM contract. Assumedly (and hopefully), the parties involved have already learned from its mistakes.

The fact that the project is already for a few years in the maintenance phase also has its advantages. It provides the opportunity to study how the plans that have been made in the maintenance phase, finally work out. In addition, it can be studied how the organisations evaluate its performance and apply these learning experiences in other projects. These are the reasons for why the analysis mainly concentrates on the maintenance phase itself, and less on the early project phases. Interviews will be conducted with the project director, the project leader of the maintenance phase, the maintenance site manager and an engineer involved in the design process of Aquaduct Langedeel. Besides, documents are studied from both the public and private parties involved.

The analysis will also make use of an evaluation performed by Buck Consultants and John Cooper Consulting (2004). The evaluation, which is performed at the request of RWS and the Ministry, mainly concentrates on the tender procedure. Though it doesn't really concentrate on the incorporation of maintenance, it nevertheless contains some useful insights.

H.2 Contract characteristics

H.2.1 Tender procedure

The public party chose to procure the contract by means of a negotiation procedure with prior announcement[63]. This procedure consists out of three phases: the prequalification, the consultation phase and the negotiation phase. A timeline of the tender procedure is presented in Figure 59.

The prequalification phase aimed to select the consortia that were supposed to be suitable to execute the project. Criteria that were evaluated, are among others expertise and financial bearing power. After the prequalification phase, four parties were selected to enter the consultation phase.

The consultation round was about clarifying and fine-tuning the draft program of requirements and the draft contract. Consultations were being held with the private parties about the execution of the contract and the conditions. The candidates were asked to come up with suggestions on how to improve the draft contract in terms of technique, risk allocation and finance. Although decisions regarding the lay-out already had been made[64], candidates were also asked to present alternatives. The client finally decided to use none of the submitted alternatives: the costs of redoing part of the planning procedure did not outweigh the advantages of the alternatives.

After the consultation phase, the preliminary bids were submitted. Subsequently, two of the four parties were invited to enter the negotiation phase. The negotiation phase was used to discuss the commercial part of the bidding and the allocation of risks. The project organisation tried to have an open conversation, and to understand the private parties' concerns. At the end, both candidates submitted their final bid.

The client applied the EMAT contract awarding mechanism. Budget restrictions however forced the client to evaluate for 90% on price. The other 10% has been assigned to safety, aesthetics and nuisance. The tender procedure was finalised with the decision that the contract was awarded to the consortium Wâldwei.com (from now on referred to as Wâldwei).

[63] In Dutch called the 'onderhandelingsprocedure met voorafgaande bekendmaking'. Most important reason for choosing this procedure was that it enabled interaction with bidders. The competitive dialogue procedure as currently applied in DBFM projects was not available until new European legislations were enforced in 2004.

[64] The public planning procedure was finalised already with a document called the 'Tracébesluit'. This is a detailed plan drawing that illustrates the main futures of the project (the route, positioning of structures, etc.).

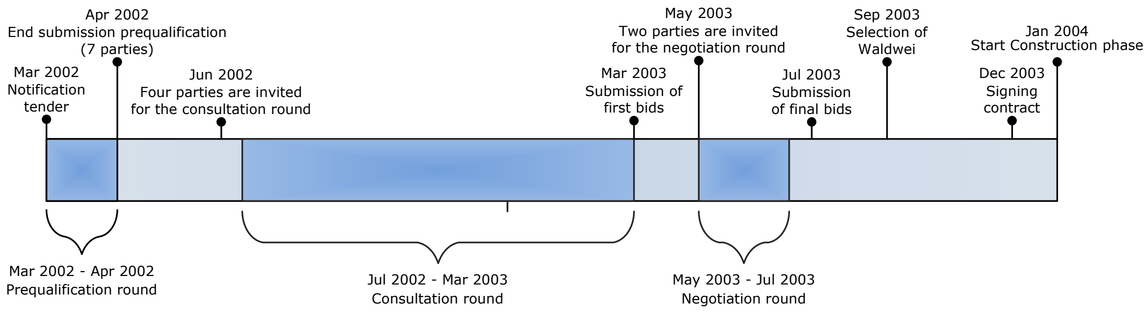


Figure 59: Timeline of tender phase

H.2.2 Payment mechanism

The payment mechanism of the N31, which is based upon the realised system availability, is illustrated in Figure 60. As explained below, different groups of payments can be distinguished[65]. The recurring availability payments consist of a basic payment, plus/minus a bonus/malus for a higher/lower availability of the road than agreed on. The value of the road availability depends, among other, on the part of the day. In addition, penalties can be imposed if the private party performs insufficiently in terms of quality control and ensuring road safety.

- PBV: a pre-availability payment, starting directly after contract awarding. In considering of ensuring availability of the existing 2x2 Drachten-Nijega and 1x2 Nijega-Hemriksein;
- TBV: a in-between-availability payment starting after receiving the availability certificate for 2x2 Nijega – Garyp. In exchange, Wâldwei ensures availability of the existing 2x2 Drachten-Nijega and 1x2 Garyp-Hemriksein, and the new 2x2 Nijega-Garyp;
- BV: the availability payment, starting after receiving the availability certificate of 2x2 Hemriksein-Garyp, Fonejachtbrug and Aquaduct Langedeel. In exchange, Wâldwei.com ensures availability of the total route (2x2 Drachten-Hemriksein) including the civil engineering structures;
- A onetime payment of €40 million, received after completing all construction activities.

Cost category	Division of costs
Construction costs	64%
Fixed maintenance	7%
Variable maintenance	6%
Corrections*	23%

*) The corrections amongst others concern performance bonuses, priced risks, and contract management costs for RWS

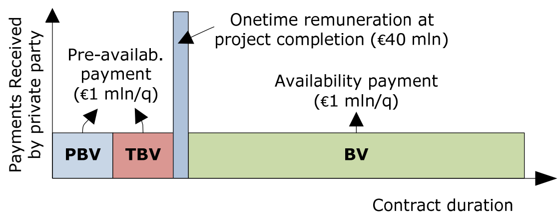


Figure 60: Composition best & final offer (left) and the payment mechanism (right)[66] (Buck Consultants & John Cooper Consulting, 2004, p. 60 & 71)

H.2.3 Maintenance obligation

The overall allocation of the is summarised in Table 10. What are the obligations during the maintenance phase? Roughly said, Wâldwei has to ensure availability of:

- Hemriksein – Nyega (11,3 kilometres of new motorway; 9 kilometres of existing motorway);
- Fonejachtbrug (bascule bridge with a span of 22 meter , concrete & movable part of steel);
- Aquaduct Langedeel (concrete).

[65] PBV = 'pre-beschikbaarheidsvergoeding'; TBV = 'tussen-beschikbaarheidsvergoeding'; BV = 'beschikbaarheidsvergoeding'

[66] It is striking that the introduction of the project evaluation of Buck Consultants & John Cooper Consulting (2004, p. 19) mentions a project value of €80 mln, while a simple summation of the individual payments results in a total value of €120 mln (€1 mln/q x 4 quarters x 20 years = €80 mln. €80 mln availability remuneration plus a onetime payment of €40 mln at project completion makes €120 mln). No further time has been spend on clarifying where this difference stems from since it is not of crucial importance for this research.

The responsibility of incident management is assumed by RWS. Wâldwei only got a supportive role in accident management. Direct non-service as a result of an incident is not deducted from the availability payment, as opposed to non-service that is a result of repair measures that are executed later. Another thing that is taken care of by RWS itself, are the anti-icing measures.

Wâldwei.com	RWS
Inaccuracies of distributed information (excl. exceptions)	Information about soil conditions
Circumstances construction site	-
Timely acquirement of all permits (excl. exceptions)	Timely acquirement of building permit Fonejachtbrug, Aquaduct Langedeel, sound screens and large-scale earth removals
Scheduling, project completion before specified date	Reasons for delays, amongst others: delayed availability of construction site, building permits risk RWS, serious soil pollution, unknown archaeological sites, explosives.
Known archaeological sites	-
Cables and pipes, other costs	Cables and pipes, costs for moving
Traffic management (excl. exceptions)	De-icing, incident-management
Insurances	-
Information- and quality management	-
Law and regulations (excl. exceptions)	Special regulations specifically regarding the construction, maintenance, and ensuring the availability of roads
Damage to roads (excl. exceptions)	Abrupt and unforeseen damage (e.g. joyriding and –sailing)
Damage to others as a result of construction activities or road usage	Force majeure (e.g. war, terrorism, explosions, disasters, flooding, earth quakes)

Table 10: Risk allocation N31 (adapted from Buck Consultants & John Cooper Consulting, 2004, p. 59)

H.3 Formal role structure analysis

H.3.1 Responsibilities

H.3.1.1 Introduction

This part of the analysis describes what actors have been responsible for maintenance, to what extent maintenance engineering is addressed throughout the different project phases, and how this has affected the incorporation of maintenance.

The organisational structure will be discussed in detail in the next subparagraph. To understand the division of the maintenance engineering responsibilities, it is important to already have an idea of the operational part of the organisation. The DBFM contract is an agreement between the client and Wâldwei bv. Wâldwei bv has passed on the design, build and maintenance activities to Wâldwei v.o.f., existing of BAM Civiel, Dura Vermeer Infra and Ballast Nedam Infra. Waldwei v.o.f. has on its turn subcontracted the design activities to Advin, IC+E, DMC, Imtech and Oranjewoud[67].

H.3.1.2 Tender phase

Only one of the interviewees was actually involved in the tender phase. According to this interviewee, limited attention has been paid to maintenance (engineering) during the tender phase. Most important was that an accurate maintenance cost estimate was developed. This estimate was so important because it provided important input for the financial models that are used to determine the bid price. Primarily responsible for the maintenance cost estimate was one of the directors of Dura Vermeer.

No specific party was made responsible for optimising the bid design in terms of maintainability or life cycle costs. One of the interviewees also indicated that there was really no time available to study the life cycle effectiveness of different design variants. That does not mean that no attention has been paid to maintainability

[67] Advin (part of Dura Vermeer nv) took care of the road design; IC+E (part of Ballast Nedam nv, now Ballast Nedam Engineering) took care of the aqueduct; DMC (part of BAM nv, now BAM Infraconsult) took care of the movable bridge. Imtech was responsible for the electrical installations while Oranjewoud provided general design support.

engineering at all. As will be explained in the task section, considerable effort has been put in optimising the life cycle cost effectiveness of the pavement system. This was mainly considered to be a joint effort.

H.3.1.3 Design phase

Unfortunately, the empirical study provided insight into the design phase of the aqueduct only. According to the interviewee, one engineer from Dura Vermeer was involved to support the design process in terms of maintenance. He also was also involved to prepare the maintenance plan. The contribution in terms of proactive maintainability engineering was very limited. The engineer was mainly involved to answer any questions that surfaced about the maintenance phase.

According to the interviewee, there was not really a need for an elaborate maintenance engineering process. Besides the pavement construction and the movable bridge, there were not that much systems with a high maintenance need. Looking at for instance the aqueduct, almost no maintenance is required as long as the construction is build properly. As a result, only limited savings can be realised with maintainability engineering. This makes it much more beneficial to focus on other aspects, like for instance constructability.

H.3.1.4 Construction phase

As will be explained more in detail in the next subparagraph, Wâldwei v.o.f. is made responsible for the design, construction and maintenance phase. The responsibility of maintaining the existing system commenced around the start of the construction phase. Two employees were made responsible for maintenance management. They had to (1) ensure the performance of the existing system, (2) prepare the maintenance phase of the new system and (3) check whether the new system was being built in a way that it could be easily maintained.

Going by the interviews, it seems like most time was spend on getting familiar with the new role of maintenance contractor. This effort mainly dealt with taking over the maintenance responsibilities of the road district, and preparing the maintenance phase of the new systems. Optimising the maintainability of the new systems was less urgent, and therefore more or less downgraded to a secondary obligation.

H.3.1.5 Maintenance phase

The responsibilities during the maintenance phase are clearly divided and described in the maintenance plan. Primarily responsible for the maintenance phase is the project leader of Wâldwei v.o.f, assigned by Ballast Nedam Beheer. The project leader is supported by several people who take care of the operational activities. One BAM employee is full-time present as a site manager. In addition, someone is made responsible for the inspections. The team is completed with an engineer who prepares the large maintenance interventions.

H.3.1.6 Analysis

The following positive finding has surfaced:

+ The interviewees agree that the division of responsibilities throughout the maintenance phase is clear for all the actors involved.

The following negative finding has surfaced:

– Maintainability engineering has not been explicitly addressed during the tender – and design phase. Attention has only been paid to the life cycle cost effectiveness of the pavement construction. Possibly, a more optimal system could have been realised if other systems were considered too;

H.3.2 Position

H.3.2.1 Introduction

This subparagraph will addresses the organisational structure and the position of the actors that deal with maintenance. The analysis will also elaborate on the extent to which parties have been stimulated to aim for a life cycle effective design.

H.3.2.2 Organisational structure N31

Subparagraph 3.3.1 described the mostly applied contractual structure in DBFM projects. As can be seen in Figure 61 is the contractual structure in this project considerably different. The DBFM contract is an agreement between RWS and the special purpose company Wâldwei.com bv. The design, build and maintenance aspect of the contract are passed on to the partnership Wâldwei v.o.f.: a general partnership in which Ballast Nedam Infra, BAM Civiel and Dura Vermeer Infra have an equal share.

This is where the structure differs from the DBFM triangle presented earlier. Normally, separate entities are created for the design and construction activities (EPC) and for the maintenance activities (MTC). In this project, all aspects have been assigned to one entity (EPCM). That means that the each of the partners bears responsibility for the design, construction and maintenance aspect of the contract.

During the design and construction phase, several engineering firms have been involved, like for instance IC+E, Advin, BAM Infraconsult and Oranjewoud. These parties were involved on the basis of a cost reimbursement type of contract. Some subcontractors remained involved till now, like for instance HSM Steel Structures and Imtech projects. They are responsible for maintaining the steel deck of the movable bridge and the mechanical & electrical systems, respectively.

Currently, a project leader of Ballast Nedam Beheer is primarily responsible for managing the maintenance phase. Unfortunately did the analysis not provide insight into the precise relationship between Waldwei v.o.f. and Ballast Nedam Beheer. It is for sure that Ballast Nedam Beheer gets some kind of remuneration for managing the maintenance phase. It is however unclear whether the payments are related to the realised system performance (and thus the availability payments received by Wâldwei).

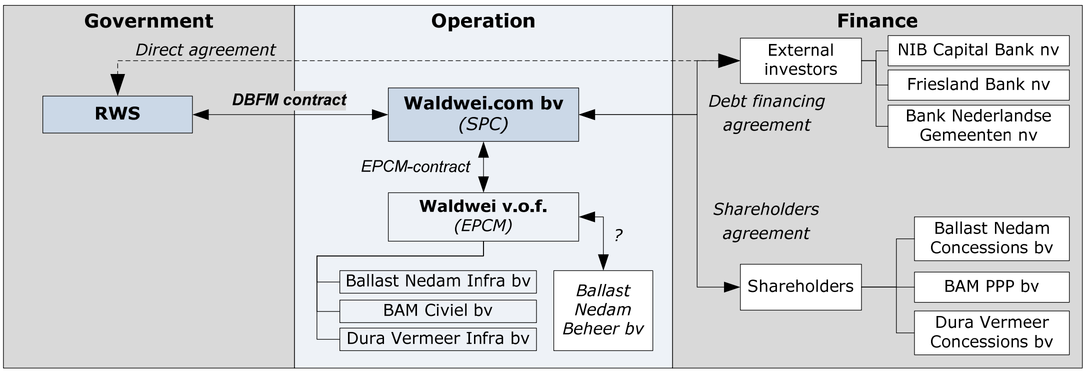


Figure 61: Formal organisational structure after contract awarding

H.3.2.3 Analysis

What is the effect of the formal organisational structure on the integration of the maintenance? The following positive finding has surfaced:

+ In contrast with the traditional DBFM triangle, one EPCM partnership has been established. The fact that all interests are aligned had a positive effect on the design process. This advantage was increased by the fact that all partners were equally committed. No elaborate discussions were required about the division of costs and benefits when a design adjustment was proposed.

The following negative findings have surfaced:

– In the EPCM, the maintenance responsibility is shared among all the actors involved. This means that no specific party is made primarily responsible for maintenance. Potential disadvantage of this shared responsibility is that each of the contractors returns to its standard routine and only concentrate on its (traditional) core activities. As a result, maintenance can get easily ignored;

– One of the interviews experienced that it is relatively difficult to initiate project evaluations. The interviewee told that this could possibly be explained by the fact that the partnership consists of competitors[68]. The fact that also two competitors benefit from the learning experiences, decreases the competitive advantage that can be achieved by each individual company.

- During the tender -, design - and construction phase, the engineers have been hired on the basis of a cost-reimbursement contract. As a result, they were not financially motivated to aim for life cycle optimisations.

H.3.3 Tasks

H.3.3.1 Introduction

This part of the analysis elaborates on the maintenance engineering tasks that have been executed throughout the project. Only a limited insight has been gathered into the tasks executed during the tender and design phase[69]. The analysis will therefore mainly focus on the engineering tasks that are executed during the maintenance phase.

H.3.3.2 Tender - and design phase

During the tender phase, a rough cost estimate has been developed by the director of Dura Vermeer. He estimated the maintenance cycles for the most important systems and made an estimation for the costs that go along. The interviewees indicate that this estimate has turned out to be rather accurate so far[70].

As mentioned already, not one party in specific was made responsible for maintainability engineering. It was however clear from the beginning that substantial savings could be realised by optimising the pavement construction. This was mainly considered to be a joint effort. What did the optimisation exactly comprise? Conventional wearing courses have a life span of around 8 to 9 years. This means that in a 20 year maintenance phase, two interventions are needed. Wâldwei therefore decided to look whether it could develop a wearing course with a lifespan of 11 years, so that only one intervention would be needed. Wâldwei finally succeeded in finding a mixture that satisfied this demand. It led to a substantial decrease in maintenance costs, which helped Wâldwei win the contract.

The design manager of the Aquaduct explained that no specific maintenance engineering analyses (e.g. RAMS, FMECA, etc.) have been performed during the tender and design process. This is understandable since an aqueduct doesn’t require any (substantial) maintenance. Instead, the consortium had to proof that the materials (e.g. the foil construction) were likely to last 100 years.

H.3.3.3 Construction phase

Two engineers were involved during the construction phase for maintenance planning and maintainability engineering. As been mentioned already, most effort was put in maintenance planning. Nevertheless, there are still some optimisations that have been realised in the construction phase.

An example concerns the mortise and tenon joint system that keeps the movable bridge in position when closed. Despites the fact that the joint system requires maintenance regularly, it was not properly accessible in the design. It took till the construction phase before they came up with the idea to install a collapsible scaffold on the column construction. One the one hand, it can be considered as positive that this optimisation has been realised in the construction phase. Better late than never. On the other hand, substantial costs could have been saved if the optimisation had been processed earlier in the design phase.

H.3.3.4 Maintenance phase

The maintenance plan[71] that has been developed throughout the design and construction phase describes, among others, the maintenance philosophy, the organisation, the scope and a planning. Three kind of planning

[68] Advantages are less competition in the tender phase and a reduction of risks.

[69] Only the design manager of Aquaduct Langedeel has been interviewed. No study has been done into the other systems.

[70] One of the interviewees mentioned that only the mowing activities have been underestimated. The estimation was that one time per year would be sufficient. It now turns out that that two times per year is required to satisfy the requirements.

[71] The ‘PKP-DKP Beheer en Onderhoud’ and ‘Instandhoudingsplan’ together form the maintenance plan.

files are drawn up: a long term planning (6 years), a short term planning[72] (1 year), and work plans. The long term planning is revised every year and delivers the input for the short term planning. The actual maintenance interventions are finally described in the work plans.

The interviewees indicate that no specific maintenance engineering analyses (e.g. FMECA, RAMS) are executed throughout the maintenance phase. The maintenance organisation mainly tries to optimise the (financial) performance by executing life extending measures. These aim to postpone large maintenance activities as far as possible to the future[73].

The maintenance plan also describes that the project performance will be evaluated every year. The evaluation reports mainly describe whether the objectives have been realised (e.g. in terms of penalties and accidents). In addition, it contains a complaint register, a risk register and some completed customer satisfaction forms. Looking at the content of the evaluation report, it seems to be mainly developed to report the current performance to the client organisation. It is much less suitable for really improving the maintenance performance.

The interviewees also indicate that Wâldwei has not yet collected learning experiences, and shared it with the parent companies. That however doesn't mean that no knowledge is shared at all. The employees that currently take care of the maintenance phase, often provide information to tender teams. Since only BAM and Ballast Nedam have someone working at Wâldwei, Dura Vermeer can only rely on the helpfulness of the other partners. One of the interviewees explained that there are plans to combine the experiences of the first few years into one evaluation. As mentioned already, some of the interviewees have the experience that it is rather difficult to initiate such an evaluation when the partnership consists of competitors.

11.4.1.1 Analysis

The following positive findings have surfaced:

+ The focus on the life cycle cost effectiveness of the pavement construction resulted in a wearing course with a life span of 11 years. This helped Wâldwei win the contract;
+ It is positive that the maintenance process is evaluated every year. Point of improvement is that the current evaluation mainly consists of an assessment of the past performance. It would be much more valuable for Wâldwei if the evaluation also described how these lessons can be used to improve the future performance.

The following negative findings have surfaced:

- Some optimisations were processed during the construction phase. Better late than never, but additional savings could have been realised if the adjustments were processed earlier;
- No specific maintenance engineering tasks are being executed during the maintenance phase. Possibly, the current approach could be further optimised if a maintenance concept was applied, and continuous improvement was pursued. This would also enable the partners to learn for future projects.

H.3.4 Authority

Four sources of authority have been mentioned in literature: network centrality, availability of means, expert power and personal characteristics. Unfortunately, the interviews and document study did not provide any insight into whether expert power and personal characteristics were a source of authority within this project. The analysis will therefore only address the formal sources of authority: network centrality and availability of means.

An EPCM is established in which all three contractors are equally involved throughout the project. This project organisation enabled a collaborative design process, in which each of the contractors benefits of a life cycle cost

[72] It contains the planned inspections, maintenance interventions, lane closures, reroutes and document deliveries.

[73] Postponing large maintenance activities has two advantages. First advantage is that maybe less maintenance interventions are required within the contract period. Second, postponing large maintenance activities means postponing large expenditures. This improves the financial performance because of the time value of money.

effective design. Each of the interviewees emphasises the advantages of the fact that all interests were aligned, and that there was only one general budget that had to be managed. No discussions were needed about the division of costs and benefits when adjustments were processed in the design. As a result of the above, there was no need for additional means of authority. This is summarised into the following positive finding:

+ A collaborative design process originated as a result of the fact that all three contractors were equally involved in the SPC and EPCM. This created a setting in which all interests were aligned and authority was no issue.

H.4 Informal role structure analysis

The interviews and document study did not provide any insight into the knowledge, skills and attitude applied in the early project phases. It is however interesting to consider what competencies are present within the project organisation that currently manages the maintenance phase.

H.4.1 Knowledge and Skills

Before getting involved within this project, none of the members of the maintenance organisation had any specific experience in the field of maintenance. All the team members have previously worked as a site manager and/or project leader of construction projects. They were not specially prepared for their new function by means any education. The strategy was simply to get involved and learn on the job. As a result, there was no-one with specific maintenance engineering skills and knowledge at the start of the maintenance phase.

H.4.2 Attitude

The attitude of the employees will be considered by means of the concept of colours, presented in paragraph 5.4.5 and Appendix G. The current maintenance organisation consists of people who have previously worked as a site manager and/or project leader for years. Their attitude largely corresponds with the attitude you would expect from a site manager. A construction realisation process is a rational process with clear goals. Project planning and control skills are required to successfully manage a construction process on site. This attitude largely corresponds with the blue attitude profile.

So, the maintenance organisation mainly consists of blue-print thinkers. This attitude seems to perfectly fit the hard organisational aspects of the maintenance process. It ensures that all the objectives are controlled and the maintenance plan is properly executed. However, literature emphasises that managing a maintenance process should also deal with learning and continuous improvement. As explained by the concept of colours, this requires someone with a green attitude. This person is able to design and facilitate learning situations, has knowledge of organisational development and specific feedback skills.

Currently, there is no-one involved with a green attitude. As a result, emphasis lays on the control aspect of the maintenance phase, and not on active knowledge development, storage and sharing.

H.4.3 Analysis

The following negative findings have surfaced:

– None of the employees within the maintenance organisation had any specific maintenance engineering competencies at the start of the maintenance phase;
– The current maintenance organisation lacks someone who is able to design and facilitate learning situations, has knowledge of organisational development and specific feedback skills (green attitude).

The following positive findings have come to light:

+ The fact that the maintenance organisation consists of people with a background in site management makes them very competent in preparing and managing the maintenance tasks.

H.5 Role of client the organisation

To what extent has the client organisation facilitated Wâldwei to incorporate maintenance into the early project phases? RWS itself was rather satisfied with the result of the tender procedure. On the moment of signing the contract, RWS predicted a 30% surplus value compared to the traditional contracting method, of which 8% can be assigned to maintenance[74] (Buck Consultants & John Cooper Consulting, 2004, p. 67&71):

- Variable maintenance[75] (4%): Savings have been realised by applying a more sustainable pavement construction, and switching to a more preventative maintenance strategy.
- Fixed maintenance (3%)[75]: An integrated approach of green, white and grey maintenance, instead of the traditionally applied separated approach, is expected to result in cost savings. All maintenance functions will be executed in a so called road train;
- Maintenance planning (1%): Less lanes have to be closed by integrating different kinds of maintenance. The maintenance that has to be done, is largely planned outside rush-hours.

Looking at how RWS has fulfilled its role as a client organisation, there is of course always room for improvement. The following points surfaced during the interviews and document study:

- RWS applied the EMAT award mechanism, but evaluated for 90% on price because of budget restrictions. The interviewees indicate that this does not motivate the market to aim for an optimal incorporation of maintenance, since part of the effort is wasted if only the cost-reducing optimisations are appreciated (and thus not the value-increasing optimisations);
- The onetime €40 million payment after completing the construction phase had a risk-reducing effect, and therefore cut down the financing costs. Downside is that it tended to shift the attention of the contractors and investors towards the short term performance (i.e. completing the construction phase as soon as possible) (Buck Consultants & John Cooper Consulting, 2004, p. 11). It is at this point in time yet impossible to say how this has affected the quality of the construction process, since possible flaws are likely to surface later during the maintenance phase. It is however the question whether the incentive that is created with the onetime payment is not in contrast with the original intent of a DBFM contract, namely to stimulate the contractor to consider the long-, instead of the short-term.
- The interviewees indicate that the client organisation finds it still difficult to apply a more hands-off approach, and behave as a network manager. It is not its task anymore to perform inspections and check the actual system condition. The interviewees explain that they would understand it when the client every now and then takes a look at the critical system parts. Complaints about relatively uncritical parts (as now sometimes filed[76]), are however considered to be a waste of time for both the client organisation and Wâldwei.

[74] 10% can be allocated to favourable market conditions (i.e. independent of contracting method). 12% to the integration of design and construct (e.g. optimisation of the construction technology and scheduling).

[75] Variable maintenance is not yearly recurring, e.g. over-layering, renovating a bridge, replacing traffic-facilities. Fixed maintenance is yearly recurring, e.g. mowing, cleaning ditches and culverts. Green = nature, white = road marking, grey = roads, yellow = electro technical installations.

[76] One of the interviews told the following example. The contract contains requirements regarding the grass length around the emergency telephones. Wâldwei claimed in its report that this requirement was met. One of the employees of RWS however observed that the grass was too long when performing a check on site. Wâldwei then had to come up with a plan to make sure this won't happen again in the future. Wâldwei saw other option than increasing the mowing frequency around the phones.

H.6 Analysis Summary

Overall, all the interviewees are very satisfied with the project performance. The general belief is that the system provided by Wâldwei is of a higher quality than the surrounding infrastructure systems, which are still under control of RWS.

Of course, there is always room for improvement. Only limited attention has been paid to maintenance in the tender & design phase. Even though a more in depth analysis of these phases is needed before any definitive conclusions can be drawn, it can at least be said that maintenance has not had a central position throughout the early project phases. Probably, an even better performance could have been achieved if, besides the pavement construction, also other parts had been optimised in terms of maintainability and life cycle costs.

Second, all the interviewees are very satisfied with the EPCM structure. The fact that all parties are equally committed throughout the project enables an integrated process. The only disadvantage of the organisational structure that can be brought up, is that the engineering firms were not financially motivated to aim for life cycle optimisations. Most however indicate that this is less of a problem if mainly in-house engineering firms are involved, as is the case in this project.

Then considering the project performance during the maintenance phase. Continuous improvement requires performance evaluation and interaction between the different managerial levels. The conclusion can be drawn that the current approach leaves room for improvement. It is positive that evaluations are done, but a shame that these mainly focus explaining the past performance. Improvements can be realised if the evaluation of the past performance is translated into recommendations for the future. If properly shared, this would not only improve the performance of the N31 project itself, but also the performance of future projects.

The lack of continuous improvement is mainly caused by the competency profile of the maintenance organisation. It can be concluded that the competencies of the maintenance organisation are perfectly suitable for controlling the maintenance performance, but less for creating a learning organisation. As a result, there is no active process of knowledge gathering and sharing.

The approach of the client organisation also leaves some room for improvement. First, there are some complaints about the application of the EMAT contract awarding criteria. The contractors would have been much more encouraged to incorporate maintenance if the evaluation did not mainly focus on price. Second, there are some doubts about the payment mechanism. The one-time payment after completing the construction phase is understandable from a finance point of view, but questionable from a life cycle perspective. Finally, the interviewees indicate that RWS still not fully behaves according to the nature of the contract. In some occasions, RWS reverts to its traditional, hands-on approach.

APPENDIX I PROJECT ANALYSIS: JOHAN FRISOSLUIS

This appendix contains an analysis of the Design, Construct and Maintain (DBM) project Capacity expansion Johan Frisosluis. This is a project of which the tender has been recently won by Ballast Nedam. The most important findings of this analysis are included in the conclusions of the empirical study, described in chapter 7.

The first paragraph of this analysis will describe the general characteristics of the project. Secondly, the most important contract characteristics will be discussed, followed by an analysis of the formal and informal role structure. Finally, this role of the client organisation will be discussed. For an explanation of the descriptive framework that is used for the analysis will be referred to chapter 5.

I.1 Introduction

I.1.1 Project introduction

The Johan Frisosluis in Stavoren is the connection between the channel Johan Frisokanaal and the lake IJsselmeer. It is the most important entrance for the recreational lakes situated in the Province of Fryslân. The Province observed that the capacity of the existing lock did not any longer satisfy the demands. In order to solve this issue, a project has been initiated. Besides aiming to increase the capacity, also ambitious objectives were formulated in terms of durability, ecology, and public information service. Below an overview of the project’s key characteristics. The winning design of Ballast Nedam is presented in Figure 62.

- Contract:
  - Client: The Province of Fryslân;
  - Contractor: Ballast Nedam (BN Infra bv and Ballast Nedam Beheer bv);
  - Value: ± € 15,3 mln (construction costs: € 9,8 mln, maintenance costs: € 5,5 mln).
- Scope:
  - Design and construction of additional lock capacity;
  - Modification of the mechanical & electrical systems of the movable bridge Brug Warns;
  - 20 Years maintenance of Invalspoort Stavoren and Brug Warns.
- Timeline:
  - Tender: March 2010 – June 2011;
  - Design and construct: June 2011 – December 2013;
  - Maintenance: December 2013 –2023.

Figure 62: The winning design of Ballast Nedam (on the left the new lock, right the existing lock) (Provinsje Fryslan, 2011)

I.1.2 Analysis approach

This analysis is made just after Ballast Nedam has won the contract. Since the purpose of the empirical study is to gather insight into the actual working methods, the analysis is mainly used to look back upon the tender phase. Less emphasis is put on the expectations regarding the future course of the contract phase.

The analysis will pay special attention to the role of Ballast Nedam Beheer. At first, because Ballast Nedam Beheer is the party that will finally become primarily responsible for managing the maintenance phase. Going by the literature research, it is interesting to see what maintenance engineering contribution Ballast Nedam Beheer has made in the early project phases to be optimally prepared for the maintenance phase. The second reason, which is more of a practical nature, is that Ballast Nedam Beheer provided the opportunity to study this project, and that it has given most information regarding its role within the project.

I.2 Contract characteristics

I.2.1 Tender procedure

The contract is procured by means of a competitive dialogue procedure, consisting of three phases: the prequalification phase, dialogue phase 1 and dialogue phase 2. The prequalification phase was approached and passed through as usual. Seven parties were selected to enter the next procurement phase.

The first dialogue phase aimed to develop a design that satisfied all the client demands and requirement specifications. One joint information meeting was held. Subsequently, two moments followed in which the seven participants were allowed to pose questions in writing. Afterwards, all parties submitted a preliminary bid design and price offer. After evaluating the bids, four parties to continue to the next phase were selected.

The second dialogue phase consisted of three one-to-one dialogues. Goal of the discussions was to optimise the preliminary design and the content of the procurement documents. At the end of this phase, all four parties submitted their final bid and price offer. Based upon the bids, the contract was awarded to Ballast Nedam.

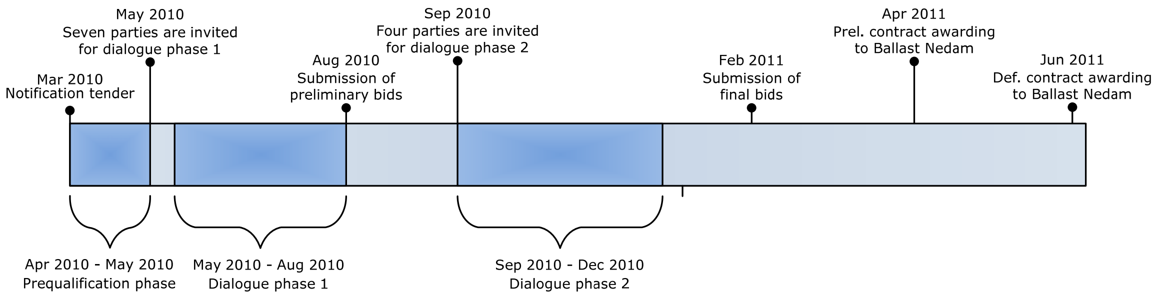


Figure 63: Timeline of tender phase

I.2.2 Awarding criteria

Besides the prequalification, the tender procedure embraced two selection moments. Table 11 contains the EMAT criteria that have been used for evaluating the preliminary and final bids. The client has decided to put a serious weight on aspects like sustainability and spatial quality. The contractors were stimulated to invent something more special than simply another conventional concrete lock.

Especially in assessing the preliminary bids, much weight has been laid on the criteria ‘capacity / price’. Minimal requirements have been set on the capacity, being a maximum waiting period of 60 minutes at a supply of 570 ships per day. More points could be earned by providing additional capacity (until maximum 660 ships a day). The idea of Ballast Nedam to expand the complex with a second lock obviously scored well on this criteria.

Another noteworthy criteria is the maintenance costs for the thirty years subsequent to the actual maintenance period. This encouraged the candidates to optimise the system over a fifty year period, instead of only considering the contract period. An independent engineering consultant was hired by the client organisation to watch over the quality of these estimates.

Criteria	Preliminary bid (%)	Final bid (%)
Capacity (ships x 10^3 / day) / Price (construction costs only)	80	-
Capacity (ships x 10^3 / day) / Price (constr. + 50 years maintenance.)	-	50
Sustainability	3	20
Spatial quality	3	20
Presentation	4	-
Project management plan	10	10

Table 11: Contract awarding criteria

I.2.3 Maintenance obligation & payment mechanism

The contract includes a 20 year maintenance period with the following scope:

- The whole system lock complex Invalspoort Stavoren, including reused and existing parts. This system includes both the existing and the new lock to be build;
- The modified parts of the movable bridge Brug Warns. This mainly comes down to the mechanical and electrical system, namely the control system and the driving mechanism (incl. lubrication);
- Transmission - and communication systems between the lock complex Invalspoort Stavoren and Brug Warns.

Ballast Nedam has submitted a final bid of approximately € 15,3 million, in which around € 9,8 million is reserved for the construction phase and circa € 5,5 million for the maintenance phase. The client organisation has decided to take care of the project financing themselves. This means that the construction costs are remunerated upon completion of the construction phase.

The € 9,8 million maintenance is divided into quarterly payments over the 20 year maintenance phase. To stimulate the contractor to deliver the demanded quality throughout the contract period, the following penalty clauses are included. For not providing the agreed on system availability[77], a reduction is carried out of €200.000 at the end of the year. Other requirements that are not satisfied are settled with a €750,- reduction per observation. When Ballast Nedam has insufficiently control over its quality management system, €1000,- per observation is charged.

I.3 Formal role structure analysis

I.3.1 Responsibilities

I.3.1.1 Introduction

This part of the analysis describes what actors have been responsible for maintenance, to what extent maintenance engineering is addressed throughout the different project phases, and how this has affected the incorporation of maintenance. The project organisation will be addressed in detail in the next subparagraph. For now it is important to know that Ballast Nedam Infra Noord-Oost bv (from now on referred to as BN Infra) took the initiative in the tender, and that it is primarily responsible for managing the tender, design and construction phase. Ballast Nedam Beheer bv (from now on referred to as BN Beheer), which has already been involved from the tender phase, relieves BN Infra after completing the construction phase, and becomes responsible for managing the maintenance phase. Another party that has been involved from the start is Royal Haskoning. Royal Haskoning is hired by BN Infra to take care of the design process.

[77] Regarding the lock system, non-availability as a result of technical failure is not allowed to exceed 1% of the service hours (ca. 40 hours/year). The maximum non-availability as a result of maintenance is determined on 2% (ca. 80 hours/year). Hours in the period may-august are multiplied with factor 2; hours beyond this period are divided by 2.

I.3.1.2 Tender phase

As explained in paragraph 4.2, maintenance engineering consist of maintainability engineering and maintenance planning. To what extent have both been noticed as important responsibilities, and how have they been addressed during the tender phase?

The EMAT criteria established by the client organisation indicated that the maintenance plan was evaluated in the final bid assessment. As a result, maintenance planning already had to be dealt with during the tender phase. All interviewees agree that it was BN Beheer its responsibility to submit all the tender that dealt with the maintenance phase. The general opinion is that BN Beheer has well fulfilled this part of its role. The fact that this responsibility is also mentioned in the tender plan of BN Beheer, shows that it is also aware of this responsibility. A plan that however never has been finished and shared within the tender organisation.

The second maintenance engineering function that will be addressed is maintainability engineering. The tender plan of BN Beheer does not mention any responsibilities with regard to system control or system optimisation in terms of for instance maintainability, availability or life cycle costs. All interviewees agree that BN Beheer has a role to play there. But, views differ on what this role should comprise. Some assign BN Beheer a leading role, in contrast, others only expect BN Beheer to monitor the process from the sideline. As a result of the varying expectations, the opinions differ on whether BN Beheer has assumed enough responsibility in terms of maintainability engineering. The general opinion is BN has mainly dealt with maintenance planning, and only limited with maintainability engineering.

The limited contribution of BN Beheer in terms of maintainability engineering has been compensated by the involvement of an experienced maintenance engineer from Royal Haskoning. This engineer also supported BN Beheer in the maintenance planning process.

I.3.1.3 Design phase (intended)

Considering the design phase, most interviewees expect that the way BN Beheer fulfils its role, will not undergo many changes. Everyone expects BN Beheer to make sure that the maintenance plan remains geared towards the system design. In addition, BN Beheer is expected to ensure that no adjustments are made in the design that negatively affect the maintenance performance (and budget). It is most likely that the maintenance engineer from Royal Haskoning remains involved to support BN Beheer, and to take care of maintainability engineering.

When asked what role the interviewees would ideally assign to BN Beheer in the rest of the design process, some interviewees indicate that they would like BN Beheer to actively search for further optimisations (while avoiding gold plating). They believe that substantial room for optimisations is left, for instance with regard to the type of materials to apply. Others believe that it is sufficient when BN Beheer controls the system performance as currently laid down.

I.3.1.4 Construction - and maintenance phase (intended)

What maintenance engineering effort is required throughout the construction phase? All interviewees assign an important role to BN Beheer. For its own good, BN Beheer is expected to monitor the quality of the construction process and make sure that no last-minute changes that affect the long term system performance are processed. However, the views differ on the exact fulfilment of this role. Some of the interviewees argue that it is necessary that BN Beheer visits the site weekly; others believe that a more hands-off approach will do.

During the maintenance phase, BN Beheer will be made primarily responsible for the system performance. The precise responsibilities are elaborately described in the maintenance plan, and clear to all the actors involved. What responsibilities will be passed on to subcontractors is not exactly defined yet.

I.3.1.5 Analysis

Certain maintenance engineering responsibilities have been assigned to BN Beheer and Royal Haskoning. In what way have these influenced the quality of the design process and its output? The following positive findings have surfaced:

+ The responsibilities regarding the development of the maintenance related tender documents are clear and agreed on by the interviewees. The interviewees also confirm that BN Beheer has well fulfilled these responsibilities. BN Beheer its responsibilities during the maintenance phase are also described in the maintenance plan;
+ The limited contribution of BN Beheer in terms of maintainability engineering has been largely compensated by Royal Haskoning. See also the 'task' section.

The following negative findings have surfaced:

– The maintainability engineering function has been satisfactorily fulfilled by the engineer from Royal Haskoning. Some interviewees however believe that even a more life cycle cost effective bid would have originated if BN Beheer had assumed a more proactive role within the design process;
– Only a few of the interviewees have a clear idea on how to manage aspects like maintainability and life cycle costs. As a result, there is no consensus about, for instance, BN Beheer its responsibility in terms of maintainability engineering. Some believe that the quality of the design process would gain from making this responsibility more explicit, other wonder whether that is even possible and useful;
– Most interviewees indicate that BN Beheer shall play an important role during the construction phase. On the one hand to enhance the process of system handing-over, but also to supervise BN Infra (and the other subcontractors). This is remarkable, since you would expect that the contractors would be able to ensure the quality of its own activities without external supervision. Especially if another Ballast Nedam subsidiary benefits from this quality. It should go without saying that the best overall result for Ballast Nedam as a whole should be aimed for.

I.3.2 Position

This paragraph contains an analysis of the project organisation during the tender phase and the contract phase. Emphasis will be put on the position of BN Beheer, its relation to other actors and the way it has affected the integration of maintenance.

I.3.2.1 Tender phase

BN Infra took the initiative after the tender notification and assigned a tender manager. The formal structure of the tender organisation is presented in Figure 64. The multidisciplinary nature of the project made the tender manager decide to involve several external parties, which can be split up into two categories.

The first group are the engineering firms Royal Haskoning and Interra, responsible for the engineering process and the concept development, respectively. Both were involved on the basis of a cost reimbursement contract. The second group consists of BN Beheer, Machinefabriek Emmen, Croon, Zomers and Sterk. These parties all participated on a risk-bearing basis. Their effort would not have been remunerated in case of losing the tender.

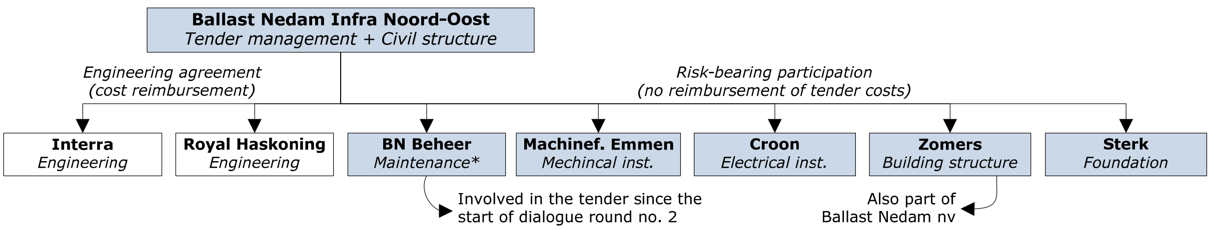


Figure 64: Formal organisational structure in tender phase

I.3.2.2 Contract phase

Negotiations about the definitive contractual structure were still going on at the moment of performing the analysis. The intended contractual structure is illustrated in Figure 65. The DBM contract will be an agreement between the client organisation (Province of Fryslân) and BN Infra. Parts of the contracts are subsequently passed on to parties that were also involved in the tender.

Logically, the same division between parties is visible as within the tender organisation. Royal Haskoning is linked to BN Infra by means of a cost reimbursement contract. Its participation ends after completing the construction phase. The design, construction and maintenance of the mechanical and electrical installations are subcontracted as a whole to Machinefabriek Emmen bv and Croon bv, respectively. These are so called 'back-to-back' agreements, meaning that problems and claims regarding this part of the system are directly passed on to the subcontractors. Also the building structure and foundation will be subcontracted.

The overall contract between the client and BN Infra covers the design, construction and maintenance phase. Management of the maintenance phase is, however, beyond BN Infra its field of expertise. Therefore, all responsibilities will be passed on to BN Beheer after completing the construction phase. This is done by means of an internal back-to-back agreement. BN Beheer then becomes responsible for ensuring the system's performance throughout the contract period, and bears the financial consequences of non-availability. Warrant clauses will be drawn up between BN Infra and BN Beheer as an incentive for BN Infra to consider the long term system performance. The subcontracts that BN Infra will enter into, contains a clause which states that the original client (BN Infra) will be replaced by BN Beheer after completing the construction phase.

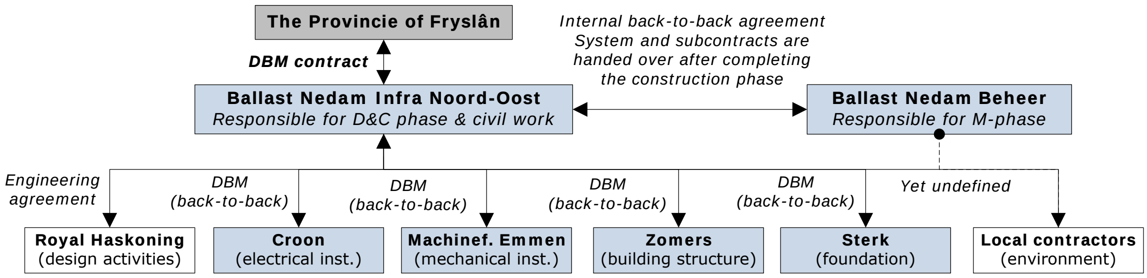


Figure 65: Formal organisational structure after contract awarding (not definitive yet)

I.3.2.3 Analysis

How has the formal structure of the tender organisation influenced the incorporation of maintenance in the tender process? And what are considered to be the disadvantages of the intended contractual structure? The following positive findings have surfaced:

+ In spite of the fact that the tender manager is employed by BN Infra, he was aware of the importance of maintenance, and prepared the organisation for an integrated design process;
+ The early involvement of subcontractors can reduce the life cycle costs. For instance, once the steel supplier Machinefabriek Emmen noticed the life cycle cost analysis of alternative materials for the lock gates, it immediately lowered its price to achieve a better score. On the other hand, it can also narrow the design space and make it difficult to make a fair comparison of alternatives;
+ There were strong informal relationships. Some of the interviewees were even unknown with the precise formal relations between the actors involved. See also paragraph I.4.

The following negative findings have surfaced:

– BN Infra has had a rather dominant position throughout the tender phase. There is no reason to belief that this will change until the actual maintenance phase. Some of the interviewees indicate that, in general, a more dominant position for the maintenance contractor (BN Beheer) may enhance the system performance. It may enable BN Beheer to more easily defend its interests and push through its demands in the early project phases (when the optimisation potential is maximal);
– In contrast to BN Beheer, BN Infra its remuneration is not dependent on the long term system performance. If an optimisation is proposed that costs money to one party and yields a benefit for the other, negotiations have to be held about the division of these cost and benefits. But this costs time and can lead to conflicts. Positive is that no such conflicts have occurred yet;

- As a result of the difference in remuneration schedules, BN Beheer and BN Infra have different incentives. The intention is to solve this by means of warrant clauses. It is however questionable whether these clauses have the desired effect;
- The involvement of subcontractors has led to fragmentation. The individual maintenance strategies have to be geared towards each other for the optimal overall strategy. Some of the interviewees suspect that opportunities have been missed here (e.g. clustering materials and inspections);
- The involvement of subcontractors on a risk-bearing basis introduces the risk of strategic behaviour[78];
- There was no direct financial incentive for Royal Haskoning to endeavour low life cycle costs[79].

I.3.3 Tasks

I.3.3.1 Tender phase activities BN Beheer

The maintenance engineering tasks executed, logically stem from the responsibilities described earlier. The maintenance planning activities that have been executed by BN Beheer are:

Drawing up a maintenance matrix (0-20 and 20-50 year), containing:

- An overview of the system parts that have to be maintained (System Breakdown Structure);
- The maintenance activities, including interval and unit prices.

Developing a maintenance plan[80] (year 0-20), describing:

- The scope of the system to be maintained;
- The maintenance strategy, including inspection types and intervals;
- Project control system (communication, quality management, risk management, etc.);
- Collecting and combining input from the subcontractors for the maintenance matrix and - plan.

BN Beheer has developed the maintenance plan in close cooperation with the maintenance engineer from Royal Haskoning. Royal Haskoning provided most information regarding maintenance strategies, inspection intervals et cetera. Point of departure was the maintenance matrix of the existing lock, that was made available by the client. Since no object breakdown structure was provided, BN Beheer had to develop a structure for the new lock system themselves.

The subcontractors took care of the maintenance matrix and maintenance plan regarding their part of the system. BN Beheer was concerned with the coordination of this process. Some interviewees indicate that this also included gearing the individual maintenance strategies towards each other and search for optimisations. The opinions differ on whether this potential has been fully realised.

Royal Haskoning managed the design process and delivered a maintenance engineer. Some maintenance engineering tasks were specifically assigned to Royal Haskoning. For instance, at the start of the tender phase, Royal Haskoning has been asked to provide a rough (percentage-wise) estimation of the maintenance costs. A typical maintainability engineering task executed by Royal Haskoning is the life cycle costing analysis on the mechanical system of the lock gates (hydraulic vs. electro-mechanic) and the material of the lock gates (steel vs. composite plastic).

The maintenance engineering activities have not been coordinated or streamlined by means of a standard maintenance engineering concepts. The interviewees also emphasize the influence of the time pressure on the

[78] "In short, strategic behaviour means that an actor's behaviour is not determined by his opinions, but is aimed at consolidating his power position… a party will rarely be explicit about its interests, since a party that reveals its interests might reveal its negotiation position and the room available for decision-making" (de Bruijn & ten Heuvelhof, 2008). A subcontractor can for instance come up with a high price for his part of the job and hope that it will win the contract anyway as a result of low price offers of the other subcontractors. Such behaviour can hamper an integrated design process.

[79] A more indirect incentive for Royal Haskoning is that a more optimal design increases the chance of winning the contract, and Royal Haskoning is likely to be hired for the subsequent phases as well if it has done its job satisfactorily.

[80] In Dutch, this plan is referred to as 'beheer- en onderhoudsplan'.

course of the design process and the integration of the maintenance aspect. The time pressure makes it for instance impossible to apply a full system engineering approach.

I.3.3.2 Design - and construction phase

What maintenance engineering tasks will precisely be executed in the coming phases, has not been defined yet. The expectation is that the main task will be to monitor the design process and to update the maintenance plan where needed. Besides, they will join in discussions about, for instance, the type materials and paint to will be applied. At the moment of writing, it is neither clear yet what tasks BN Beheer will execute during the construction phase.

I.3.3.3 Analysis

The following positive findings have surfaced regarding the maintenance engineering tasks:

+ Royal Haskoning came up with design alternatives regularly. Some however preferred Royal Haskoning to more often present and defend its view on the optimal solution, instead of only bringing forward alternatives;
+ Besides taking care of the concept development, Interra also stimulated creativity by frequently proposing innovative ideas, involving everyone in the discussion and sharing successes. The fact that the designer didn't consider the financial and/or technical implications, has resulted in creative ideas;
+ All interviewees are convinced that, in view of the limited amount of time available, an almost 'optimal' bid design has been developed[81]. The limited input of BN Beheer in terms of maintainability engineering has been compensated by the efforts of the tender manager, Royal Haskoning and the creative input of Interra.

Following negative findings have surfaced:

– The tasks executed by BN Beheer mainly stem from the responsibility to submit maintenance related tender documents. For instance, the maintenance cost estimate is initially made because it a compulsory tender document, and not because it can be used to support the design process. Possibly, the activities of BN Beheer could have been of even more value if they were more specifically integrated within the overall design process;
– A simple maintenance concept or roadmap that streamlines the maintenance engineering process in the tender seems to be lacking. Positive is that the interviewees are aware of the possible advantages of such an aid in terms of quality management;

I.3.4 Authority

I.3.4.1 Introduction

The following section will provide insight into the authority structure. This is done by discussing the four sources of authority that have been distinguished in the framework, presented in paragraph 5.3.5. In general, the interviewees all emphasized the informal setting in which the tender process has been developed. During the process, no conflicts in which the actors felt urged to apply its formal authority, have occurred.

I.3.4.2 Network centrality and Availability of means

Such as already explained in paragraph I.3.2 (Position), the objectives of the actors involved are not all fully aligned. During the tender phase, BN Beheer can derive some authority from the fact that the other actors need BN Beheer for developing a successful bid. After contract awarding, BN Beheer is practically the only actor who is confronted with the long term system performance. Consequently, none of the other actors within the project organisation any longer needs BN Beheer its input.

[81] A few noteworthy design choices that have enhanced the life cycle cost effectiveness. Composite plastic girders are applied within the lock chamber, just as steel & composite plastic fenders (both usually timber). One has also planned to replace several parts of the existing lock system (e.g. the timber jetty) while constructing the new lock, instead of waiting another few years till the limit state is reached. This results in a higher system availability throughout the contract period.

Second source of authority that will be discussed, is the 'availability of means'. Considering the project organisation within the tender, design and construction process, most authority has been assigned to BN Infra. This is mainly caused by the fact that it employs the tender manager and enters into the contracts with the engineering firms[82]. It is however not the case that BN Beheer is totally enslaved. BN Beheer is free to decide on how it is going to maintain its part of the system, and what budget is required. Later on, in the construction phase, BN Beheer can derive authority from the warrant clause that will be agreed on with BN Infra. What this clause will exactly look like is not determined yet.

The other two sources mentioned in the framework are 'expert power' and 'personal characteristics'. The interviews have not indicated that any specific authority has been derived from one of these informal sources of authority.

I.3.4.3 Analysis

The following positive finding has surfaced:

+ No conflicts occurred, and as a result, none of the actors was forced to actually apply its authority.

The following negative findings have surfaced:

- In theory, a conflict can easily arise due to the authority of BN Infra over BN Beheer within the tender, design and construction phase. The interviewees however expect that the parties will always come to an agreement before the project performance is endangered;
- No agreements have been made yet about the precise authority of BN Beheer within the future design and construction phase, for instance with regard to the approval of construction drawings.

I.4 Informal role structure analysis

I.4.1 Introduction

All interviewees agree on the fact that there was a good team spirit and there were strong informal relationships. Most of the interviews indicate that this enabled efficient and effective communication between the actors involved. Some of the interviewees found it a bit too unstructured and informal, especially in the beginning of the process[83]. With hindsight, the approach has turned out to be successful.

The following subparagraphs describe what maintenance engineering competencies have been applied during the tender phase. Other competencies that have made a contribution to the integration of maintenance will be addressed as well.

I.4.2 Knowledge & skills

BN Beheer mainly contributed its maintenance planning competencies in terms of detailed cost estimation skills and cost figures. At BN Beheer, there was no specific knowledge regarding lock maintenance. BN Beheer had never had a lock project in its portfolio before. Neither had the employees of BN Beheer any particular experience in this field.

This gap of competencies has been largely compensated with the skills and knowledge of the maintenance engineer of Royal Haskoning. He could contribute his knowledge regarding life spans, maintenance strategies and intervals. Royal Haskoning also had the expertise to make a first approximation of maintenance budget early in the tender. Later on, he contributed his skills and knowledge with regard to innovative construction materials and life cycle costing. This made it possible to perform the analysis on the lock gate alternatives.

[82] What if BN Beheer would like to adjust the design in order to approve the maintainability? Formally, Royal Haskoning can only process this request if approved by its client (BN Infra). A design adjustment that increases the constructability (and for instance affects the maintainability) can however be processed by BN Infra without approval of BN Beheer. But, the general expectation is that such situation will never result in a serious conflict since both parties are after all part of the same company.

[83] One of the remarks of the interviewees was that no reports were made of the first few meetings. As a result, there was no general list with actions that had to be pursued, and the actors that were responsible for it.

Looking ahead at the actual maintenance phase, there have been discussions about the best way to cluster the inspection activities of the different maintenance subcontractors. The interviewees mention that it is most efficient if the parties, together, hire a multidisciplinary condition assessor. Some are convinced that it would be even worthwhile to educate one, specifically for this project. Until now, no decisions have been made about whether, and how this is going to be arranged.

I.4.3 Attitude

The concept of colours described in the literature study will be used to draw a picture of the attitude of the different actors involved. BN Beheer has mainly acted as a blue-print thinker. This attitude is of course closely interrelated to the concrete nature of the tasks and responsibilities that BN Beheer has dealt with (e.g. maintenance plan), and the background of the employees involved. The interviewees indicate that this attitude has been exercised in a rather expectant and reactive way. In favour of BN Beheer, it must be said that it is of course also very difficult to assume a proactive attitude if you are largely unfamiliar with the subject.

The input of the employees of Royal Haskoning can also be typified as blue-print. Nevertheless, they seem to have assumed a more proactive attitude towards the integration of maintenance. This especially applies to the maintenance engineer. He was well aware of the fact that a proactive attitude was required to optimize the design.

What can be said about the attitude of some of the other employees involved? The designer of Interra has typically acted as a white-print thinker. His contribution enabled a creative design process by triggering the others to think outside the box. The tender manager of BN Infra can be qualified as a red-print thinker. Each of the interviewees emphasized that he was, besides of the traditional hard project management aspects, well aware of the importance of soft organisational aspects.

I.4.4 Analysis

The following positive findings have surfaced:

+ BN Beheer lacks specific (lock) maintainability engineering knowledge and skills. This has been compensated by the involvement of an experienced maintenance engineering from Royal Haskoning. The interviewees notice that the close cooperation between both parties was instructive for BN Beheer;
+ The competencies of the maintenance expert brought in by Royal Haskoning were valuable for optimising the design, and developing a maintenance plan. Especially its knowledge regarding innovative materials and lock – and bridge maintenance turned out to be useful;
+ There are plans to cluster the inspections of the different subcontractors by hiring one common multidisciplinary condition assessor. It remains to be seen how this develops.

The following negative finding has surfaced:

– There has not really been (and still is) a green-print thinker involved: someone who focuses on collecting instructive experiences to improve the future performance. Most interviewees hold the opinion that it is BN Beheer its responsibility to involve someone with this attitude during the maintenance phase.

I.5 Role of the client organisation

All interviewees agree on the fact that the procurement strategy of the client organisation largely determines how a private party approaches a tender process. The contract awarding criteria and payment mechanism play a very important role. These determine how much effort is put in, for instance, a life cycle optimisation process. Needless to say, the interviewees of the (winning) tender team belief that the Province of Friesland did a good job in stimulating the integration of maintenance early in the process:

+ All interviewees point out that the EMAT criteria forced them to pay substantial attention to the integration of maintenance. Besides evaluating the maintenance plan and its costs for the 20 year contract period, the client also took into account the maintenance costs for the period of 20-50 years.

The general belief is that, the longer the period of analysis, the more emphasize is put on maintenance.

Some things however could have done better:

- There was a difference in level of detail between the requirement specifications of the lock (abstract) and Bridge Warns (detailed). As a result, the private party was not very well informed about the level of detail expected for the bid specification. The difference in level of detail can be explained by the fact that the Province of Friesland initially tried to put the contract on the market by means of a traditional contract. The design that was originally made however turned out to be much too expensive. The Province of Friesland therefore decided to opt for an innovative procurement strategy instead. The detailed requirements for Bridge Warns were however left untouched since this part of the design was considered to be fine;
- Unfortunately, not only the Province of Friesland, but also other public authorities influenced the optimisation process. The LCC analysis of Royal Haskoning showed that composite plastic lock gates are more cost-effective than steel doors. The client organisation was fine with the idea. The Water authority on the other hand, is generally no supporter of using innovative materials in the water defence system. This made the tender team decide to select the steel alternative after all. The financial benefits did not outweigh the risk of not acquiring the required permit;
- The Province of Friesland has decided to manage part of the maintenance activities itself, such as dredging, cleaning, repairing damage caused by third parties (e.g. graffiti) and lock & bridge control. There is no incentive for BN Beheer to optimally integrate these activities in its design & construction process, and include them in its maintenance plan[84]. The sequential interface, such as traditionally present (between construction and maintenance & operate), has now been replaced by a parallel interface: two parties are simultaneously responsible for ensuring the system's performance. As a result, inefficiencies are to be expected.

[84] This came to light when BN Beheer presented its final bid. The attending lock keepers immediately started expressing their worries about parts of the design. It turned out that they had not been sufficiently consulted by both the Province of Friesland and Ballast Nedam. The coming design phases will now be used to assess these comments. The Province of Friesland will be charged for any additional (cost increasing) requirements.

I.6 Analysis summary

In summary, the interviewees are very satisfied with the way the tender phase has been passed through. Of course, there is always room for improvement. The analysis amongst other things showed that the interests of the different parties are (formally) not perfectly aligned. Until now, the good atmosphere and informal setting have made sure that this had no negative effect on the project. It of course remains to be seen how this works out in the future.

No specific maintenance concept has been applied to streamline the maintenance engineering process. Some think that maintenance could have been even better incorporated if BN Beheer had assumed a more dominant position within the design process, and put more emphasis on the maintainability engineering aspects. Most however understand that this was impossible for now, simply because BN Beheer lacks experienced maintenance engineers. Bringing in operational experiences was difficult as well, because BN Beheer has not managed the maintenance phase of a lock before. Royal Haskoning successfully filled this gap by involving an experienced maintenance engineer. After all, everyone is rather satisfied with the way maintenance is incorporated.

The Province of Fryslân has made a positive contribution by requiring the private party to consider a 50 year maintenance period instead of only the contract duration. On the other hand, the Province has denied the market the opportunity to develop an (overall) optimal design, by only leaving part of the maintenance responsibilities to the market.

APPENDIX J INTERVIEW PROTOCOL

J.1 Introduction

The purpose of the interviews sessions is twofold. First objective is to provide insight into the current working methods. This supports the empirical analysis, presented in the second part of this report. Second, the interviews aim to gather suggestions for improvement from experts in the field. These suggestions support the development of the prescriptive role structure, presented in the third part of this report.

J.2 Protocol

The most important properties of the interview approach are as follows:

- A semi-structured interview method is applied;
- The questions are send to the interviewee, at the latest one week before the interview;
- The duration of the interview is around one hour;
- At the start of the interview, permission is asked for using a voice recorder;
- After the interview, a transcript is made and send to the interviewee for approval;
- The key findings of the interview sessions are anonymised and summarised in the report.

At the start of the interview, the research is briefly introduced. Explained is the purpose of the interview and the way the output is processed. All output is anynomised before processing it in the report. This enables the interviewee to speak freely about, for instance, the role and competencies of other members within the (project) organisation.

J.3 Example questions

The interviews mainly aim to gather insight into the vision and experience of the experts in the field, and not the standpoints of the organisation it is working for. In order to make the subject of research more tangible, each interviewee is asked to relate its answers to specific situations.

The following subparagraphs contain some example questions that give an idea of the content of the interviews. The introduction questions have been asked to all the interviewees. The rest of the interview is geared towards the position of the interviewee. In each interview, a different part of the role structure is emphasized. For instance:

- The interview with the legal advisor is used to study the elements position and authority, since these are closely related to the contractual setting;
- The interview with a maintenance engineer is used to provide insight into typical maintenance engineering responsibilities and tasks;
- The interview with a project- or tender manager is used to study how maintenance is approached throughout a DB(F)M project, and how a manager can facilitate an optimal incorporation.

The overview below, which addresses only a part of the role structure elements, is structured as follows. The main questions are listed with a dash. The key words that are used to ask follow-up questions and steer the conversation, are mentioned below the questions and listed with an open dot.

J.3.1 Introduction

- Could you please introduce yourself?
  - Current position;
  - Previous jobs;
  - Study background;
  - Projects (experience with DBM and DBFM in particular).
- What do you think about the way the civil engineering industry deals with maintenance?
- Throughout your career, what developments have you noticed in the area of maintenance?

J.3.2 Responsibilities

- What responsibilities are currently assigned to a maintenance engineer?
  - Maintenance planning, maintainability engineering;
  - Tender-, design-, and construction phase.
- What responsibilities should be ideally assigned to a maintenance engineer?
  - Maintenance planning, maintainability engineering;
  - Tender-, design-, and construction phase.

J.3.3 Position (within a contractor its organisation)

- What maintenance knowledge is present within the different parts of the organisation?
  - Maintenance planning, maintainability engineering, maintenance phase management, operational maintenance.
- How is this knowledge applied in DB(F)M projects?
- In what way does the organisation try to improve its maintenance approach?
  - Exchange of knowledge between the different units, in- and outside projects;
  - Evaluation and feedback;
  - Staff hiring and training policy.

J.3.4 Position (within a project organisation)

- What formal organisational structure is applied?
  - EPCM, SPC-EPC-MTC
  - Collaborative design
- Which parties deal with maintenance planning and maintainability engineering?
- To what extent does the organisational structure facilitate the incorporation of maintenance?
  - Incentives for a life cycle cost effective system.
- What organisational structure would best facilitate the incorporation of maintenance?

J.3.5 Tasks

- What maintenance engineering tasks are executed in the tender- design and construction phase?
  - The distinction between maintenance planning and maintainability engineering;
  - Function of the tasks within the overall process;
  - The system parts that the tasks usually deal with;
  - The reason for executing the tasks;

- What methodologies are applied to support/structure these tasks?
  - Reliability Centred Maintenance, RAMS, a custom concept, etc.
- What maintenance engineering tools are applied?
  - FMECA, LCC, FTA, ETA, etc.

J.3.6 Role of the client organisation

- How does the client organisation facilitate the incorporation of maintenance within the design process?
  - EMAT criteria;
  - Requirement specifications;
  - Approach during dialogues;
  - Scope of the maintenance obligation.

J.3.7 Suggestions for improvement

- What steps have to be made in order to realise a better incorporation of maintenance in the early phases of DB(F)M projects?
- What role should be played in this process by the client organisations, engineering consultancy firms, contractors and maintenance contractors?
- What knowledge, skills and/or attitude is required in order to move forwards?
- Where should these competencies be developed?
  - Universities, knowledge institutes, companies, client organisations, etc.