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Specialization:	Transport Engineering and Logistics
Report number:	2017.TEL.8111
Title:	**A decision support tool to assess maintenance policies for electronics in Dutch movable bridges; From a Circular Economy Perspective**
Author:	R.L.M. Tans

Title (in Dutch)	Een decision support tool om onderhoudstactieken voor electronische systemen in Nederlandse beweegbare bruggen te beoordelen; Vanuit het perspectief van de Circulair Economie
Assignment:	Master's thesis
Confidential:	no
Initiator (company):	ing. J. Kornet (Johan) (Witteveen+Bos)
Supervisor:	drs. W. Beelaerts van Blokland
Date:	March 30, 2017

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Student:	R.L.M. Tans	Assignment type:	Master project
Supervisor (TUD):	drs. W. Beelaerts van Blokland	Creditpoints (EC):	35
		Specialization:	TEL
		Report number:	2017.TEL.8111
		Confidential:	no

Subject: **A decision support tool to assess maintenance policies for electronics in Dutch movable bridges; From a Circular Economy Perspective**

Large infrastructural objects such as water locks and moveable bridges are designed to have life cycles of several decades or even centuries. The electrical and mechanical installations within these objects however have significantly shorter life expectancies. Currently, the maintenance on these installations is responsible for a large uncertainty in operational costs. After replacement, some value of the replaced equipment is recovered by for instance recycling. The current recovery strategy might however not be optimal when the whole life cycle of these assets is considered. Possibly large financial and environmental gains can be attained when both the maintenance and recovery operations of these installations are more aligned by using a circular approach. Such an approach can lead to the development of new business models where the value proposition of 'selling a product' shifts toward 'delivering a service', as has already been seen in other sectors (e.g. LeasePlan, Philips lighting). New forms of collaboration between stakeholders need to be developed and possibly new monitoring techniques (sensors, RFID) need to be applied. Total costs of ownership, life cycle performance, asset disposal rate etc. are all parameters that can be optimized.

The assignment is aimed at identifying business opportunities regarding the improvement of the integration between maintenance and recovery operations of technical installations Dutch infrastructure.

To achieve this goal, amongst others, the following questions will be answered:

- Which KPI's should be used to evaluate the different scenarios?
- Which scenarios are expected to perform well on these KPI's?
- Which theory can be applied to model these scenarios?
- Which solution approach is expected to perform well on such a model?
- How do the proposed scenarios perform when using data from practice?
- Which (combination of) scenarios can be recommended regarding this performance and how can the costs and benefits be distributed over the stakeholders?

The report should comply with the guidelines of the section. Details can be found on the website.

The associate professor,

Dr. Ir. D.L. Schott

Preface

This thesis is the result of a graduation project from the study of Mechanical Engineering, master track 'Transportation Engineering & Logistics', at the TU Delft. The assignment was started at the Dutch engineering firm 'Witteveen & Bos', primarily active in the infra sector, and was finalized at the TU Delft. The Circular Economy perspective has been taken to respond to an increasing amount of endorsement this subject has been given recently, as a means for addressing the changing set of expectations many infrastructural organizations are facing regarding 'future-proof' operations.

The main aim of the thesis is to support the infrastructure sector with insights into the costs and benefits of implementing practices that are typical to the Circular Economy framework. The secondary aim is to contribute to research by relating other fields of study to this buzzword riddled concept. The thesis could thereby both be used by both policy makers and practitioners, to identify a promising approach for the future, and by researchers, as an example of how these buzzwords relate to practice. During the thesis, a decent of preliminary knowledge is thereby assumed regarding the infrastructure sector, fields of engineering and operations management. Readers who would like to skip most of the practical context of this thesis are referred to appendix A.

First, I would like to thank the TEL section for supporting me throughout the research with both time and dedication. Especially, I would like to thank Wouter Beelearts van Blokland for giving me full trust in determining my own path, while making sure this path was headed in the right direction. Secondly, my special thanks go out to Mark Duinkerken for really taking the time to review my modelling. Being able to discuss such complex matters with an experienced researcher has really helped to build my confidence. Finally, Daan Duppen and Maarten Stuyvesant, thank you for the occasional feedback meetings we had to discuss the goings of being a graduate student.

Regarding my contacts in the field, my special thanks goes out to Jeroen Vermeulen (VolkerInfra), who managed to supply me with useful data regarding current practice. Furthermore, I would like to thank Matthias Buyze (RWS), Bert van de Pas (RWS), Justin Sap (W+B), Wieteke Meijer (W+B), Michiel Berkheij (Vialis), Peter Oud (Dynniq) and Erik Bakker (Hacousto) for sharing valuable insights regarding a promising future practice.

To conclude, I would like to thank my family for supporting me throughout the process of graduating. Mom, Dad, Sis, thanks for listening to my train of thought whenever necessary, and staying patient whenever I could not. Last, but certainly not least, I am thanking the most important person in my life. It was her with whom I could share the joy when things were looking good. It is her to whom I owe the strength to keep going whenever motivation was low. I doubt that I could have done it without you, my fiancée and soon to be wife, Özge.

Reinier Tans
Delft, 30 March, 2017

Summary

The Dutch infrastructure sector is currently facing a period in which a lot of movable bridges require replacement or upgrades. It is expected that due to technological advancement and increased costs for personnel, the amount of electronic systems within these systems will increase significantly. Currently, the fact that periodic manual inspections fail to provide preliminary fault indicators for electronic systems cause a lot of availability related problems. Furthermore, malfunctioning electronics are most often replaced by new systems and disposed of without any form of value recovery.

Considering the prospective of having to deal with more stringent environmental regulation in the future, while still having to run an economically viable business, a change is required. However, because the incentives for change between the Asset Owner (AO), Service Provider (SP), and Original Equipment Manufacturer (OEM) are not aligned, there is little room for innovation. A new strategy is therefore required that is able to make the maintenance supply chain under consideration future proof, while satisfying the demands of the involved stakeholders. The 'Circular Economy' (CE) concept has been suggested in both practice and literature as a framework to devise such a strategy, by aiming to integrate maintenance and recovery processes by improving the quality of component level information available during decision making. Often, the implementation of CE practices is accompanied by innovative business models, and corresponding contracts.

The objective of this research has been to identify and quantify promising changes to the current state maintenance and end-of-life recovery strategy for electronic systems in movable bridges, by which the operational expenditure (OPEX), CO_2 emissions, and unexpected downtime decreases, while complying with the boundary conditions from the AO, SP, and OEM. The following was hypothesized:

> *Implementing monitoring based maintenance with a corresponding recovery strategy is preferred over the current periodic, manual inspection based maintenance strategy without recovery regarding OPEX, CO_2 emissions and equipment downtime, and becomes profitable within 10 years.*

A preliminary research of both practice and literature has been conducted to identify the common ground between the stakeholders, and to develop a corresponding maintenance and recovery policy. Subsequently, a simulation based decision support tool has been built. After verification and validation, the tool was used to perform a comparative simulation case study regarding the dominant wear out failure mode of a specific system of focus. Hereby, the difference in performance between several policy variants, both with and without improved information, is assessed.

Besides improving KPI scores, it was beyond dispute that a future state should allow the AO to keep full ownership of strategically vulnerable systems. For the AO and SP, a future state should at least be profitable. Improved electronic system design, enabling contracts, and possibly innovative business models were identified as prerequisites for a future state. Under the assumption that these criteria are met, the potential of a predictive maintenance and remanufacturing policy was identified. The implementation of such a policy could be enabled by establishing a collaborative agreement between the SP and OEM, and a long-term use-based contract between the SP and AO. The SP-OEM combination would retain ownership over specific parts of non-strategically vulnerable electronic systems, and thereby have an incentive to invest in monitoring systems and corresponding decision support infrastructure. During periodic take-backs, the systems could be upgraded with the latest technologies. The OEM would have to design and deliver electronic systems according eco-design (modular, standardized) standards, whereas the SP could perform the role of OEM certified contract remanufacturer. The AO would pay a fixed fee per month to the SP-OEM combination for using the installations.

The policy as proposed has been modelled by considering a discrete network with a SP depot and a geographically distributed 'fleet' of degrading electronics at known locations and transport distances. Based on a simulation of the degradation and failure, schedules and routes are determined. Replacements according schedule are remanufactured at the depot whereas failed systems are assumed to be sold off to material recyclers.

The model was applied to a fictive case study considering CCTV camera assemblies, based on data from the Vaarwegen Zuid Holland service region. The cameras were assumed to be remanufacturable by replacing their wearing out pan-tilt-zoom. It was deducted that a 40% reduction in emissions, a yearly downtime of less than 2 hours per asset, and a break-even point of less than 10 years should be achieved. The future state should furthermore be realistic in terms of operational load on the current state SP organization. Both the current state *run-to-failure* policy without EOL recovery (scenario 1), a future state predictive maintenance policy with remanufacturing (scenario 2a), and several predictive sub-policies with remanufacturing have been simulated. The following was concluded:

- The predictive scenarios outperform the current state sufficiently regarding CO_2 emissions and unexpected downtime.
- Scaling up the service area from 10 single unit systems, to 100 10-unit systems results in an acceptable profitability, but exceeds the capacity constraints of the SP. Applying a grouping maintenance policy improves the cost performance further, but exacerbates the capacity exceedance.
- Applying a clustering maintenance policy together with an increase of the monthly service fee of 15%, and a reduction of CAPEX of 15% results in a situation that complies with all constraints considered.
- Implementing remanufacturing is not economically viable, while laws and regulations are not in place nor will they be sufficient without substantial additional subsidization.

It can thus be concluded that considering this fictive case, implementing a predictive maintenance is preferred considering OPEX, CO_2 emissions, and equipment downtime, and that this could become profitable within 10 years by implementing a complementary predictive maintenance policy. In the practice of movable bridges however, this ideal case is far from realistic. Furthermore, the hypothesized CO_2 emission reductions are highly uncertain because remanufacturing does not improve the business case by a long shot.

Following these conclusions, is was recommended to policy makers to further develop law and regulation that enforce the development of improved designs, sustainable business models, and improved stakeholder collaboration.

For practitioners, it was recommended to improve the gathering of data regarding the operational performance of equipment. With this information, the method as applied in this thesis could be repeated with more reliable results. A pilot study could be executed to provide more insight into the practical implications of the proposed future state, while providing a source of data for operational validation.

Regarding research, it was recommended to investigate the possibility of applying the model to other systems, system levels, time scales, and other sectors. The model itself could be greatly improved by further developing the prognostics model to allow for real sensor input. Furthermore, the scheduling model could be extended to account for an additional grouping optimization. To be applicable on larger organizations, the routing model could be extended to a multi-crew setting. Finally, the modelling of recovery processes could be extended to provide a more realistic representation of recovery yields.

Inhoud

Glossary

In the following, a list has been composed of concepts that are used throughout the thesis, and may require a definition at this point. It should be noted that the first time these concepts are used in the remainder of the thesis, they will be in bold font.

Strategy
A high-level plan to achieve long term (decades) goals under conditions of uncertainty

Tactic
A mid-level plan to achieve medium term (years) goals, translating the strategic plan to an operational plan

Operation
A lower-level plan to achieve (typically short term) goals, translating the tactical plan to day to day decision making.

Organizational strategy
Represents the direction in which an organisation wants to. For example, the organisational strategy might be to become more environmentally friendly and cost effective.

Asset Management Strategy
High level plan representing the organisational strategy regarding (physical) assets on a decade time scale. For instance, to acquire, retain, replace, and dispose physical assets within the organisation in a way that allows it to become more environmentally friendly and cost effective. This involves making choices regarding **maintenance** (retain, replace), **end-of-life** (dispose), and suitable **information support systems** (acquire).

Maintenance strategy
A high-level plan representing the asset management strategy regarding activities that are in place to keep an asset in, or restore an asset to operating condition.

Maintenance policy
The maintenance policy defines the set of maintenance actions that are to be performed on specific subsystems or components in the case of a certain event. The policy should reflect the maintenance strategy on a tactical timescale.

Maintenance operations
The maintenance operations, or actions, are a direct consequence of executing the maintenance policy on a day to day basis. It is here that much of a maintenance-organisation’s operational expenditure (OPEX) is incurred, since it involves the deployment of its main resources to execute maintenance actions, such as repairs, replacements, etc.

Eco-design
A design methodology in which there is a focus on environmental sustainability, by considering the complete lifecycle of the product.

Recovery strategy
A high-level plan representing the asset management strategy regarding activities that are involved with recovering value (or not) from physical assets after they have been replaced.

Recovery policy
The end-of-life recovery policy defines the set of recovery operations that are to be performed on a physical asset once it has been replaced. The policy should reflect the end-of-life strategy on a tactical timescale.

Recovery operations
The recovery operations, or processes, are a direct consequence of executing the end-of-life policy on a day to day basis. It involves processes such as dismantling, disposing, reusing, remanufacturing, and/or recycling.

Remanufacturing
Remanufacturing is the term used for returning a system to as good as new (AGAN) condition. This can be accomplished by repairing or replacing some or all its subsystems. When the possibility of upgrades has been considered during the design stage (see eco design), newer generations of subsystems can be added during remanufacturing.

Supply chain strategy
A high-level plan that is in place to maximize customer value and to achieve a sustainable competitive advantage for the supply chain partners. It involves making decisions regarding the flow of products, services, or both, from conception up until consumption, as well as decisions regarding the flow of information to enable this flow optimally. Proper business models (value proposition, logistic support, revenue model) and corresponding contracts should be in place to steer supply chain performance in the desired direction.

Inspection
During inspections, the condition of a system is determined by using expert opinions objectively. These inspections are typically carried out periodically and manually.

Condition monitoring
Condition monitoring is considered as an alternative to inspections, in which the condition of a system is assessed automatically by processing signals acquired through embedded sensors. Monitoring could enable a (real time) remote assessment of a single or several performance related characteristics.

Prognostics
Prognostics is considered to be the process of forecasting the condition of a system at a later point in time, by using information acquired through monitoring. By using prognostics, certain 'predictive' maintenance policies (see maintenance policy) become possible in which there can be anticipated on a failure that is incipient.

Information Support Systems
An information support system is a system that enables acquiring, processing, and presenting system condition information, in order to support decision making. Information support systems typically consist of both hardware and software.

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List of Abbreviations

AGAN	As Good As New
ALT	Accelerated Life Testing
AM	Asset Management
AML	Algebraic Modelling Language
ANN	Artifial Neural Network
AO	Asset Owner
CAPEX	Capital Expenditure
CBM	Condition Based Maintenance
CCTV	Closed Cirquit Television
CE	Circular Economy
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
D2B	Device to Business
DBFM	Design Build Finance Maintain
EAP	Enterprise Asset Management System
FEM	Finite Element Modeling
FMECA	Fail Mode Effect & Criticality Analysis
FMMEA	Failure Mode Mechanism & Effect Analysis
GM	Group Maintenance
GUI	Graphical User Interface
IMS	Intelligent Maintenance System
ISS	Information Support System
LBM	Load Based Maintenance
LCC	Life Cycle Costs
MIP	Mixed Integer Program
MLP	Minimum Latency Problem
NLP	Non-Linear Program
OEM	Original Equipment Manufacturer
OM	Opportunistic Maintenance
OPEX	Operational Expenditure
VoI	Value of Information
VRP	Vehicle Routing Problem
WEEE	Waste Electric and Electronic Equipment
WOf	Wear Out Failures
PCB	Printed Cirquit Board
PM	Preventive Maintenance
PPP	Public Private Partnership
PrM	Predictive Maintenance
PSS	Product Service System
PSSC	Product Service Supply Chain
PTZ	Pan Tilt Zoom
QoI	Quality of Information
RCM	Reliability Centered Maintenance
Rf	Random Failures
RH	Rolling Horizon
ROI	Return On Investment
RUL	Remaining Useful Life
RWS	Rijkswaterstaat
SCADA	Supervisory Control and Data Acquisition
SCM	Supply Chain Management
SLA	Service Level Agreement
SMA	Simple Moving Average
SP	Service Provider
TDT	Total Downtime
TEm	Total Emissions
TMP	Traveling Maintainer Problem
TPM	Total Productive Maintenance
TSP	Traveling Salesman Problem
UBM	Use Based Maintenance

1. Introduction

1.1. Problem background

The large presence of water in the Netherlands has had a large role in its economic development. As a result, there is a very dense network of waterways, roads, and railroads (see figure 1). At the intersection of these networks on land (road, rail) and water, it is often preferable from a spatial planning perspective to have movable bridges that can accommodate the traffic flows through the networks (see figure 2). In total a couple of hundred movable bridges are present in the Netherlands, with a total value of several billion euros (Coelman 2001).

Figure 1. Infrastructure networks

Figure 2. Movable bridges

Because of aging, many movable bridges in the Netherlands require replacement or upgrading in the near future (Rijkswaterstaat, 2008). Due to technological advances, accompanied by a steep growth in the costs of manpower, electronics are increasingly being applied to replace functions that were traditionally performed mechanically or manually. It can therefore be expected that there will be a significant increase in the amount of installed electronics in the decades to come. Typical characteristics of electronics are that they fail without warning and that they contain a lot of materials that have a significant impact on the environment during manufacturing.

1.2. Problem definition

Downtime

There are quite some reports of problems with movable bridges not performing adequately (see figure 3). The movable bridges in the Afsluitdijk, an iconic Dutch infrastructure object, have recently been in the news due to malfunctions (Tweede kamer 2016). The Botlekbrug is an example of a modern movable bridge with recurring problems (Tweede Kamer 2013). Much of the downtime is a result of unreliable equipment, long response times, long time to repair or a combination of these (Verkeerskunde 2016a). Especially for electronics, these problems are caused by the fact that **inspections** currently do not provide reliable preliminary fault indicators and that the equipment reliability specifications that are used during planning, turn out to be erroneous.

Figure 3. Malfunctioning movable bridge

Value destruction

Figure 4. Waste Electric and Electronic Equipment

Generally, it can be said that in the infrastructure sector, there is very little **recovery** of residual value of replaced electronics at their **end-of-life** (EOL) moment. Although environmental consciousness seems to be growing, in practice there is very little priority demonstrated through law and regulation. When electronic systems are replaced, the only thing considered is that they are disposed of in an environmentally legal manner. Because of low volumes, technological redundancy, and the lack of knowledge about the remaining useful life (RUL), this often results in low grade recycling. See figure 4 for a typical example of waste electric and electronic equipment (WEEE).

Clearly, a new and improved **strategy** is required that reduces downtime and increases the resource efficiency. In literature, it is argued that improved information of the system condition has both the potential to reduce unexpected failures as well as to increase recovery rates of EOL electronics. In the case of assembled systems, preferably real time RUL **prognoses** on component level are available during maintenance decision making (Fleischmann 2001).

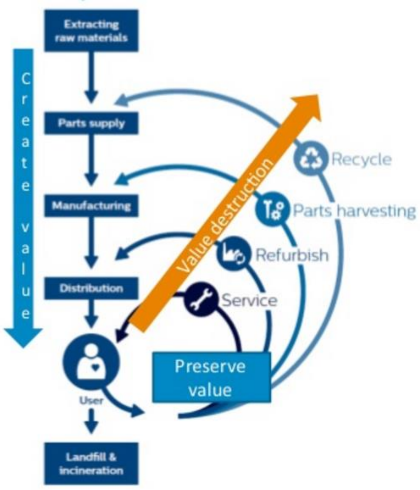


Figure 5. CE concept. Source: (Morlet et al. 2016)

With an eye on the CO_2 emission targets set at the UN climate convention in Paris 2015, the need for an improved strategy has been translated into ambitious targets for the EU member states regarding a move towards a 'Circular Economy' (CE). The CE concept is intended to counteract resource wastage by maximising utilisation of resources and minimising value destruction. In order to 'close the loop', CE advocates direct reuse, maintenance, **remanufacturing** and e.g. recycling, by improving the quality of information and coordination throughout the supply chain (see figure 5). CE thereby essentially is no more than a buzzword for integrating processes typical to **Supply Chain Management** (SCM) and (physical) **Asset Management** (AM) from a waste minimization perspective. Applying CE principles can help decrease the dependency of the EU on resources from other parts of the world, decrease the load of our society on the environment and has the potential to stimulate economic growth (TNO 2013). On a national level, the CE ambitions have been translated to, amongst others, the infrastructure sector (Council for the Environment and Infrastructure 2015; Schippers 2012). In the energy sector (offshore wind farms), aviation sector (airplane engines), rail sector (railway switches) and electronics sector (photocopiers), CE practices have been enabled by implementing state-of-the-art real time remote **condition monitoring** with a corresponding predictive **maintenance policy**. In several examples, this has been enabled by a redesign of the **business model** (Andrews, Prescott, and De Rozières 2014; Besnard 2013; Van den Broek 2014; Smith 2013).

Although that these opportunities are acknowledged by the stakeholders, the underlying reasons that prevent the necessary innovations, seem to be structurally related to the misalignment between stakeholder incentives.

1.3.Drivers

The stakeholders under consideration are the Asset Owner (AO), Service Provider (SP) and the Original Equipment Manufacturer (OEM).

The AO under consideration is the government body responsible for the functioning of the Dutch national infrastructure. Because the AO is funded with tax money, all expenses must be justifiable to the public. Recently, reducing the organization's carbon footprint has become an additional responsibility. With the EU parliament lobbying to change the current emissions trading scheme to a more enforcing CO_2 tax plan (Alonso 2016), it only seems a matter of time before the costs for unsustainable practices go up. In the last decades, the AO has seen a shift from having an in-house maintenance department, to almost complete outsourcing through large Public Private Partnerships (PPP) under the pretext of privatization. Especially the latter development is believed to have resulted in several problems that currently slow down the innovations that are required: a lack of in-house knowledge as well as a lack of proper coordinating mechanisms.

The SP in this research is a typical private company that intends to make profit. SP's tend to specialize in certain technical services to stand out from the competition, making them the main driving factor behind innovation. However, SP's need to be properly incentivized to perform certain actions since they typically do the least possible to meet the contract. There are examples from practice in which SP's were incentivized to invest in advanced **information support systems (ISS)** by being granted full ownership for several decades (Doodeman 2013). While such ownership is crucial for an SP to be able to reap the benefits from the investment, it is far from the first choice from the AO perspective.

Like SP's, OEM's are private companies trying to make a profit. OEM's thereby try to sell as many products as possible, meaning that they support a generation of products as long as this is profitable. Although that sustainability is also becoming more of an issue for OEM parties, a lack of clear and committing regulations in the infra sector, as well as a lack of financial incentives, have not yet resulted in sustainable designs, product takebacks and/or recovery **operations**.

1.4.Objective

The objective of this research is to identify changes to the **maintenance and recovery strategy** for electronics within Dutch movable bridges, due to which the maintenance supply chain's cost performance, operational performance, and environmental performance would improve, while complying with the boundary conditions set by the AO, SP, and OEM.

With respect to this objective, the following has been hypothesized:

> *Implementing monitoring based maintenance with recovery is preferred over the current manual inspection based maintenance strategy without recovery regarding OPEX, CO_2 emissions and equipment downtime, and becomes profitable within 10 years.*

This thesis provides a structured approach for analysing promising improvements for the current state **asset management strategy** for electronics in Dutch movable bridges. This method delivers a first version of a decision support tool, with which policy makers, AO's as well as SP's could explore the cost and benefits of such changes, thereby gaining more insight into a successful approach for the future.

The method of Verschuuren and Doorewaard (2010) is applied to translate the objective into a set of research questions. See figure 6. Here, the arrows roughly represent the sub questions to be answered.

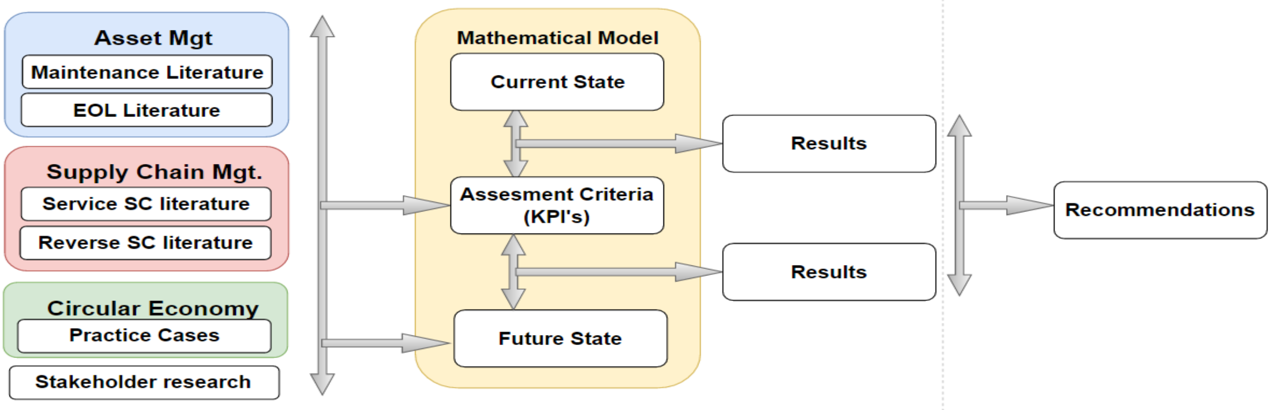


Figure 6. Research Question Framework. Source: (Verschuuren and Doorewaard 2010)

To reach the objective, the following set of key questions and sub questions will be answered:

1) What are the relevant influencing factors when developing a maintenance and recovery strategy for movable bridges in the Netherlands from a Circular Economy perspective?
   a) *Which factors can be derived from the interests of the involved stakeholders?*
   b) *Which factors can be derived from Circular Economy practice?*
   c) *Which factors can be derived from Asset Management literature?*
   d) *Which factors can be derived from Supply Chain Management literature?*
   e) *How do these factors change, or what new factors can be formulated when they are mutually confronted?*

2) How does the maintenance and recovery strategy currently perform regarding these factors?
   a) *On which electronic systems should be focused for a new maintenance and recovery strategy to have maximum effect?*
   b) *Which procedures are currently executed during maintenance and after replacement of these systems?*
   c) *What is the current maintenance and recovery policy for these systems regarding timing, place, and resource allocation and what are the boundary conditions?*
   d) *How can this policy be modelled so that the performance can be evaluated?*

3) What kind of improvements to the maintenance and recovery strategy should be implemented to increase its performance for the system of focus?
   a) *Whom requires which information and when to be able to improve the performance for the system of focus?*
   b) *What kind of data analysis is required to produce this information?*
   c) *What kind of physical support infrastructure is required to deliver this information as specified?*

4) To what extent do these changes improve the performance of the overall strategy?

5) What can be recommended regarding the functional specifications of the information support system, the corresponding maintenance and recovery strategy, and the stakeholder collaboration when both the current state and future state are compared?

Table 1 lists the sections where (parts of) the respective research questions are being answered. Sections that are not used specifically to answer research questions are used to provide background information, indicate report structure and/or to provide (intermediate) conclusions.

Table 1. Research question vs. report section

RQ		**Report Section**
1	A	2.2 / 2.3
	B	3.1
	C	3.2
	D	3.3
	E	3.5
2	A	2.1 / 6.1
	B	2.3 / 6.2.1
	C	2.3 / 3.2.1 / 8.1
	D	3.6 / 4.1 - 4.3
3	A	3.1 – 3.4.1 / 6.2.2
	B	3.4.2 / 6.2.2
	C	3.4.3 / 6.2.2
4		Ch. 8 / Ch. 9
5		3.1 – 3.3 / 3.4.2 / 3.5 / Ch. 11/Ch. 12

1.5. Approach

The information that was required to answer the research questions has been gathered along the following routes:

Practice research:

- Semi-structured interviews with domain experts from AO, SP and OEM parties.
- Reviewing websites from AO, SP and OEM parties
- Reviewing professional magazines from the AO
- Attending a conference about ‘dynamics based maintenance’, organized by KIVI
- Attending a conference about ‘Circular Economy’, organized by TU Delft

Literature research:

- Reviewing scientific papers and theses
- Reviewing educational books

When the problem is further analysed and its formulation is refined, a comparative simulation case study is performed following the methodology for case studies from Dul and Hak (2008). More on this in chapter 4 and 7.

1.6.Scope

The scope of this thesis is limited to identifying, demonstrating, and evaluating a suitable monitoring based maintenance and corresponding recovery strategy for a single electronic assembly within a movable bridge. Implementing such a strategy is expected to require both technological (hardware, data-analysis) as well as organizational (contracts, business models) innovations. The research perspective is thereby defined by the overlap of PPP, CE, AM and SCM, as depicted in figure 7. Furthermore, the following demarcations apply:

- The focus will be on a single service area in the Netherlands, in which only the AO, SP, and OEM are considered. No additional stakeholders will be introduced nor will any be dismissed.
- The organizational analysis will be limited to identifying the type of business model and corresponding contracts, in which the implementation of a new strategy could become feasible according literature and practice. Organizational details are out of scope.
- The analysis is limited to current age and future electronics within movable bridges, during their lifecycle from 'placement' to 'replacement'. During the thesis, further demarcations will be applied regarding the subsystems of focus.
- The focus will be on the dominant wear-out failure mode of a single electronic assembly, based on an analysis of the recovery opportunities, function criticality and prognostics potential.
- For the system of focus, the hardware requirements will be deducted by analysing the type of data processing techniques required for fault diagnosis, prognosis and decision making. Technical details (hardware selection, placement, etc.) are not considered.
- Both the prognostic accuracy and the reliability of the information support system will be out of scope.
- The investment costs for implementing the proposed information support system will be estimated by using capital expenditure (CAPEX) estimates for the hardware. Monetary devaluation will not be considered.
- The costs and benefits of improved condition information will be assessed by comparing the performance of the current state (inspection based maintenance without recovery) against the future state (monitoring based maintenance with recovery) regarding maintenance related OPEX, CO_2 emissions and equipment downtime.
- The costs and benefits of the proposed strategy will be estimated by modelling several representative policies that could be implemented when this strategy would be pursued. The output of the experiments with this model will be operational schedules over the course of several years with corresponding KPI scores.

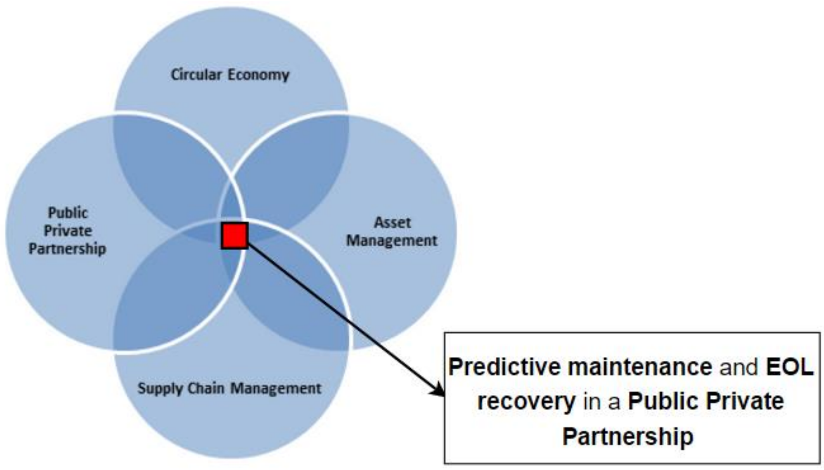


Figure 7. Schematic representation of research perspective

1.7.Outline

Now that the context of the problem has been introduced, the problem has been defined, and the perspective has been determined, the remainder of this report will be outlined as follows:

Ch2 will be used to describe the object of study and its surroundings in more detail in order to provide a firm practical basis to the problem definition. Next, **Ch3** is used to introduce the related research areas and to place the result from **Ch2** within this frame. Afterwards, the chapter will continue by refining the research objective, and defining the key performance indicators based on the intermediate conclusions. **Ch3** will concluded with a description of the theoretical scope that is attained to test the hypothesis. **Ch4** will present the mathematical model that is the result of applying the theoretical scope from **Ch3** to the research scope.

Ch 5 to Ch8 *are used to describe how the link will be made between the 'refined objective' as described in* ***Ch3*** *to the research yields in* ***Ch9*** *and* ***Ch10****.*

In **Ch5** this link will be described in terms of methodology, by defining the research strategy that will be applied in subsequent chapters. In **Ch6,** the scope is further narrowed down regarding the system of focus, and correspondingly, the scenarios will be introduced. **Ch7** will focus on verifying and validating the model presented in **Ch4**. Then, **Ch8** is used to perform a comparative case study by gathering data from practice and applying the model. Finally, **Ch9, Ch10** and **Ch11** are used to present the results from the case study, to discuss the yields, and to draw conclusions respectively. See figure 8 for a schematic representation the thesis outline.

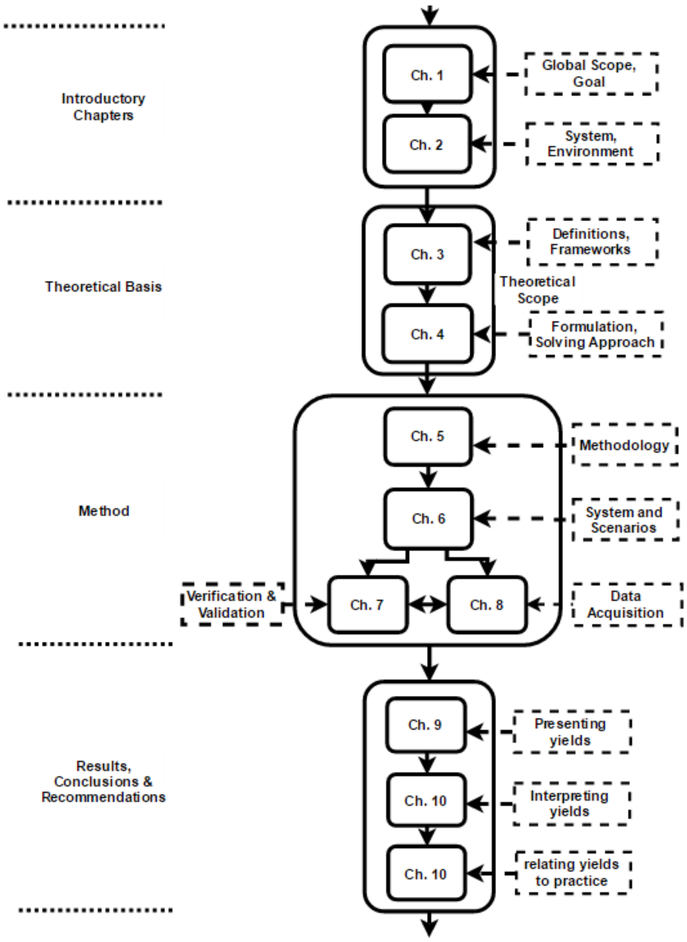


Figure 8. Thesis outline

2. System and Environment

This chapter will be used to further analyze the background of the problem that was outlined in the introduction. The figurative dimensions of the problem context namely greatly determine the feasible scenarios for improvement. In order to structure the analysis, the framework from Dekker et al. (2003) is used. Per the authors, the most important dimensions to consider are the system characteristics, use pattern, the involved stakeholders, and the supply chain process.

Section 2.1 will further motivate the focus on electronic systems in movable bridges. In section 2.2, the typical lifecycle characteristics of the systems of focus will be described. Section 2.3 will introduce the stakeholders under consideration, as well as the maintenance supply chain in which they are active. Finally, section 3.4 will conclude the chapter by listing the identified barriers and rooms for improvement.

2.1. System Description

In order to describe the different system levels in this context, an adapted form of the framework by Murthy and Jack (2014) is used. The authors apply a seven-level decomposition of any system, namely:

- **System**
- **Subsystem**
- **Assembly**
- Subassembly
- Module
- Submodule
- **Component**

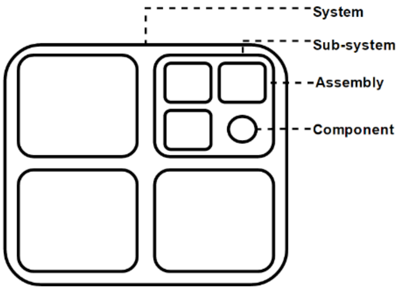


Figure 9. System levels considered

In the context of maintenance, such a decomposition is important because maintenance can be done at different system levels. The failure of a module might involve replacing the whole module, a submodule or only a failed component. In this research, only four system levels (system, subsystem, assembly, and component) are considered. See figure 9 for a schematic representation. The following sections will be used to scope down to the system of focus.

2.1.1. Infrastructure networks

As was mentioned in the introduction, several infrastructure networks stretch the Netherlands. These networks facilitate the flow of goods and people across the country and are therefore critical for a functioning economy. Infrastructure networks are inherently complex and are almost always custom designed to cope with specific geographic characteristics and societal demands (Murthy and Jack 2014). Infrastructure networks comprise of spatially distributed elements (roads, rails, waterways), as well as discrete elements (bridges, locks, pumping stations). These discrete elements often fulfil a crucial role in the network by facilitating the interaction at the intersection of networks. An example is for instance the closing or opening of a bridge to let a ship or truck pass respectively. From this point on, the focus will be on the discrete infrastructural objects in an infrastructure network. The spatially distributed elements, such as roads, rail and water ways are out of scope.

The term ‘object’ will be used to address the discrete objects within an infrastructure network. The terms ‘technical system’, ‘installation’ and ‘asset’ are used to address subsystems, assemblies, or components within an object, depending on the context.

2.1.2. Movable infrastructure objects

Objects can be subdivided into movable, non-movable and into wet and dry objects. Typical dry infrastructure objects are bridges, tunnels, and overpasses whereas typical wet infrastructure objects are locks, pumping stations, and weirs.

Regarding maintenance, movable infrastructure objects are the most critical. This can be explained by the fact that the main function of these objects is supported by electronic and mechanical installations, which are prone to disturbances. As for infrastructure networks, generally also for movable objects it can be said that they are custom built for a specific application. This is because of several factors, such as differences in span length, traffic density, weather conditions etc. Also, prestige for developers and design engineers play a large role in this matter. Generally, the common engineering disciplines that run through movable objects can be classified as (Berger, Healy, and Tilley 2015):

- Electrical
- Electronic
- Mechanical
- Civil

The largest share of movable objects in the Netherlands are pumping stations (90%), followed by movable bridges (5%), locks and sluices (4%) and weirs (2%) (Coelman 2001; Nijhof and Arends 2004; Rijkswaterstaat 2008).

2.1.3. Technical installations

In appendix A, a detailed schematic is depicted that gives an oversight of the different types of movable objects within each object family (movable bridge, lock, etc.), the main functions that the technical systems in these objects fulfil, and the subsystems, assemblies and components present to fulfil these functions. The functions, and therefore the system groups and corresponding installations of different object families show large similarities. Generally, the following mechanical, electrical, or electromechanical sub-systems can be found in all movable objects.

- Energy connection and distribution
- Control and operation
- Drive and transmission
- Signalling and communication

While other subsystems also show similarities, it is especially these subsystems that are interesting for this research because they are critical for the functioning of the object and are subject to technological advancement and changing safety regulations. It should be noted that the exact components that make up these subsystems can differ by type, size, rating etc., depending on the object and situation. Figure 10 depicts a schematic of the relevant subsystems of a movable object.

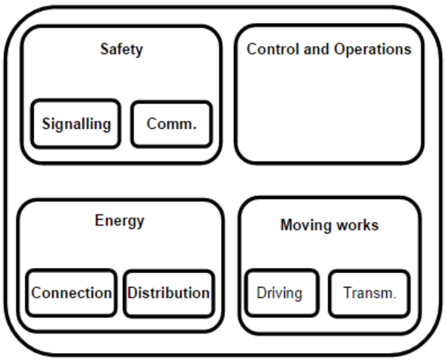


Figure 10. Subsystems under consideration

As was mentioned in the introduction, there is a trend of increased automation which also applies to infrastructure objects. The introduction of electronic systems has made much of the presence of human personnel unnecessary. However, electronic systems were found to be accountable for most of the disruptions during the operation (App. E, SP2, Q1), and a lot of replaced electronic systems are disposed of without value recovery (App. E, CON1, Q1).

The remainder of this research will focus on the electronic systems within movable objects, specifically movable bridges. As was mentioned in the introduction, movable bridges are relatively large in number, are at the intersection of infrastructure networks, and many require an upgrade in the near future. These features make them eminently interesting objects to focus on. The following section will describe the typical life cycle characteristics of electronics in movable bridges.

2.2. System Lifecycle

The life cycle of any system, is the period during which it is 'in existence'. This 'existence' can be defined in different ways, depending on which system level and corresponding perspective is taken. From the perspective of the AO, the object life cycle is the time between initiation of the development process up to discarding or upgrading of the object. The life cycle thus involves the contract phase, design phase, development phase, build phase, delivery phase, operation and maintenance phase and the discard or upgrade (new lifecycle) phase (Murthy and Jack 2014). This is depicted in figure 11.

Figure 11. Object life cycle: AO perspective

From the AO point of view, the lifecycle of electronic installations within an object is the time from the purchase of the system to the time where it reaches the end of its lifetime. This time involves the purchase phase, operation and maintenance phase and the phase where the system is discarded and/or replaced by new (Murthy and Jack 2014). This perspective is depicted in figure 11. Since the expected lifetime of an electronic installation is much shorter than that of the object itself, the life cycle phases depicted in figure 11 in practice elapse multiple times during the 'operate and maintain' phase of figure 10. The actual expected lifetimes of technical installations will be given in the next section. The AO is responsible for the functioning of the object and the long-term planning of renewals. In the current situation, the SP thus only serves as an executing party that performs the replacements. This situation is depicted in figure 13.

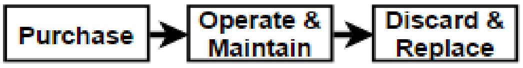


Figure 12. Electronic system life cycle: AO perspective

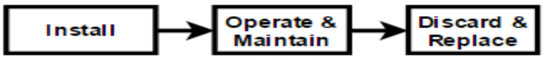


Figure 13. Electronic system life cycle: SP perspective

From the OEM's perspective, the life cycle of a generation of electronic installations is the time from initial concept of the product to withdrawal of the product from the marketplace. These phases are characterized by the differences in sales volumes seen by the manufacturer and the degree of support a manufacturer offers for the product. The life cycle phases from the OEM's perspective are depicted in figure 13.

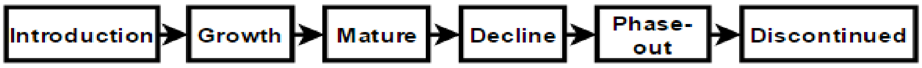


Figure 14. Electronic system Life Cycle: OEM perspective

In practice, this results in a conflict of interest between the OEM and the AO. While the OEM is aiming to sell as much as technical systems as possible and to support them as short as possible after sale, the AO is aiming to buy technical systems that can be supported with spares for as long as possible. This conflict can be exemplified by situations in which the availability of spares is shorter than the actual expected lifetime of the systems determined by the specs. The AO thus agrees on a design with certain expected lifetimes, but long before this time expires the AO must choose between ineffective repair or an expensive upgrade. Because of the absence of sufficient budgets often the former is chosen.

2.2.1. Lifetime

The lifetime of a system is the period were it can satisfactorily comply with all of its requirements (Coelman 2001). Several different forms of lifetime can be distinguished:

- The *economic lifetime* is reached when the yearly expenses of maintenance and use exceed the expenses for building a new system, including interest and pay-off. The pay-off period should always be lower than the economic lifetime.
- The *technical lifetime* is the period were in a construction of component should be replaced, for example because of fatigue, wear, corrosion, leakage, etc. The technical lifetime defines the moment for re-investment. The technical lifetime should be larger than the economic lifetime.
- The *constructive lifetime* is defined as the boundary value to which the installation can still be used.
- The *societal lifetime* is reached when for instance the requirements for the object have changed. For instance, when the deck of a bridge does not comply anymore with the current traffic density.

The optimal situation is when all lifetimes described above are equal. However, in practice often the constructive lifetime exceeds the technical lifetime and the technical lifetime exceeds the economic lifetime (Coelman 2001). For electronics, especially the economic lifetime plays a large role, since the repair costs of these systems easily become high enough so that replacement is cheaper.

In table 1, the typical life expectancies of several standard technical systems are depicted. As can be seen, there are large variations in the life expectancies of the technical systems within a movable bridge. Especially electronics such as signaling and communication systems have short life expectancies. In practice, the systems often perform worse than according the specs, conflicting the technical and economical lifetimes.

Table 2. General expected lifetimes of technical systems. Source: (Coelman 2001; W+B 2015)

Moving Works	**Exp. Life time [yr.]**
Mechanical parts	50
Hydraulic parts	25
Electric Installations	
General installations	25
High/Low voltage	50
DC motors	25-50
AC motors	50
Control and Ops	25
Lighting	20
Signalling & Communication	10
Transformers	30-40

2.2.2. Remaining Useful Life

The remaining useful life (RUL) of a technical system is defined as the remaining constructive lifetime from the moment where the system is taken out of service. The RUL can be translated into a certain *residual value*, or *salvage value,* depending on its condition. Because often no information of the condition is available, the residual value is often approximated as a best guess which negatively influences the market value (Coelman 2001). Often the value turns out to be too low to be able to cost effectively retrieve it (App. E, SP4, Q2).

2.2.3. Life cycle costs

The collection of costs during the life cycle of an object are termed the *life cycle costs (LCC)*. For movable bridges, the typical distribution of LCC are depicted in figure 14.

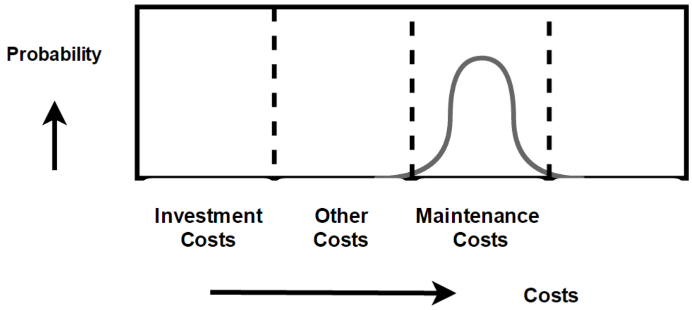


Figure 15. Typical life cycle cost distribution of a movable bridge. Source: (Coelman 2001)

Clearly, the maintenance costs are subject to the most variation. Much of these costs can be accounted to unexpected events of failure. Yearly around 7.5 billion euros are budgeted for maintenance and replacement of movable bridges (Peelen 2016). For an average bridge, roughly 5 % of the maintenance costs are due to the use of spare parts and consumables. Inspections account for roughly 3% of the maintenance costs. The remaining 92% consist of execution costs which are predominantly personnel related (App. E, CON3, Q1). Focusing on decreasing the maintenance related personnel costs therefore has the most potential to improve cost performance (Coelman 2001; Nijhof and Arends 2004; Werkgroep Herziening Cultuur Technisch Vademecum 1988)

2.3. Maintenance Supply Chain

Recent studies have shown that the new preservation strategy for infrastructure requires an integral approach, wherein bridges are seen as part of a network rather than separate entities (Verkeerskunde 2016a). However, the ability of governments, companies, and knowledge institutes to steer policy decisions in the sector is low. This can be explained by the fact that these organisations have never really been challenged to develop sustainable future minded solutions. Unlike the water sector, the mobility sector is macho-like and every organisation is going its own course (Verkeerskunde 2016b).

This section will be used to describe the supply chain under consideration in more detail to better understand the problem underlying the problem definition from section 1.2. This analysis will be used to reveal room for improvement from the stakeholder perspectives. Chapter 3 will then relate these aspects to literature to make well-founded recommendations for improvement. In section 2.3.1, the stakeholder roles are introduced, along with their drivers regarding the objective. In section 2.3.2, the current state supply chain processes will be described. In section 2.4, the stakeholders and their drivers will be classified by using the framework introduced by Dekker et al. (2004).

2.3.1. Stakeholders

In practice, many stakeholders play a role when maintenance on movable bridges is concerned. These stakeholders range from everything in between civilians, who are the users of the bridge, to regulating instances, that have the task of guarding that the executing parties operate per the law. Also within the domain of a single stakeholder, multiple departments or levels can have different roles. As mentioned, the focus here is on the AO, SP, and the OEM (see figure 15), since they are directly involved in decision making. It is found that these stakeholders play a dominant role in the current state and should remain to do so in a future state, albeit with in an improved setting. The remainder of this section will be used to describe these stakeholder roles and to address their drivers and attitudes within the scope of this research.

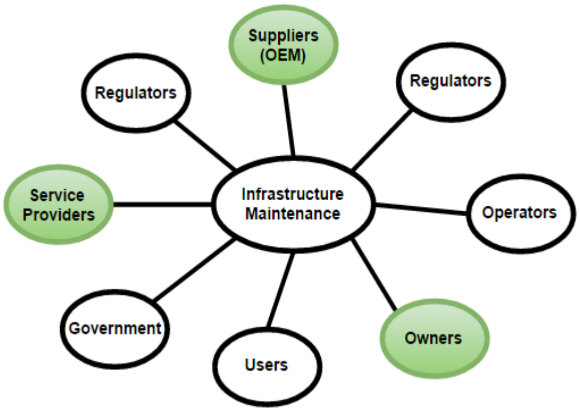


Figure 16. Stakeholder roles under consideration

Asset Owner

The AO's under consideration here are governmental bodies that are funded with tax money. AO are responsible for managing maintenance of those parts of the national infrastructure network that lie within its geographical domain. The main mission of an AO is to have properly functioning infrastructure within budget (IMaintain 2016). In the case of the Netherlands, being a European Union (EU) member state, the definition of 'properly' is determined on a European level, and subsequently translated to national policy. Over the past period there has been a focus on decreasing the dependency of the EU on foreign resources as well as on promoting sustainable practices. For waste electronics, this has resulted in the following directive for the coming decades (European Parliament and Council 2008):

> *'Where appropriate, priority should be given to reuse equipment (or its components, subassemblies and consumables). Otherwise, all waste electronics should be collected and sent for recovery, during which high yields should be achieved. In addition, the use of recycled material should be encouraged.'*

Given this directive, the ministry of Infrastructure and Mobility determines which performance, for instance the overall recovery rate, the national infrastructure should meet for the coming period. The task of meeting these specifications is then assigned to the party that manages the national infrastructure, who translates this assignment into contracts with specialized SP's. The process of entering performance contracts will be further explained in section 2.3.2.

Public AO’s in the Netherlands are organized in different levels of scale and responsibilities, namely National, Provincial, Municipal and Waterboards. Rijkswaterstaat (RWS) is the manager of the Dutch national infrastructure, such as the main road network and waterway network. For the remainder of this research the analysis of the AO stakeholder role will be based on the RWS organization. See figure 16 for a schematic representation of the stakeholder landscape as described.

Rijkswaterstaat is divided into districts, each with their own budget, asset portfolio and activities, and into national divisions. Every district has an AM department and, amongst others, a unit that is responsible for the communication with internal and external parties.

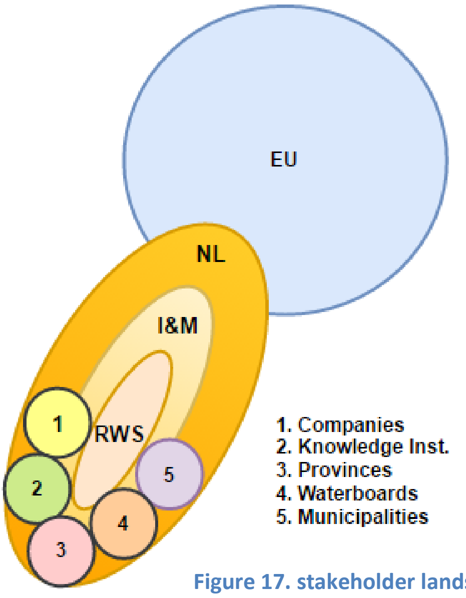


Figure 17. stakeholder landscape

Trends

In the last couple of decades, a trend has been observed where an increasing amount of maintenance related work has been outsourced to specialized SP’s. A special group of SP’s are technical consultants, to who most of the AO management tasks (contract specification, SP selection, contract management) have been outsourced. The result of this has been that the AO has little practical knowledge regarding fields of research that have developed considerably in the last decades. The AO is however still the decision maker. Generally, the AO acknowledges that there should be a change in approach from the traditional infrastructure management to a more knowledge driven approach, but there are still a lot of questions regarding how to approach this challenge technically (Peelen 2016). Currently, AO’s are again trying to attract specialized and young personnel to fill this knowledge gap (App. E, SP4, Q8).

Another trend is that the AO is aiming to move towards more environmentally friendly operations by incorporating environment related performance indicators, such as the ‘future value’ and ‘carbon footprint’, into the organisational strategy (Zeegers 2016b). It is acknowledged however that this is currently still a challenge.

Service Provider

The SP under consideration, typically is a private contractor company that is specialized in delivering a certain technical service. These services can be any combination of lifecycle services such as designing, building, operating, maintaining and/or end-of-life management of technical systems in movable objects such as those described in section 2.1. Like AO's, SP's vary in size. The service portfolio of SP's can vary from a couple of objects to several dozens.

Being private companies, SP's intend to make profit. This makes SP's the main driving factor behind innovations because developing services with higher efficiencies make them stand out from the competition. Examples of relevant innovations are for example the automation of inspection by offering PDA modules to replace manual notepads (SPIE), camera systems that enable remote monitoring of objects (Cofely) and complete control centers for multiple objects (Dynniq).

As will become more clear in section 2.3.2, SP's typically have a contract with the AO and intend to comply with this contract in the most cost effective way. This means that unless tasks are explicitly mentioned in the contract, the SP does not perform these tasks. Another consequence of being a profit driven stakeholder is that SP's are generally reluctant to share information that may help the competition.

Manufacturer

The OEM of the electronic systems is the heart of the product supply chain. The OEM is the party that designs, produces and markets electronic products and thereby they direct the quality standards for the upstream suppliers. Typically, OEM's operate globally in various sectors with a diverse product portfolio.

Recently, sustainability is becoming increasingly important for manufacturers since legislations are becoming stricter. Several certifications were called to life by governing bodies that force manufacturers to take responsibility for their products to a certain extent.

In other sectors of industry, cooperative partnerships between OEM's and other parties exist that profitably work towards a more sustainable future (Matsumoto et al. 2016). Many OEM's for instance offer full life cycle services regarding their equipment, such as maintenance and end of life services (decommissioning, resale, disposal, and recycling), along with corresponding monitoring systems. In the infra sector however, these practices have not been established.

2.3.2. Process description

In this section, the general process regarding the maintenance of movable infrastructure objects is introduced. The activities for which the AO is responsible (inspection and corresponding reporting procedure, planning, contracting) as well as subsequent activities performed by the SP (scheduling, performing maintenance, disposing) and by the OEM (supplying) will be described. The Delft Systems Approach by Veeke, Ottjes, and Lodewijks (2008) is used as a framework for schematically representing these processes (see figure 15). This schematic is no were near complete and only is meant to support the description of the processes in the following subsections.

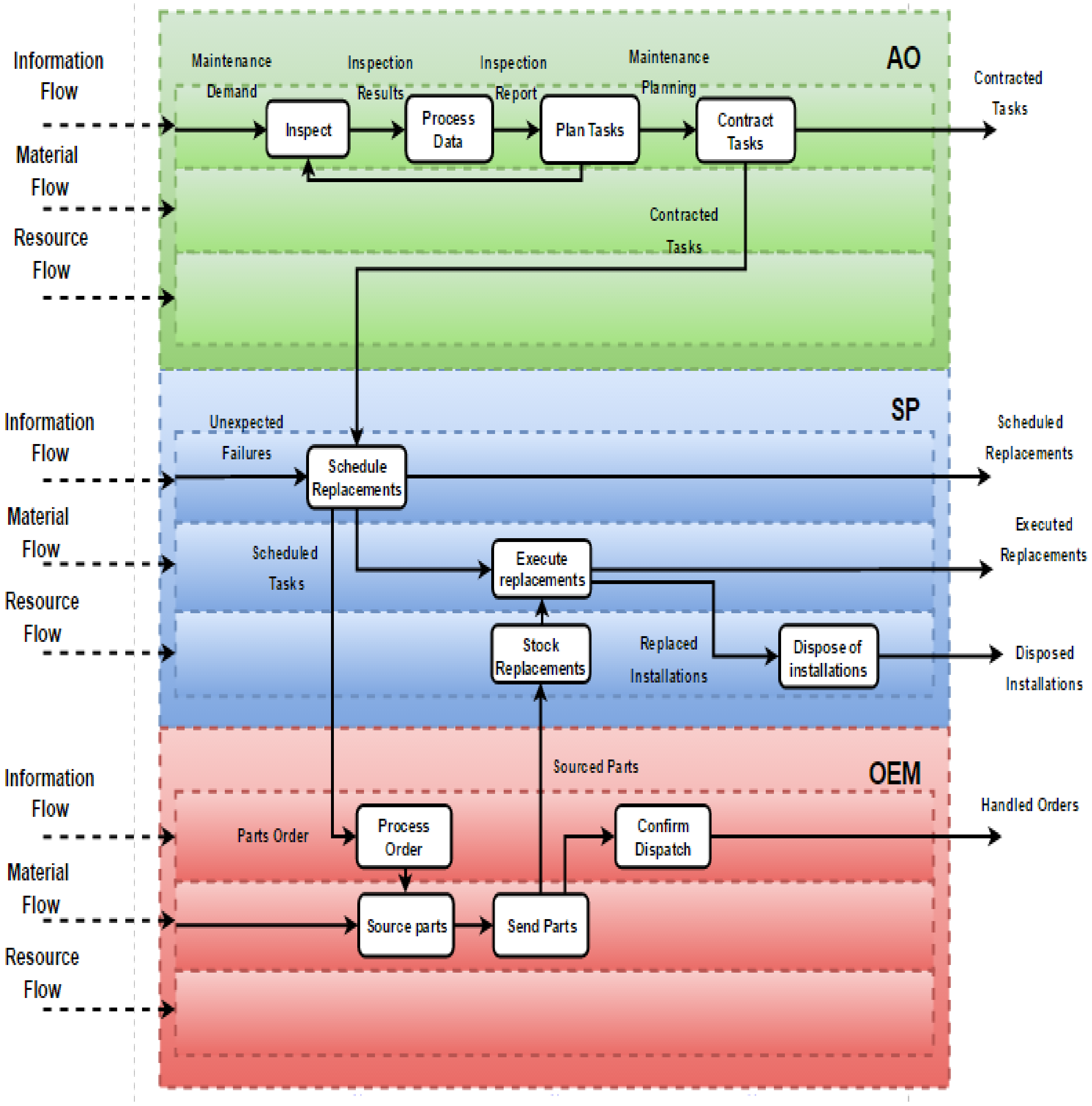


Figure 18. Schematic represenation of maintenance supply chain. Based on: (Veeke, Ottjes, and Lodewijks 2008)

Inspecting

To determine the technical condition of a system, an expert assessment is required. These assessments are periodically performed through inspections. Inspections should be performed with the right frequency, since too much inspections result in unnecessary high costs and too little inspections can have disastrous effects. An optimal inspection frequency should therefore be found, depending on the age, utilisation frequency, and the type of technical installation (Nijhof and Arends 2004). Generally, each type of installation (i.e. mechanical, electrical, civil) within a movable object has its own inspection strategy. There are several inspection types with differing level of frequency, detail and required manpower. Some of these types are:

- first inspection
- visual inspection
- technical inspection
- special inspection.

Only technical inspections will be considered in the remainder of this research, since especially these inspections provide input for the maintenance plan. During technical inspections, the residual life of electronics is determined by using standardized NEN (2015) procedures. In the absence of visual signs of degradation for electronics, the standard prescribes the use of component age as an estimator. When electronics show for instance discoloration, or deformation, this is indexed subjectively by relying on the expert opinion of the inspector.

Practice

In practice, the described approach is leading to a lot of the reliability problems. Over the last decades, technological advancement has made automated monitoring of equipment performance possible. Although that it is acknowledged that these innovations would bring large operational benefits (App. E, SP2, Q10), in the case of movable bridges they are scarcely implemented. Typically, only very basic operational event logging takes place. From the interviews with stakeholders, a couple of reasons for this could be deducted:

- Movable bridges are less critical for public safety than for instance rail and tunnels. Besides, the total value of the electronic installations is negligible compared to the total value of the bridge. Upgrading the installations with monitoring capabilities does not have priority (App. E, SP1, Q10).
- Because there is little practical knowledge of high tech monitoring systems, priority is given to technologies and procedures that are known to work. Also in the upcoming renovations, monitoring innovations are not accounted for (App. E, AO2, Q2).
- There is little budget available to invest in monitoring systems. The service providers do make proposals for technical upgrades (including monitoring techniques), but these initiatives do not make it past higher level management of the AO (App. E, AO1, Q1; SP2, Q3).
- There is no incentive for the SP to invest in condition monitoring systems because of the contract structure (App. E, SP2, Q10). More on the contract between AO’s and SP’s will follow later in this section.

Data processing and storage

After inspection, the results are submitted on standardized inspection forms and processed into inspection reports. In these reports, instructions for maintenance and further inspections are included. Because of increasing system complexity and economical pressure, the planning and budgeting procedure for maintenance have become increasingly complicated over the last decades. A lot of information is required to make responsible maintenance decisions. It is necessary that this information is standardized and kept in an automated information system to be able to use it effectively (Nijhof and Arends 2004).

According to several documents that where published by the AO (Gooijer and Noortwijk 2001; Nijhof and Arends 2004), a lot of information should have been gathered in digital files during the inspection and maintenance of movable objects. In these ‘object passports’ information regarding type, important components, year of construction, geographic location etc. is linked to information that was acquired during inspection and maintenance, including costs.

Practice

After reviewing several data sources however, it was found that this information is not as thoroughly documented as stated above. The following could be concluded:

- Since the inspection and maintenance is outsourced to SP’s, the AO does not keep records. The SP’s are only assessed on meeting the service level as specified in the contract. There are no explicit responsibilities stated that demand a more thorough documentation of maintenance records. Furthermore, since outsourcing on maintenance tasks on technical installations is typically done in relatively short term contracts, frequent data migration between SP’s results in suboptimal transparency.
- The registration of inspection and maintenance data is currently only done for administration purposes. Failure registrations are typically done on a very low level of detail by using hard-copy lists that are kept on-site. The registration and storage of system specific inspection, failure, and maintenance data with the goal of analysing and optimizing long term replacement strategies is non-existent (App. E, SP2, Q6).
- Due to a lack of coordination, the software packages adopted by the AO and SP are incompatible. Sharing of information does now require manual migration of data from one software package to the other (App. E, AO1, Q1). Often this migration never takes place.

Maintenance Planning

Typically, every object should have a running document, the maintenance plan, in which general object information is linked to detailed, up-to-date information acquired from inspections and maintenance. This information should result in an accurate planning for the coming period and corresponding detailed instructions for the maintenance personnel. Currently however, this process does not produce an effective planning due to inaccurate information. Since the main responsibility of the AO is to have working infrastructure within budget, the availability of critical infrastructure is being guaranteed by conservative (preventive) maintenance planning (App. E, AO2, Q2). For less critical infrastructure, a run-to-failure maintenance approach is taken (App. E, SP2, Q1). The maintenance planning typically is made for mid-long range of 10-20 years.

Practice

The following could be concluded regarding the maintenance planning of the electronic installations, from reviewing a maintenance planning document of a movable bridge in the Netherlands (W+B 2014b):

- Clustering of **maintenance actions** over time is done suggestively based on 'closeness' of the planned maintenance tasks in the schedule.
- Electronic systems are inspected yearly, correctively serviced upon failure and replaced at the end of their technical life time.
- In the maintenance planning, there is accounted for 5 corrective maintenance actions a year for an entire object.
- In practice, the replacements are not performed according the clustered schedule. The planning is adjusted based on the expert judgement of the asset manager.

Overall, it can be concluded that a lot of subjective judgement is used in maintenance planning.

Maintenance Contracting

Typically, every couple of years the AO makes a tender for several assets for the coming period. The tender contains the planning of when each asset should be maintained along with its budgeted costs. Per installation, several tenders are made from different policy perspectives (Spit et al. 2012). These tenders are then contracted out in aggregated packages. SP's can apply for a tender containing the maintenance plan of all technical systems belonging to an object. In practice, often a single contract is agreed with a service provider regarding one or more movable objects. The service provider then has the option to subcontract parts of this contract to specialized sub-contractors.

Public-Private-Partnership

The term public-private partnership (PPP) is often used to describe such partnership constructions between a public sector AO and one or more private sector SP's. PPP variants that are often seen in the civil infrastructure sector range from DBFMO's (Design, Build, Finance, Maintenance and Operate), DB's (Design and Build) and O&M (Operation and Maintenance contract). The amount of new infrastructure objects being built in the Netherlands is negligible compared to the number already present. Furthermore, most movable bridges owned by the AO are currently in the 'Discard or Upgrade' life cycle phase as described in section 2.2. A lot of movable bridges, along with their electronic technical installations, will be either completely replaced or fitted with more modern installations in the near future (Zeegers 2016b). This brings the opportunity to integrate technological and contractual innovations. The most popular contract form currently applied in such projects, and therefore the contract form under consideration here, is the *Design, Build, Finance, Maintain* (DBFM) contract (see figure 16).

DBFM contract

In DBFM contracts, typically a private sector consortium forms a Special Purpose Vehicle to design, build, finance and maintain a new or to be upgraded publicly owned object (e.g. Movable bridge) for a certain contract period. The contract between the SPV and the AO typically consists of a construction agreement, representing the 'Builders', and a service level agreement (SLA), representing the maintenance SP. In construction agreements, the building contractors are in control and take full risk to complete the building stage within time and budget. In SLA's, the AO is responsible for the adequate working of the objects, for which the tasks are outsourced to the SP. The SP is paid based on the contract sum, minus penalties for not delivering the agreed service level. The advantage of such a contract structure for the AO is that he does not have to take large financial risks themselves to get infrastructure projects completed (CivieleTechniek 2016a).

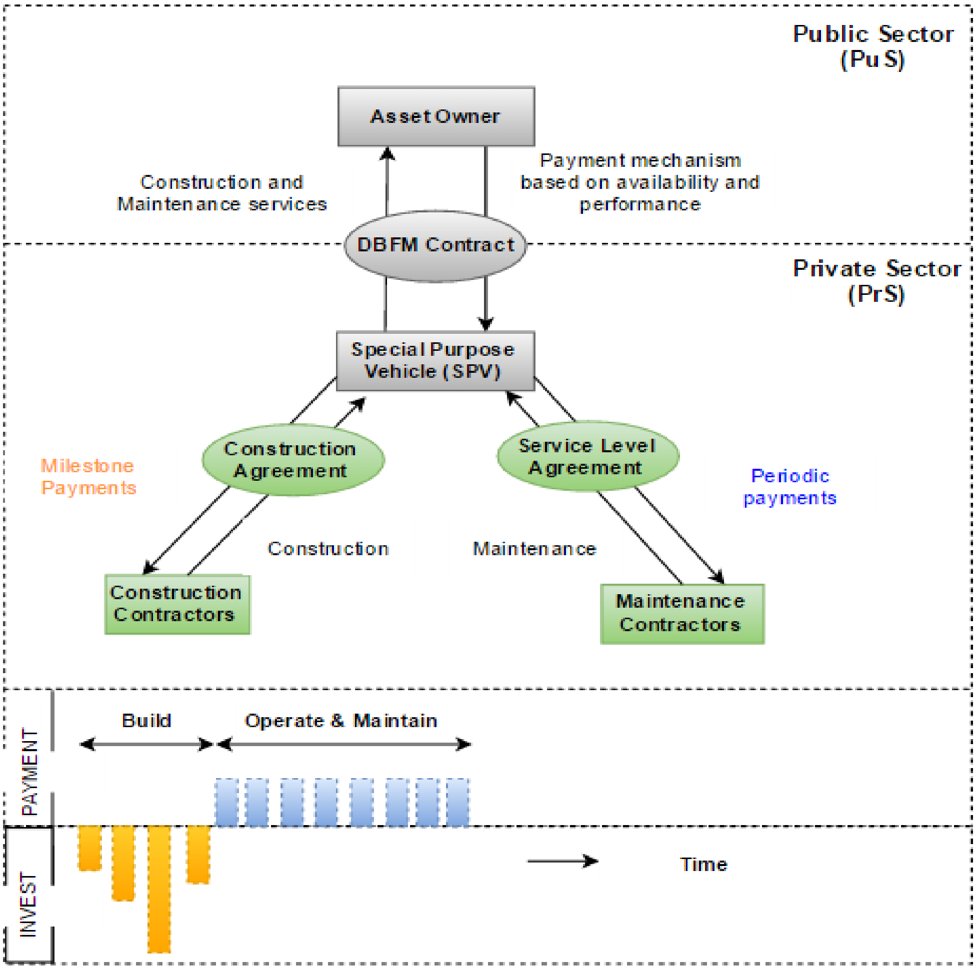


Figure 19. Typical DBFM contract structure

The DBFM contracts considered here, are those that constitute the design, building, finance, and maintenance of electronic installations of movable bridges. The 'builders' within such a contract are often the OEM's themselves. As argued before, the focus is on the 'operate and maintain' phase of the electronic installations. In formulating improvement scenario's in chapter 6 therefore, it is assumed that the electronic installations are already built and that the 'operate and maintain' phase has commenced. This phase can however not be seen separate from the other phases and therefore processes belonging to the 'design', 'build' and/or 'finance' phases will be considered where these appear relevant.

Practice

The results from the stakeholder research have shown that the contracting process as described yield non-satisfactory results regarding system reliability and end-of-life value recovery. The following could be concluded from the stakeholder perspectives:

- Because of the short contract durations, there is no incentive for the SP to invest in the technical installations. Namely, there is no guarantee that the SP will be able to reap the benefits of these investment in a subsequent contract period (App. E, SP2, Q10).
- The lack of contractual freedom in combination with insufficient requirement formulation leads to a race to the bottom. Namely, the replacement parts to be used during replacement are functionally specified, meaning that the AO specifies the performance a replacement must meet. This approach was thought to stimulate innovations by leaving room for the SP to come up with

alternatives within certain specified bounds. Unfortunately, the innovative character has disappointed in practice (App. E, AO1, Q1). Moreover, some of the availability and resource efficiency problems mentioned in the introduction can be traced back to this policy:

- The lack of knowledge at the AO (or responsible consultant), often caused by a lack of cooperation of the OEM (see section 2.2, 2.3.1), results in specifications that are insufficient (App. E, SP3, Q10). Furthermore, the AO is unaware of the residual value of the installations after replacement (App. E, CON1, Q2), while policy reports from higher level management advocate intensive value recovery practices (Schippers 2012).
- Considering the functional specifications, SP's are often incentivized to select the cheapest replacement parts.

Furthermore, initiative from the SP to make technical adjustments on the AO's expense are often not honoured. Although AO asset managers on district level seem to agree with SP's regarding proposed changes (App. E, AO1, Q1; SP2, Q11), and policy reports from the higher management layer of the AO propose similar changes ((Peelen 2016); (Schippers 2012)) initiatives strand higher up the chain. This is believed to be the result of budget restrictions (App. E, SP2, Q10).

- Because of the split contract structure between the builders and maintainers of the technical installations, the communication between these two parties is suboptimal. Since the builders have the objective to build as fast and cheap as possible, and are not responsible for the maintenance phase, thinking about maintainability often happens too late in the process (App. E, SP2, Q11). Furthermore, direct communication between the SP and AO on district level has been restricted to prevent a conflict of interest (App. E, SP2, Q11). A side effect of this is that there is little crossover of knowledge between both parties that could potentially benefit both. There are even cases known in which a SP was assigned a contract after which it became clear that there was no structured plan of approach (App. E, AO1, Q1).

For both the SP's as the AO on district level, more budget for innovation, more freedom for the contractors, a longer contract duration and improved communication are considered as changes that could improve the innovative character (App. E, AO1, Q1; SP2, Q11; SP3, Q10). Although that the need for new innovation enabling contracts has been acknowledged (Schippers 2012), the law and regulation that are a prerequisite for these contracts are not yet developed (App. E, SP3, Q10).

Scheduling maintenance

During the contracted period, the SP is responsible for scheduling the planned maintenance actions and delivering the agreed service level. As was described previously, information systems and optimization models are required to make responsible (short-mid range) schedules for all the objects in the SP's portfolio. The maintenance actions are hereby grouped as much as possible to reduce downtimes and setup costs. During this process the constraints on personnel, spare parts and required equipment are considered.

Besides planned maintenance tasks, the SP is also involved in responding to unexpected failures. When such failures occur, the SP should reschedule the short-term tasks for the maintenance crew depending on the criticality of the failure. Changes to the operational schedule are communicated directly to the maintenance crew (App. E, SP2, Q5). Such changes often result in higher costs than budgeted.

Executing Maintenance

The maintenance crew daily executes the operational schedule. In the case of an unexpected failure, an operator or user informs the SP, often only indicating that the object is 'not working'. Corrective maintenance actions in response to those failures are thereby relatively expensive due to long downtimes. The following factors can explain this:

- There is no knowledge of which part of the system has failed
- There is no knowledge of which failure mode has occurred

To acquire this knowledge, maintenance personnel must visit the object for a fault diagnosis. This diagnosis could conclude that a replacement part is required, many of which are not kept on stock by the SP. In such a case the maintenance personnel often must order the replacement part from the OEM, resulting in even large schedule disruptions.

When electronics are considered, service providers are in practice primarily involved in performing corrective maintenance tasks (App. E, SP2, Q1). The lack of preliminary fault indicators and postponement of preventively planned replacements, make wear-out failures the dominant cause of disruptions.

End-of-Life recovery

The contract as described in the previous section also involves services for handling installations after replacement. In practice, mechanical systems are either restored to new condition for reapplication in the same moving object or sold as scrap to material recyclers (App. E, CON1, Q2). Electronic systems often contain a lot of precious metals that are of high value. Until now however, an efficient reverse supply chain for replaced electronics has not yet developed. From the stakeholder research, it could be concluded that the following is done with replaced electronics:

- (Parts of) The replaced systems are returned to the AO to be used in another application (SP1, Q2). Since AO's typically want new systems, this is only the case for replaced systems that are not supported anymore by the OEM, but are still in use in other objects (App. E, AO2, Q3). In practice this rarely happens (App. E, SP3, Q2).
- The replaced systems are disposed of in an environmentally legal way (App. E, SP1, Q2; SP2, Q2). Often the contracts state that the SP is responsible for an environmental disposal of the systems (W+B 2014a). In practice the AO often does not care what the SP does with the replaced system, since nothing would be done with it anyway (App. E, AO2, Q3).
- (Parts of) The replaced systems are repaired and kept as spare parts by the SP to be used in other objects (App. E, SP1, Q2). In practice this is only the case when it involves high end parts that are more expensive to replace than to repair (App. E, SP2, Q2). Often the SP then runs an OEM certified operation to restore the systems to as-good-as-new.

Besides, it became clear that there are no OEM's that take back replaced electronics. The main reasons for this were found to be:

- There are no economic incentives for the OEM to take back the systems. The volumes of electronics that become available within a district are too low. Dismantling and storing the valuable parts after replacement is therefore not cost effective. Furthermore, recovering replaced systems with the goal of reusing or refurbishing is thought to cannibalize the sales of newer generation systems. OEM's seem to prefer that replaced systems go to the shredder as soon as possible (App. E, OEM1, Q1).

- There are no legislative obligations in the infrastructure sector for the OEM to take back the systems they have produced.
- There are no clear and committing contractual specifications regarding the dispositioning strategy (App. E, SP2, Q2). Neither are there cooperative agreements between stakeholders regarding this.

End-of-life electronics therefore often end up in low grade recycling streams. Some third-party players have anticipated to this opportunity by collecting and shredding end-of-life electronics to recover material value (App. E, CON1, Q3).

2.4. Conclusions: Current practice

In the previous, it was decided that the analysis will focus on electrical installations in movable bridges. Movable bridges are critical for the operation of two important infrastructure networks: namely the main waterway network and the main roadway network. Electrical installations account for both the most unexpected downtime as well as the most value destruction after replacement and are therefore in need of an innovative preservation strategy for the future.

Based on an analysis of the current practice, most unexpected downtime was found to be attributable to:

- Electronic systems performing below specs
- The lack of preliminary fault indicators for electronics
- The use of inaccurate information for maintenance planning and scheduling

Furthermore, it was found that a lot of resource inefficiency of electronics could be explained by the fact that:

- Fast technological cycles make electronics become obsolete
- There is little knowledge of the residual value of replaced electronics
- The value to be recovered is not high enough to justify the costs for recovery

It was found that in other sectors these problems have been tackled by implementing advanced information support systems (ISS). Although technologically possible, these innovations have not broken through here. According to the stakeholders, this can be accounted to:

- The degree of collaboration between parties
- The conditions and management of contracts
- The absence of clear and stringent regulations

The main drivers for changing the status quo were found to differ per stakeholder. The following could be concluded:

- The AO is being confronted with an increasing pressure on being both cost effective and environmentally friendly. The demographics of the installed base make that a lot of upgrades are required on a short term. From several sources, it became clear that the AO acknowledges the need for technological innovations regarding the maintenance process. However, the lack of budget and specialist knowledge make that this challenge is not yet challenged head on.

- The SP is aiming to get ahead of competition through innovation and by entering lucrative markets to increase their profit.

- The OEM too, is being confronted with increasing regulation regarding environmentally responsible operations. Currently however these regulations are not stringent and there are no economic incentives pushing the OEM to change.

According to the framework by Dekker et al. (2004), the stakeholder roles can be classified as follows:

- The AO is fulfilling the 'responsible' stakeholder role. In the maintenance supply chain as described, the AO considered is the principal client. Besides having a large responsibility to the public therefore, the AO has the power to steer the market in the desired direction. Both the SP and OEM therefore are looking at the AO to take a leading role and to create the circumstances in which real improvements become feasible. Per example, contracts explicitly demanding higher recovery yields are an absolute prerequisite. Although this seems to be acknowledged, there is currently is still a big gap between the targets set by government bodies on international and national level and those at district level.

- In a future state the SP would be a suitable 'executing' stakeholder. SP's namely have the ability to specialize in technological services and the incentive to innovate, making them the main driving force behind the technological innovations. From the response of multiple SP parties, it could be concluded that improved information support during maintenance is considered the way forward. Because of the absence of the proper circumstances however, this direction has not yet been explored sufficiently.

- Because the OEM's have the control over product design, close cooperation with these parties is key for any innovations to take place. Accordingly, the OEM can be classified as the 'facilitator'.

3. Literature review

In the previous chapter, the problems underlying the situation as outlined in the introduction have been further analysed. Furthermore, the support base within the current practice for improving this situation have been identified. This chapter will be used to relate these findings to literature, to propose founded improvements, and to determine the theoretic scope to test the hypothesis.

Electronic systems in movable bridges can be considered through the perspective of different research areas. From the perspective taken in this research, in-service electronic systems are considered to be in the field of Asset Management (AM). All processes before placement and after replacement, are assumed to be part of Supply Chain Management (SCM). Both AM and SCM will be approached from the perspective of the Circular Economy (CE) framework, which is considered to improve AM and SCM processes simultaneously, thereby improving their compatibility. See figure 17 for a schematic representation of the interrelation of CE, AM and SCM.

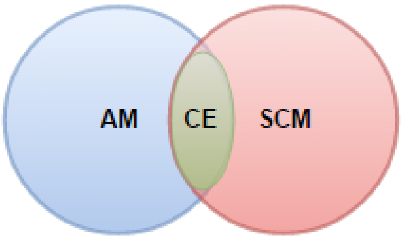


Figure 20. Relation between CE, AM and SCM

In section 3.1, the CE framework will be introduced. Section 3.2 will be used to address the relevant processes of AM and put them into the context of CE. Similarly, section 3.3 is used to describe SCM from the perspective of CE. Section 3.4 is used to analyse the requirements for an ISS. In each of the sections mentioned above, concepts and frameworks from literature will be applied to arrive at a refined objective in section 3.5. Section 3.5 will conclude with a description of the key performance indicators (KPI's), by which the scenarios in Chapter 8 will be compared. Finally, section 3.6 will describe the models and frameworks that are considered during mathematical modelling. See figure 18 for a schematic representation of the chapter outline.

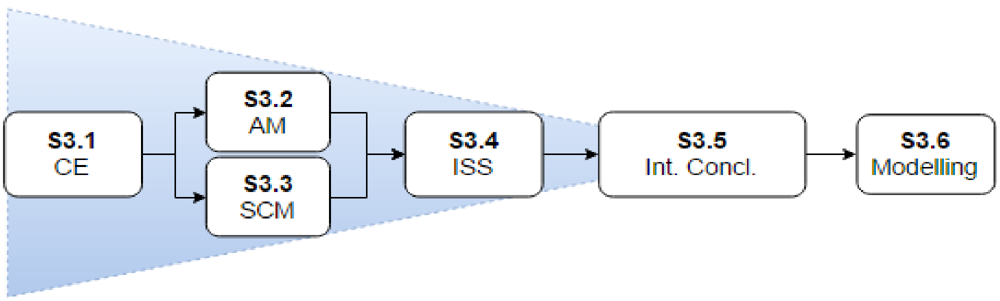


Figure 21. Literature review outline

3.1.Circular economy

Resource efficiency is one of the major challenges of the 21st century. The increase of population, increase of consumption and corresponding increase in waste production is leading to resource scarcity, volatile prices, and environmental damage. These problems have long been acknowledged in both practice and theory, and a substantial amount of literature dedicated to this subject can be found.

In 1979, the 'Ladder van Lansink' was introduced to increase the waste management efficiency of the Netherlands by prioritising waste streams using a certain hierarchy. In the 90's, the concept of **eco-design** (see section 3.2.2) became popular to prevent waste by designing products with an eye on recycling. The cradle-to-cradle concept was introduced in 2002, bringing a more comprehensive approach to the waste challenge. In general however, all these practices only focused on environmental issues (Witjes and Lozano 2016). It thereby has missed much of its goal of transforming our economy because it did not highlight the potential economic benefits. Recently, the CE framework was introduced to move from our current linear (make-use-dispose) economy, to a circular economy (Yuan, Bi, and Moriguichi 2006). See figure 19.

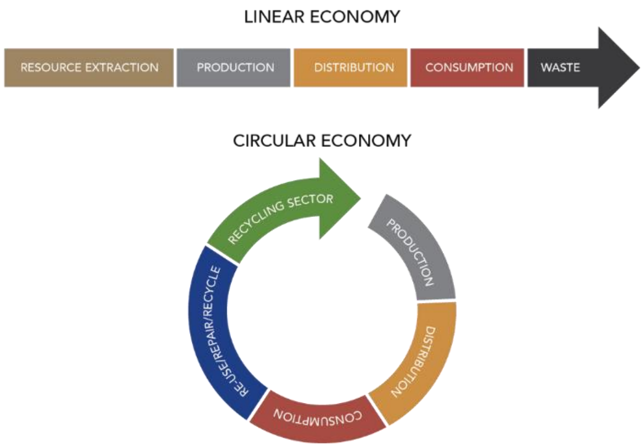


Figure 22. From linear to circular

The circular economy concept has been growing in popularity since and from the looks of it, has really become a buzzword in both practice and politics (Council for the Environment and Infrastructure 2015; Schippers 2012;Hieminga 2015; Lacy 2015). In fact, CE is an economic system based on supply chain collaboration. It is intended to counteract resource wastage by maximising utilisation of products and materials and minimising value destruction. Morlet et al. (2016) defines CE as:

> *'A framework that aims to keep products, components and materials at their highest utility and value at all times.'*

In CE literature, a distinction is made between up to 9 gradations of 'circularity'. There is however some ambiguity in how much gradations there are, and which practices are accounted to which gradation. The Dutch research institute TNO (2013) mentions four gradations, namely reusing, maintaining, remanufacturing, and recycling, in descending order of circularity. The principle behind the circular economy was depicted previously in figure x.

The idea is to close the loop, and to have the tightest loop possible. Reuse is thereby preferred over maintaining, and maintaining preferred over remanufacturing and recycling. Often however, reuse is technically not possible, and maintaining technical systems beyond their economic lifetime is not cost effective.

The benefits of CE are expected to be significant. For the Netherlands alone, TNO (2013) has quantified the following benefits:

- An increase of 7 billion euro's turn-over (± 1% of BBP)
- The creation of roughly 50000 jobs (± 0.5%)
- A decrease in use of resources of 100 Mt (± 25% of import)

The decrease in resource consumption would imply material cost savings and CO_2 emission reductions for the involved stakeholders (Ellen MacArthur Foundation 2015). There are however still some barriers that complicate the transition. These barriers are of organisational, legal, economic, behavioural and technological nature (Cramer 2014), namely:

- Inadequate design
- Inadequate information
- Inadequate collaboration
- Inadequate contracts
- Inadequate business models

These barriers, along with the corresponding improvements found in literature, will be described in section 3.2, 3.3 and 3.4 by using the relevant concepts from Asset Management and Supply Chain Management.

3.2. Asset Management

The concept of Asset Management (AM) is aligned with the basic philosophy of 'Terotechnology', which is defined as (Williams 1994):

> *A combination of management, financial, engineering, building and other practices applied to assets in pursuit of economic life cycle costs.*

From now on, only physical assets are considered. AM is a systematic process of designing, deploying, operating, maintaining, upgrading, and disposing of physical assets. It can thus be said that it involves all life cycle stages as described in section 2.2. The AM strategy is defined as the action plan (acquiring, retaining, replacing and disposing assets) in an organisation that is in place to reach the organisation's goals (Hastings 2010). This research considers AM decision making that is associated with maintenance (retain, replace), end-of-life strategies selection (dispose), and identifying a suitable ISS

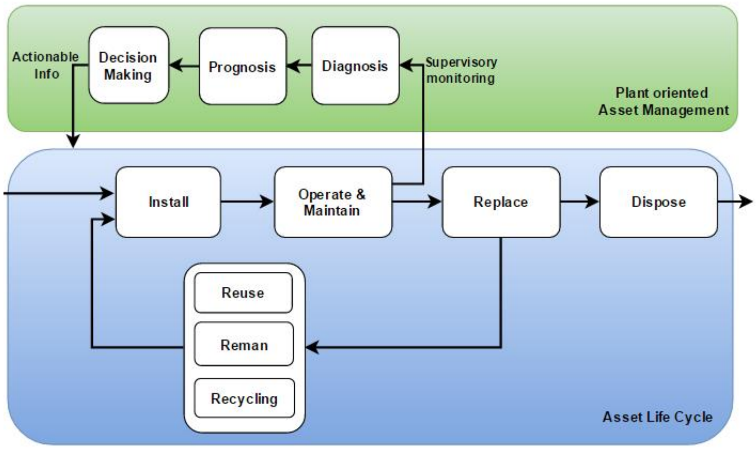


Figure 23. Asset Management scope

to improve these activities (acquire). The focus thereby is on plant-oriented asset management, which has the goal to conserve and/or enhance the value of the technical systems within, in this case, a movable bridge. In a wide sense, plant-oriented AM means to optimize decisions regarding the costs for maintenance as well as for performance improvement. Modern plant-oriented AM includes diagnosis (fault detection), prognosis (forecasting future failure behaviour) as well as fault management (repair, replace) based on supervisory condition monitoring (Isermann 2011). A schematic representation of the concepts of AM under consideration is depicted in figure 21.

In section 3.2.1 maintenance related concepts that are of interest to this research will be defined. In the section 3.2.2 thereafter, typical recovery processes that take place after replacement are described. Finally, in section 3.2.3 the coordinating mechanisms that could be implemented to provide better information for, and coordination between these processes are introduced.

3.2.1. Maintenance

Maintenance is intended to maintain or improve the condition of an asset. Murthy and Jack (2014) define maintenance as:

> *All different functions or activities required to keep a system, or to restore it to operating condition.*

In the last decades, maintenance has moved from being seen as a necessary evil, to an important factor of the business strategy. The common understanding has become that maintenance should be defined on a strategic level, **tactical** level, and operational level. Kobbacy and Murthy (2008) write that the maintenance strategy typically considers long term strategic decisions like whether to outsource or not, or whether to make capital investments. This strategy should be coherent with other facets of the organization, e.g. finance. The tactical level of maintenance deals with planning and scheduling of maintenance, including system degradation analyses, specifying maintenance policies, and deciding on corresponding logistic issues. On an on operational level, the main factors to consider are data collection, data analysis and executing maintenance actions. In a paper from Pintelon and Parodi-Herz (2008) about the evolutionary perspective on maintenance, it is noticed that one of the major challenges in research currently faced, is integrating the tactical and operational aspects of maintenance on the one hand and the **organizational strategy** on the other. A proper maintenance strategy should secure this linkage (See figure 22).

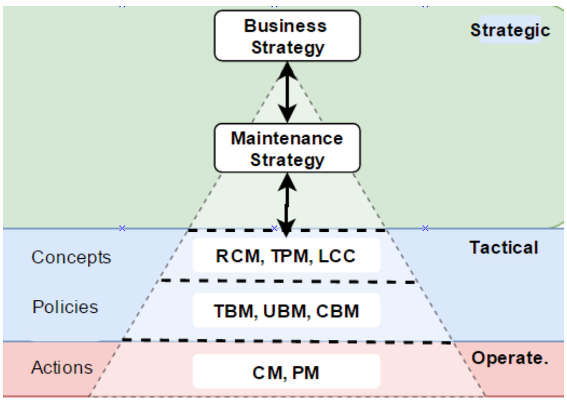


Figure 24. Maintenance on strategic, tactical and operational level.
Based on: (Kobbacy and Murthy 2008)

Maintenance strategy

Linking strategic, tactical, and operational objectives requires a clear and concise formulation of the maintenance strategy throughout the organisation. Regarding the AO, it is assumed that the organizational strategy aims to achieve goals regarding the availability of infrastructure, the costs for maintenance and the environmental performance of the organisation. Currently however, the latter is not propagated to the maintenance strategy. By considering this in conjunction with the conclusions from chapter 2, it is hypothesized that the maintenance strategy should be updated to convey:

- The development of an advanced ISS
- A revision of the decisions regarding stakeholder alignment

In a paper by Tsang (2002), indeed, the strategic dimensions of maintenance are found to be (1) Service delivery options (outsourcing, contracting), (2) Organisation and work structuring, (3) The maintenance policy and (4) Support systems. The author highlights the key decision areas of these fields, provides guidelines for selection and describes the critical success factors. The paper concludes with the common denominator for these dimensions, which were found to be human factors and information flow. The focus in this research is mainly on the latter, for which the author confirms that computerized maintenance policies should be adopted to improve maintenance efficiency. More on maintenance policies will follow in the next subsection. In section 3.4, an analysis of the required support systems will be conducted. Finally, the service delivery decisions will be considered in section 3.3.3.

Maintenance policy

Maintenance can be split into two categories, namely in maintenance that is organized with forethought and in maintenance without a logical and predetermined plan. The following sections will be used to elaborate on forms of planned and unplanned maintenance, and to introduce some of their related maintenance approaches, or *policies*. The maintenance policy defines the set of maintenance actions that are to be performed on specific subsystems or components in the case of a certain event. In figure 23, the relationships between various forms of maintenance is depicted. It should be noted that this figure is by no means complete and is only meant to support the analysis. Maintenance 'concepts' such as Total Productive Maintenance (TPM) and Reliability Centred Maintenance (RCM) are added in the figure to indicate their place within the framework. Since these concepts are perceived to be policies that do not only consider maintenance, but also derivatives such as 'training' and 'safety', they will not be considered.

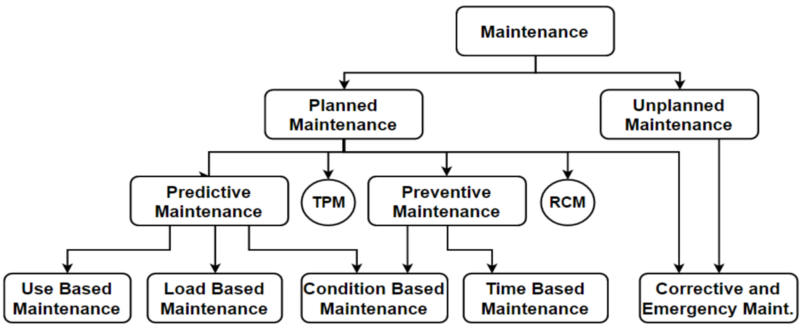


Figure 25. Maintenance relationsships. Based on: (Tinga 2010; Williams 1994)

Unplanned maintenance

Unplanned maintenance, or *run-to-failure*, essentially means that no maintenance is performed until the system breaks down. At failure, the system is either repaired, replaced or overhauled. Having an unplanned maintenance approach can be justified when the impact of failure is negligible or the investments in preventive maintenance do not outweigh the benefits.

Corrective maintenance

The actions performed to restore a failed system back to an operational state are called corrective maintenance (CM) actions. CM actions can be applied on any system level depending on the system and type of failure (Murthy and Jack 2014). Generally, corrective maintenance tasks are identified by using a Failure Mode Effect and Criticality Analysis (FMECA) as described in INCOSE (2015).

Planned maintenance

Planned maintenance is organized and carried out with forethought, control, and the use of records to a predetermined plan. As can be seen in figure 23, corrective maintenance can also be part of planned maintenance. As this might seem contradictory, an example of planned corrective maintenance is a planned improvement of a sub optimally working system.

Preventive maintenance

Unlike corrective maintenance, preventive maintenance (PM) is always part of planned maintenance. Preventive maintenance embodies the desire to prolong effective operation, availability or useful life of a system by conducting regular (periodic) inspection and/or maintenance on that respective system (Williams 1994, Murthy and Jack 2014). As was shortly mentioned while describing unplanned maintenance, the choice between a preventive or run-to-failure approach is very much dependent on the risk and costs of failure, essentially being a trade-off between under-maintenance and over-maintenance. In practice, a RCM approach as described in INCOSE (2015) is used to identify tasks suitable for PM. As an effect, only functionally critical parts of critical infrastructure are preventively replaced in practice. The more critical the part, the more conservative the replacement interval.

Predictive maintenance

Predictive maintenance (PrM) proposes to perform maintenance only when necessary, by monitoring and forecasting the condition of a system (Camci 2015). The most important aspects of PrM are detecting an incipient failure (diagnostics), and forecasting the time of failure (prognostics)(Eker, Camci, and Jennions 2012). When properly applied, this approach can reduce the number of unexpected failures as well as the unnecessary maintenance actions. Furthermore, the prognostic RUL information allows for a more efficient execution of the maintenance tasks by providing a lead-time for organizing. From the perspective of Reliability, Availability and Maintainability (RAM) improvement therefore, PrM would be an effective approach. Finally, applying a PrM approach could improve the environmental performance, as it is found to increase the efficiency of the recovery strategies as introduced in section 3.1 (Fleischmann 2001).

Now that PrM has been identified as the most promising approach for a future state, the following subsections will be used to describe some typical PrM policies. This level of detail is required to make justified statements about the ISS in section 3.4. Finally, some sub-policies relating to the executional details of PrM will be described.

Predictive policies

Tinga (2010) classifies maintenance policies using three criteria, namely (1) the point in the lifecycle the policy is determined (before/during service), (2) the method of determining the condition during the lifecycle (measurement, experience, or model based) and (3) the prognostics approach followed (measurement, experience, or model based). These criteria will be applied here to reason which approach is most suited.

1) Currently, the maintenance intervals are pre-determined by using the specifications of the OEM. During service, these expectations are passive dynamically adjusted based on expert judgement or visual signs of degradation. Such methods only allow for rough estimations of the RUL and indeed do not result in the desired performance. Predictive maintenance as proposed opts for a proactive dynamic approach, in which information about actual degradation is considered.

2) A typical proactive dynamic approach is condition based maintenance (CBM), where failure data (direct monitoring) or process data (indirect monitoring) is directly used for fault detection (Bouvard et al. 2011). Experience based fault detection methods use algorithms that correlate usage profiles and degradation based on past experience to estimate the condition, as is demonstrated by Hilberink (2005).

3) Dynamic proactive policies use prognostics to predict the RUL of systems from the moment the condition information is updated. This can be done according an experience based approach, measurement based approach, and a model based approach, in increasing order of accuracy and cost. Experience based prognostic approaches have the advantage of requiring relatively simple sensors. Measurement based approaches are generally far more accurate, but often require special sensors that cannot be scaled down to be embedded into electronics. Tuchband, and Pecht (2016) and N. Vichare and Pecht (2006) found that a model based approach is suitable for predictive maintenance on electronics. Model based approaches use physical models that simulate degradation based on load inputs. An evolutionary method is subsequently used to extrapolate the evolution of the calculated degradation. This has the advantage that the degradation can be determined without failure data, once the failure mechanism has been modelled. In addition, it allows for what if analyses by varying the model inputs.

Tinga (2010) proposes two model based policies that combine the benefit of measurement based maintenance and experience based maintenance: namely Use Based Maintenance (UBM) and Load Based Maintenance (LBM). Both policies require only simple sensors for monitoring usage (start-stops, cycles) and/or loads (temperature, current). Figure 24 depicts how these two policies relate to CBM.

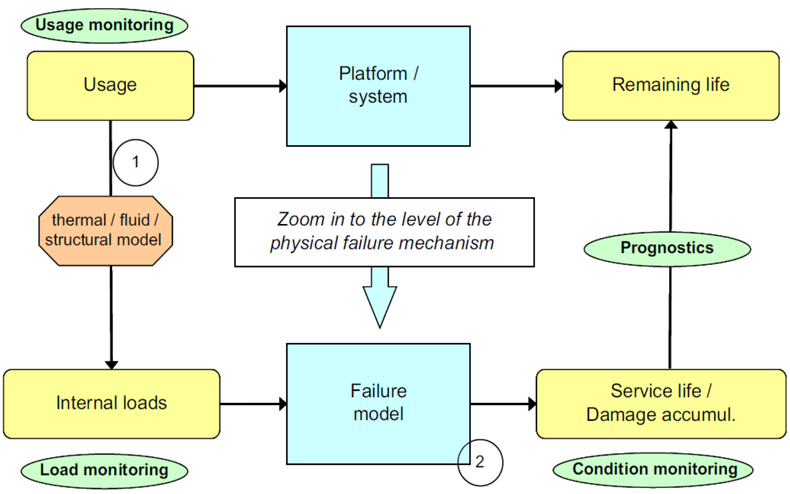


Figure 26. Relation between CBM, UBM and LBM. Source (Tinga 2010)

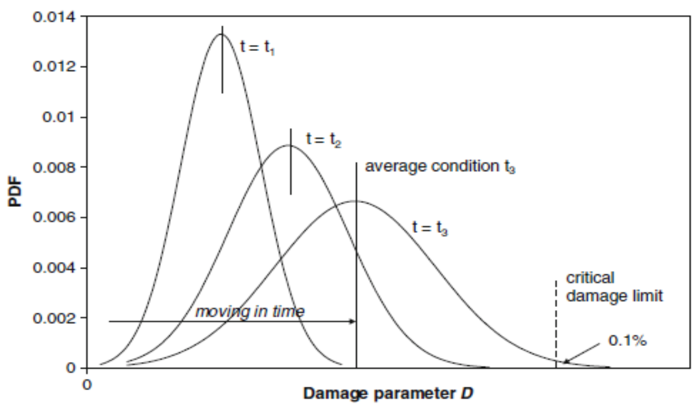


Figure 27. prognostic accuracy. Source: (Tinga 2010)

Due to inherent modelling uncertainties, CBM, LBM and UBM are accurate in descending order. The accuracy of an approach is expressed by the width of the failure probability distribution at a certain degradation (D) as depicted in figure 25. From now on it is assumed that in a future state, the electronics under consideration are serviced using a LBM policy.

Group Maintenance, Opportunistic maintenance, and clustering

According to Murthy and Jack (2014), Opportunistic *maintenance* (OM) and *Group maintenance* (GM) are typical predictive maintenance policy variants. GM aims to group components based on their spatial closeness, expected lifetimes, and other properties. When one component in a group fails, all other components belonging to the same system and group are replaced. OM aims to identify possible PM actions that can be performed during the maintenance on other components. The term *clustering* is used to indicate maintenance actions that are grouped between multiple objects.

Because of the large differences in type, location, age, and use-pattern of electronics between movable bridges, clustering is currently not cost effective (App. E, SP1, Q1). Replacing electronics following an OM or GM approach neither occurs in practice. This can mainly be accounted to the fact that for the decision maker, preventively replacing components is generally more expensive than a run-to-failure approach (App. E, SP3, Q5).

3.2.2. End-of-life recovery

Once electronics have been replaced, the responsible party must decide what to do with it. Possibly, the system represents a certain residual value which could be recovered through recovery processes. Decisions regarding this recovery strategy are crucial to ensure efficient resource utilization. The concept of value recovery is defined as:

> *The process of maximizing the value of end-of-life assets through effective re-application or divestment.*

For electronic assemblies, the maximisation of this value most often requires inspection, disassembly, followed by remanufacturing, recycling and/or disposal (Kuo 2013). It is assumed that replaced electronic assemblies are not suitable for direct reuse. Some processes related to the other 'R's', as listed in section 3.1, are also considered to be of lesser interest here because they can be accounted to product design (refuse, reduce), or only provide a temporary reprieve (repair, refurbish). Furthermore, it is assumed that recovery processes, should they take place, are performed off-site at a central facility where the replaced systems are collected. The remainder of this section is used to define the recovery processes under consideration in this research and to highlight key research areas.

Remanufacturing

Remanufacturing is the term used for returning a subsystem or assembly to as good as new (AGAN) condition. This can be accomplished by repairing or replacing either some or all the assemblies and/or subassemblies of the respective systems. Over the last decades, remanufacturing has been growing in importance in both practice and research (Andrew-munot, Ibrahim, and Junaidi 2015).

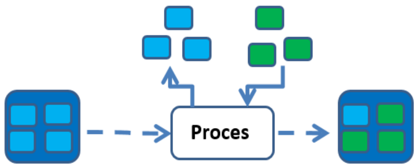


Figure 28. Remanufacturing process

Recycling

Recycling is regarded as the recovery process of reducing technical systems to secondary raw material flows. Typically, this requires a size reduction process (disassembling, shredding), and one or multiple sorting processes. In this research, a distinction is made between low grade recycling and high grade recycling. During high grade (closed loop) recycling, materials that are recovered from the collected end-of-life systems are fed back into the production process of the same products, whereas in low grade (open loop) recycling, the reprocessed materials are applied elsewhere.

Figure 29. Recycling process schematic

Disposal

Disposing is regarded as the processes that discard the technical systems without recovering any of the material value. Examples of such processes are landfilling or incineration without energy recovery. In the Netherlands, there is a ban on landfilling and incineration always takes place together with recovering the energy released. Material 'value' therefore always finds its way back into the economy one way or the other (App. E, CON1, Q1). Disposal will not be further considered.

Compared to new production, remanufacturing is up to 50% cheaper (Andrew-munot, Ibrahim, and Junaidi 2015), saves up to 90% of materials, and can have a 6 to 1 ratio when the energy consumption is concerned (Matsumoto et al. 2016). Furthermore, compared to recycling, remanufacturing is preferred from an environmental perspective (Zhang et al. 2013). In the remainder of this research, the both remanufacturing and low grade recycling are considered in the recovery strategy decision. This choice is made because these processes represent the two extremes within the current scope as far as 'circularity' is concerned. Besides, it is expected that remanufacturing could largely leave the current physical supply chain structure unchanged because some SP's are already involved in remanufacturing activities. It is expected that only the scale and operational details of these processes would change. Open loop recycling is currently already being done, but could become more efficient when the challenges as discussed previously are addressed. On the contrary, implementing closed loop recycling would either require large investments into reprocessing equipment or it would require the formation of new alliances with third parties. It is therefore that remanufacturing and open loop recycling are more likely to become part of a solution. To increase the scale of remanufacturing there are however some barriers to overcome. The main challenges in research regarding remanufacturing are listed by (Matsumoto et al. 2016):

- (Eco) Product design
- Remanufacturing process (engineering & optimization)
- Business model design

Issues regarding the product design will now be explained shortly. The supply chain remanufacturing processes and business model design are topics that are covered in section 3.3.1 and 3.3.3 respectively.

Eco-Design

The Ellen MacArthur Foundation (2015), a major driving force behind the CE movement, mentions design for remanufacturing as a major requirement for success. The characteristics of each product namely greatly determine the extent to which remanufacturing can be applied. For instance electrical equipment, which was identified by TNO (2013) as one of the groups with highest potential, faces barriers for remanufacturing because of embedded electric components (Bigum and Christensen 2010). Thinking about remanufacturing during product design can make the remanufacturing process more efficient. To enable remanufacturing, a product should (Andrew-munot et al. 2015):

- be durable
- have a modular design
- have stable technology
- fail functionally rather than dissipative

Furthermore, for remanufacturing to be cost effective, the product should:

- have a high residual value
- be available in bulk

Typically, electronics have fast technological cycles and are therefore becoming obsolete in no time. This is indeed the situation as described by various stakeholders (App. E, SP1, Q10; SP3, Q10). There are however examples of companies that have combined the advantages of remanufacturing with electronic products. Some examples are photocopiers (Xerox, Océ), cellular phones (FairPhone), and single-use camera's (Canon). Besides having fulfilled the design requirements listed above, these companies have implemented ISSs and innovative business models that make this kind of operation feasible.

3.2.3. Support systems

So far it can be argued that implementing ISSs has the potential to save maintenance costs, reduce downtime and lead to lower life cycle costs. Furthermore, from the examples from practice where remanufacturing has been adopted, it seems that the improved information from such systems works both ways. Cigolini et al. (2009) indeed confirm that remote maintenance services are rightfully seen as a way to improve the recovery of residual value during the phase of disposal.

Developing ISSs for maintenance and recovery processes as described, is an important part of AM (Hastings 2010). Such systems literally provide the information required to make effective decisions. Effective implementation and exploitation of these systems requires proper coordination between the involved parties. Developing coordinating procedures that ensure that the organisational, legal, economic, and behavioural requirements are fulfilled are part of SCM. Section 3.3 will further elaborate on the factors that determine the coordination in a maintenance supply chain, such as contracts and business models. In section 3.4 the physical requirements for an ISS will be analysed.

3.3.Supply Chain Management

SCM is the active management of activities within a supply chain to maximize the customer value and to achieve a sustainable competitive advantage. According to Simchi-Levi, Chen, and Bramel (2005) the concept of Supply Chain Management (SCM) is based on two main ideas. Firstly, every product that reaches an end user represents a joint effort of multiple organisations. These organisations combined are referred to as the supply chain. Supply chains can also be regarded at as *logistic networks,* or *value chains.* The second idea is that supply chains can only be effective when its management covers everything from product development, sourcing, production, and logistics as well as the information systems that are required to coordinate these activities, rather than only focusing on the processes within a single organisation. Organizations within a supply chain are thus linked through physical flows as well as information flows. Physical flows are the most visible piece of the supply chain, involving the transformation, transportation, and storage of goods. Although less visible, the information flow is crucial in supply chains because it allows supply chain partners to coordinate their long-term plans and to respond to short term fluctuations up and down the supply chain (Simchi-Levi, Chen, and Bramel 2005).

Based on Wang et al. (2015), the supply chain under consideration in this research can be classified as a Product-Service Supply Chain (PSSC). Such supply chains, in which the delivery of a physical product (electronic system) is accompanied by delivering a service (maintenance), are growing in popularity and are predicted by Arnold, Javorcik, and Mattoo (2011) to rule the world economy. According to Ellram et al. (2004), the management of PSSC's should consider the management of performance, finance, information, and both forward and reverse flows of tangible goods. To improve the recovery of residual value from replaced electronics (physical flow), the quality of information (information flow) and the coordination between these flows need to be improved.

In the remainder of this section, the concepts from logistics will be applied from a recovery perspective. Secondly, the relevant concepts related to the quality of information will be introduced. Finally, the importance of coordination between physical and information flows will be described and promising contracts and business models will be proposed.

3.3.1. Recovery network

The physical flows in a supply chain can best be described with logistic concepts, such as transport and inventory. In the PSSC considered here, the forward supply chain required to deliver the products (technical systems) from the supply chain partners (OEM and SP) to the end user (AO) is established. The part of the network that is required to efficiently recover value from end-of-life technical systems however is largely absent. To increase the recovery rate, an improved reverse supply chain or *recovery network* is crucial.

Fleischmann (2001) classifies recovery networks into reusable item networks, bulk recycling networks, and assembly product remanufacturing networks. Dekker et al. (2004) describe the important issues to consider regarding recovery networks with four dimensions (why, what, how and who). This section is used to apply a somewhat adapted form of this framework.

Return drivers

Electronics can be returned because of service returns, end-of-use returns or end-of-life returns. End-of-life replacements represent the largest share of returned systems (App. E, CON3, Q1), and will therefore be considered here. Fleischmann (2001) motivates that the drivers for returning products for both the receiver as the sender side should be considered. Here, OEM and SP fulfil these roles respectively.

The drivers for the OEM for accepting returns can in theory be economical, legislative or because of corporate citizenship. Currently there are no stringent legislations, as was elaborated on in section 2.2.5, nor is there a danger of negatively influencing the company image. Regarding economics, Fleischmann (2001) states that recovering *manufacturing added value* would be the main driver in the case of assembly product remanufacturing networks. Currently however, product designs and low volumes do not allow for cost efficient remanufacturing. Furthermore, OEM's are wary of remanufacturing because it is believed to cannibalize sales.

Similarly, legislation nor environmental consciousness is pressing service providers to return products. Since there most often is no cooperation with the OEM regarding returns, economic drivers are absent. To improve recovery within the supply chain, the SP and OEM need to be incentivized. To achieve this, the AO must enforce better cooperation within the supply chain by improving the contracts and contracting procedures. Again, it is stressed that legislations from national governments are required to enable this.

Return characteristics

The characteristics of the returned electronics can be defined in terms of the type (electronic), composition, use pattern, and the degree of deterioration of the recoverable system.

- The composition of an asset is defined by its size, the components and/or assemblies it is composed of and their respective constituent materials. Typically, electronic assemblies are relatively small, consist of multiple components, and contain metals (copper, tin, gold), semi-metals (silicon), and plastics.
- The relevant characteristics related to the use pattern of a returned asset are the location of use, intensity of use and duration of use. Since the use pattern determines the quantity and location of recoverable products, it very much determines the collection phase.

- The deterioration of an asset is determined by its intrinsic deterioration, the homogeneity of this deterioration over the different parts of the asset, and the economic deterioration. Product design, use patterns and technological obsolescence mainly determine the extent of these forms of deterioration. For replaced end-of-life electronic systems is can be assumed that they have deteriorated during their useful life and are therefore not 'as-good-as-new'. Fleischmann mentions that in that case some form of reprocessing is required.

Recovery Processes

All steps that are required to return a degraded electronic system to as-good-as-new condition are considered as recovery processes. Generally, these processes can be subdivided into collection, value recovery and redistribution. Since in this case the focus is on business to business (B2B) returns, 'collection' and 'redistribution' are assumed to be carried out by the SP while they execute maintenance. According to Hua, Liu, and Zhang (2015), the actual recovery involves inspection, disassembly, reprocessing and reassembly in the case of remanufacturing. See figure 28.

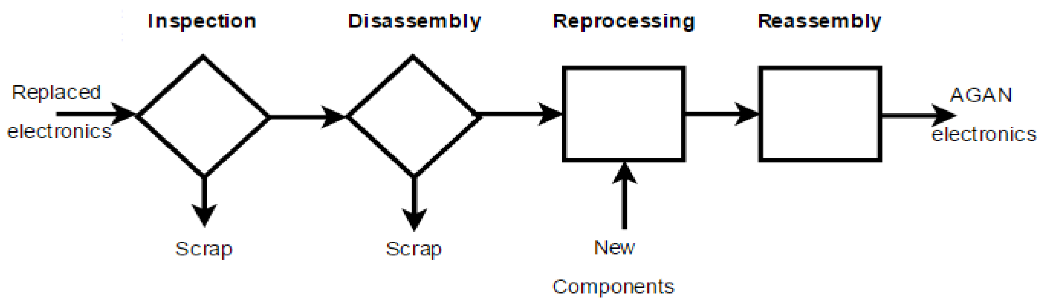


Figure 30. Recovery processes. Based on: (Hua, Liu, and Zhang 2015)

Generally, the forward logistic structures are a good starting point for the design of a recovery network (Dekker et al. 2004). It is therefore assumed that the remanufacturing setup as described by SP3 (App. E, Q10) is scaled up. Fleischmann (2001) reasons that the type, sequence, and yield of recovery processes mainly depend on the condition of the product. The design as well as the RUL thereby directly affects the potential for recovery (Hu et al. 2014). In the remainder of this research it is assumed that in a future state scenario, the design requirements as listed in section 3.2.2 have been met. Furthermore, since the maintenance resources are limited and only a small subset of the service area can be under maintenance simultaneously, it is assumed that the systems are collected in relatively small batches. Due to these assumptions, the following can be expected (Andrew-munot, Ibrahim, and Junaidi 2015):

- Disassembly and inspection can take place simultaneously.
- All processes can be performed by using general purpose tools
- There is low RUL variability with corresponding high remanufacturing yields

3.3.2. Information

Having quality information is crucial for effective decision making on strategic, tactical, and operational level. The focus here is on the reverse supply chain, which is assumed to be integrated with the current state forward supply chain. It should be noted that although not explicitly considered, the information flow from both forward as reverse supply chain should be integrated as well. Furthermore, it is assumed that one specific electronic system type is handled and that the design and corresponding composition is completely known. The following types of information were found to bring opportunities (Brito, Dekker, and Flapper 2004; Morlet et al. 2016; Toktay, van der Laan, and de Brito 2003):

- Location of returns
- Quantity of returns
- Quality of returns
- Timing of returns (e.g. arrival times)
- Timing of recovery (e.g. processing times)

In a research on information technologies for reverse logistics, Kokkinaki, Zuidwijk, Nunen, & Dekker (2003) reason that ideally, this information is available on product level. Uncertainty arises when such information is not available to the decision maker. Besides adopting eco-design strategies, Kokkinaki et al. (2003) confirm that decision makers should invest in information systems to reduce this uncertainty.

However, before such investments are made, there ought to be a solid business case justifying its costs. Srinivasan and Parlikad (2013) define the difference between the total expected costs incurred by the decision maker with and without information support as the *Value of Information* (VoI). The VoI thus represents the total costs saved, or the amount the decision maker would be willing to pay for the information. To optimize the value of information, choices should be made regarding:

- Quality of information (accuracy, frequency)
- Sharing of information

These factors determine the degree to which the information can reflect the actual situation to whom. Srinivasan and Parlikad (2013) use the concept of *Perfect Information* to indicate a situation where there is a one-to-one relation between the real state and the information, and *Imperfect Information* is defined as the case when the information contains uncertainty. The difference in quality of information as seen by the different stakeholders can be defined by the *Information Symmetry*, which is an important factor to consider when coordinating the supply chain (Dekker et al. 2003).

Here, component level information is assumed on an operational timescale. This fits the concept of real time monitoring as introduced in section 3.2.1. In section 3.4, this concept will be extended and the corresponding hardware requirements will be analysed.

3.3.3. Coordination

In all supply chains, multiple decision makers are involved in decision concerning efficiency and profitability. Unfortunately, decision makers typically pursue their own objectives. Debo, Savaskan, and Wassenhove (2003) reason that coordination is required to optimize supply chain performance. In the business climate as described, the stakeholders have developed business models that are not fit to bring about the change that is required. Measuring up to the updated strategic goals therefore seems to require the introduction of innovative business models and corresponding contracts. In the field of supply chain management, there has been a lot of research into using complex contracts for incentive alignment. In a review about the application of OR tools in service supply chain management, Wang et al. (2015) mention that game theory and principal-agent theory should be used to examine the effects of different contract structures in this context. Applying such advanced analytics was found to reveal cooperative scenarios in which the profits of all stakeholders increased. For the remainder of this research however, such dedicated OR models are out of scope. Instead, suitable business models and corresponding contract forms will be identified using practice oriented papers.

Business Model

Previously, the maintenance supply chain was classified as a Product Service Supply Chain, offering a Product Service System (PSS). A PSS can be product based, performance based and usage based. Currently, the SP business model can be characterised as product based, since a technical installation is sold to the AO, together with a short-term maintenance service. At the end of the line the AO must decide when maintenance actions are executed and what the recovery strategy should be. The lack of expertise of the AO regarding these decisions result in suboptimal solutions. Witjes & Lozano (2016) propose to make the PPP construction more service-oriented, such as in performance-based and usage based business models, to increase the degree of circularity. Per the authors, such a redesign of the business model should encompass both technological, social, and organisational factors.

Product service systems with remanufacturing have the potential to have large economic as well as environmental benefits, because they reduce the amount of virgin materials required for production. However, because of the barriers and rebound effects as described earlier (cost efficiency and sales cannibalization), end-of-life electronics with RUL are in practice often disposed. In a paper by Chierici and Copani (2016), a 'PPS with upgrade' is proposed as a way to remedy these effects, by enabling the introduction of technological innovation during a system's life cycle. The authors take a business model perspective to describe its implementation, covering the value proposition, the supply chain infrastructure, and the revenue model. In the following, this setup is applied.

Value proposition

To be able to deliver up-to-date products, Chierici and Copani (2016) reason that at least the following services should accompany the physical assets along their lifecycle:

- Periodic takeback and upgrade through remanufacturing
- Installation and training services to minimize the discomfort of upgrading

Supply chain support

To deliver such a value proposition, the following supporting resources are required (Chierici and Copani 2016; Morlet et al. 2016):

- Product embedded monitoring and connectivity systems
- Continuous collection and analysis of usage conditions, failure patterns, etc. to be used in the prediction and management along the product's lifecycle.
- An optimized logistics infrastructure that is able to cope with the inevitable uncertainties, although reduced through improved information, of the return volumes.

It can be concluded that these prerequisites are firmly aligned with the conclusions up until now.

Revenue model

The adopted revenue model should guarantee that the upgradable product cores are collected, in order to deliver the promised 'reman-with-upgrade' service. To this regard, revenue schemes in which the SP retains ownership are found suitable. A 'Pay-per-use' revenue scheme, where the party formerly known as the AO pays a periodic fee, has had success in examples from practice. The classic example is Rolls Royce with 'Power-by-the-hour' as analysed by Smith (2013). More recently, also companies in the Netherlands have developed similar revenue schemes such as Philips Lighting ('pay-per-light- hour') and Bundle ('pay-per-wash'). Generally, these business models have brought the following benefits:

- Low investment costs for the 'customer'
- State-of-the-art technology
- Distributed stable cash flow for the SP
- Long term relationships

Indeed, it can be confirmed that such benefits in addition to the environmental benefits would fit the requirements perfectly. In all examples from practice however, the SP is also the manufacturer of the assets. For such a scheme to work in this sector, a close cooperation should exist between the classic SP and OEM parties. Another possibility is that either the SP or the OEM pioneers more into developing products with full life cycle services. As was described in chapter 2, both SP and OEM are doing this to some extent. As concluded earlier, the innovative character and ability to specialize in a certain service make the SP the most promising party to develop the ISS. The SP would own the electronic installations, and perform the role of OEM certified remanufacturer. This brings the benefit for the OEM that their intellectual property as well as their quality standards are safeguarded. Furthermore, information from monitoring throughout the system life cycle can be used for redesign. From now on it will be assumed that although remaining separate entities, the OEM and SP work closely together in a future state. See figure 29 for a schematic representation of the proposed stakeholder roles.

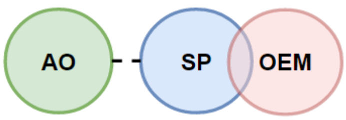


Figure 31.1 Proposed stakeholder roles

It should be noted however, that the proposed stakeholder roles can never be a universal solution. Because of the strategic importance of national infrastructure, market parties should not be given complete ownership. More on this trade-off will follow in the next section about contracting.

Contracting

Contracts should secure proper execution of the business strategy and thereby the success of the business model. It followed from chapter 2 that currently there is a lot of in dissatisfaction regarding the maintenance effectiveness. Tsang (2002) describes a similar situation, in where the potential benefits of the strategy are not realized because of the fact that the AO wants to minimize costs and the SP wants to maximize profit. This creates an environment in where competitive bidding is used for SP selection, leading to short term commitment and minimal investment of the SP. Being unsatisfied, the AO changes to another SP party and a vicious cycle has commenced.

Clearly, change is required when maintenance contracting is concerned. In addition, a suitable contract for securing successful remanufacturing operations is required. In the following, the degree of outsourcing and both the contracts related to maintenance (AO-SP) and remanufacturing (SP-OEM) will be considered.

Outsourcing

According to Tsang (2002), the main questions to ask oneself when reviewing the maintenance strategy are: (1) what should and should not be outsourced?, (2) How should the risk of outsourcing be managed, and (3) which contractual relationship should be chosen? This framework will be applied here.

1) Services in which there is strategic vulnerability, typically those activities that are crucial elements of the core competencies, should not be outsourced. This is because this could bring the following risks:
    a. An overly powerful SP can hold the AO organisation hostage
    b. An overly weak SP cannot supply quality and innovative services
    c. The AO organisation does not have the competency to assess the SP

Non-core activities can be considered to be outsourced, depending on how the costs of outsourcing (searching, contracting, controlling) relate to the costs of performing the activities in-house (research, development, personnel, investment) (Tsang 2002). As was described in chapter 2, currently the whole maintenance process is being outsourced, and this has indeed led to the occurrence of (a) and (b). In an article in the opinion section of a well-known Dutch newspaper, Prof.dr.Ir de Ridder (2017) of the TU Delft concludes that this can largely be explained by the fact that consultancy firms that are hired to perform the contract management have nested themselves between the AO and the SP. It is in the interest of these firms to make everything as big as possible. The result of such large contracts is that the SP's develop into multi-service 'facility managers', which typically do not have the specialty knowledge for innovation. Per de Ridder, the consultants thereby have created a situation in where knowledge plays a subordinate role in the contracting procedure, and SP's are selected based on process rather than content.

2) To avoid the risks listed under (1), Tsang (2002) mentions that the AO could adopt the following approaches:
    a. Creating a conflict resolution process for inevitable uncertainties
    b. Insist on a stable team at the SP, and provide frequent and close contact with employees involved in the contract
    c. Use specialized teams in the contracting process, namely one for contract negotiations, one for contract management and one for technical expertise.

As partly became clear in chapter 2, not all of these approaches are explicitly adopted. For (b) it can even be said that it is prohibited for the specialists on either side to keep contact. Regarding (c), it can be said that there are primarily technical managers employed at the AO (de Ridder 2017). These managers are also the ones that take care of contract management (App. E, AO1, Q3) and therefore there cannot be spoken of a dedicated expert team.

Contracts

According to Tsang (2002), maintenance contracts are classified into 'work package' contracts, 'performance contracts' and 'term-lease' contracts, which differ in contract complexity, duration and the amount of knowledge that the AO is able to keep in such a contract. See figure 30.

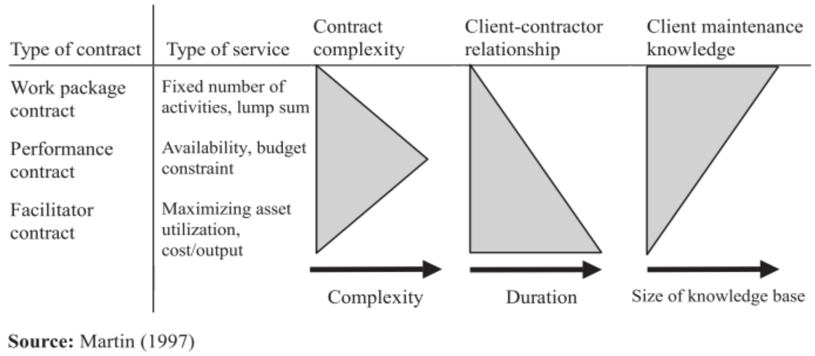


Figure 32. maintenance contract classification. Source: (Tsang 2002)

I. In work package contracts, the SP typically only delivers the manpower to execute predetermined maintenance tasks
II. In performance contracts (SLA's), a range of services is contracted to the SP. The contract specifies key outputs such as equipment availability, failure response times and repair times When there is sufficient freedom for the SP, and good performance is linked to rewards, this approach is found to stimulate innovations and investments.
III. In term-lease contracts, the equipment is owned and maintained by the SP and the AO is only the user. Such contracts require long term partnerships because the equipment often has to be engineered especially for the AO. For the SP, these contracts typically have the highest rewards.

Tsang (2002) mentions that the ability of performance contracts to leverage the SP's knowledge, makes it the preferred contract form for strategic outsourcing. The contracts described in chapter 2 therefore, by name seem to be the best choice. For these contracts to have the desired effect however, Tsang (2002) describes the following requirements:

a) The performance measures (availability, sustainability) should be properly aligned with the businessplan and regulatory requirements
b) The SP personnel should be located on the AO premisis to provide in-house benefits.
c) The SP and AO should use the same information system
d) Good performance should be rewarded with contract extension.

Tsang also mentions that the AO organisation should focus on:

e) Capturing knowledge in stead of only buying services
f) Developing strong relationships with few suppliers rather than enlarging the base.

Especially requirement (b) and (c) are not fulfilled in practice. Direct communication is prohibited, and the information systems in use at both parties are incompatible.

Regarding requirement (e), it can be said that the AO is currently more driven by cutting costs through outsourcing, than by ensuring a strategic amount of knowledge in the organization. Also for (f) it can be said that practice is different. Namely, the AO is engaged in aggregated multi-service contracts with a single SP, that were selected on lowest costs. Such contracts consist of multiple sub-contracts with other SP's, which were also established by competing on lowest costs. In effect, this may often mean that there are many parties involved that are not the best for the job performance-wise, nor are there strong relationships being formed in which specialty knowledge is transferred. According to de Ridder (2017), the trade-off between the size of the contracts and the amount of knowledge transfer between the SP and AO needs to be optimized.

A possible approach here would be to distinguish between (proper) performance contracts and lease-term contracts within the management of a single movable bridge. In an interview with an AO asset manager, the leasing concept is confirmed as an option (Zeegers 2016a). It is also mentioned however, that most probably this will not be the case for strategic assets, wherein the AO want to keep full control. In the following, an optional contracting structure will be introduced.

Maintenance contract

For functionally critical systems within strategic objects, an improved form of the performance based contracts could be adopted. In these contracts, at least the following aspects should be (re)considered:

- Either, there should be a clear incentive for the SP to innovate by granting long term contracts with design freedom and performance rewards, or, the maintenance specifications should be more prescriptive to prevent a race to the bottom.
- The communication between both parties should be improved by locating at least some of the responsible SP staff at the AO facility, and by integrating compatible information support.

For non-strategically vulnerable objects, the AO could enter into term-lease contracts with specialized SP parties directly. The 'pay-per-use' business model that was highlighted in the previous section would pre-eminently be a suitable fit here. From experimenting with these new practices, lessons could be learned in whether to extend them to other objects and how to do this responsibly. Because of their good fit with the problem definition, from now on the focus will be on usage based business models. The analysis will thereby be limited to non-strategic objects.

Remanufacturing contract

A suitable contract also needs to be found for the introduction of remanufacturing in the supply chain. Sporadically, a credit based approach as described by Andrew-munot, Ibrahim, and Junaidi (2015) is followed, where the SP performs the role of contract remanufacturer. This only happens with certain high-end models and in certain partnerships (App. E, SP3, Q10). To expand this business, the following aspects need to be addressed:

- For successful remanufacturing, the volumes of identical recoverable systems would have to increase. When the SP develops a specialized service under a term-lease contract, they have full control over the electronic system type. The AO could stimulate the SP further by entering contracts that are large enough to have the systems become available in sufficient quantities. Another way to improve the volumes of identical recoverable products would be to stimulate the cooperation between SP's offering similar services.

- Furthermore, remanufacturing requires improvement of the contractual incentives. When environmental criteria would be explicitly incorporated into the contract, the SP would have an incentive to invest in remanufacturing. This is believed to greatly improve the supply chain's environmental performance.

Contract management

Given the purchasing power of public organisations, it can be said that they can enlarge the market for sustainable services considerably (Witjes and Lozano 2016). The AO that a change of the procurement policy is required to stimulate the CE (Zeegers 2016a). The current contracting procedure does not stimulate CE practices, because the knowledge transfer is minimal. In a paper by Witjes and Lozano (2016), propose a framework in which the collaboration between the AO and SP changes from the sourcing stage to the preparation stage of the PPP process (see figure 31 and 32). It is expected that this change would improve the knowledge transfer considerably.

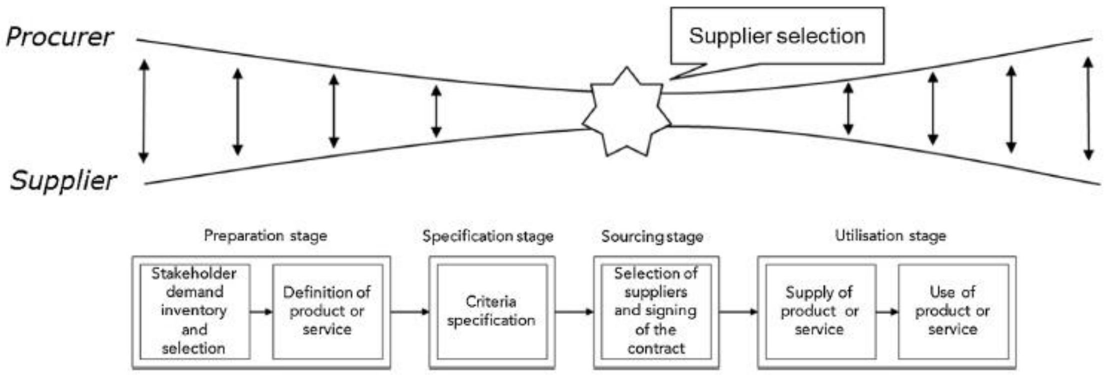


Figure 33. current state contract management. Source: (Witjes and Lozano 2016)

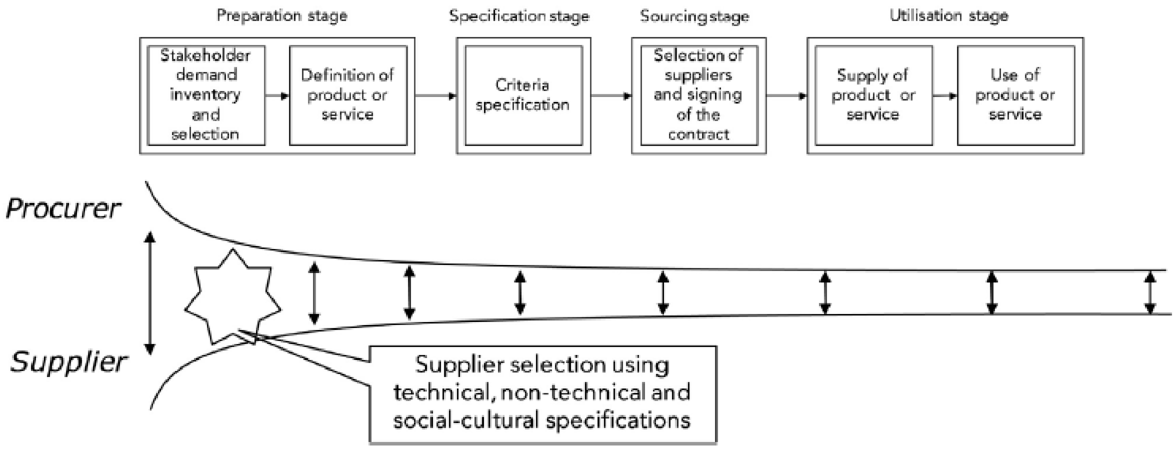


Figure 34. future state contract management. Source: (Witjes and Lozano 2016)

3.4. Information Support system

Effective deployment of information support systems is crucial in support of maintenance and recovery operations (Cigolini et al. 2009; Tsang 2002). Most developments in this field of research have been aimed at maintenance. For instance, computerized maintenance management systems (CMMS) nowadays offer substantial support for decision making. Current research is considering the development of more sophisticated 'intelligent maintenance systems' (IMS) (Lee and Wang 2008), which actively utilize real time data to predict and prevent failures (Isermann 2011). The main objective of these systems is the reduction of breakdowns. Being able to simultaneously improve the EOL recovery, is most often seen as a nice 'by-product' (Ashraf 2008). The main question that remains here, is what kind of physical support infrastructure (sensors, communication hardware, and decision support hardware) is required to implement predictive maintenance. The answer to this question depends on the signals to be monitored, which again depend on the system to be monitored. Section 3.4.1 will be used to further elaborate on the specific information requirements. Section 3.4.2 will introduce the corresponding data analysis requirements. Section 3.4.3 will conclude with an analysis of the general hardware requirements for electronics. The results of this analysis will be used in chapter 6 to translate this to a practical application.

3.4.1. Information requirements

To be able to select suitable hardware to enable load based predictive maintenance, it should be thoroughly investigated which information is required. To answer the question: who needs to know what, when why and how, the method of in 't Veld (1978) is applied. In 't Veld describes a structured approach to determine what there is to know about what, to be able to evaluate which of these forms of information is required by who to reach the organizations objective. The analysis is applied from the perspective of the party responsible for the technical installation. Currently this role is performed by the AO, which does not have the resources to invest in an ISS. It is assumed that in a future state were a ISS is installed, the SP performs this role. A depiction of this method along with the other choices made during application can be found in appendix B. The following information was found to be required in practice:

Information about end-of-life electronics:

- The quantity of systems required in stock to be able to perform maintenance
- The quantity of replaced systems and (AGA) new systems in stock
- The quantity (number of) of replaced electronics and the corresponding remaining useful life should be considered. This information should be shared with the party performing the reprocessing operations as soon as new information becomes available (when a replacement action is planned). It is assumed that this information is registered until the end of the, say monthly, interval to be able to plan the reprocessing capacity accordingly.

Information about personnel:

- The number of maintenance personnel assignments and the duration of the assignments should be considered. The personnel costs were explained in Ch2 to be a major cost driver.

3.4.2. Data analysis requirements

Applying predictive maintenance generally involves two stages. The first stage of the process is acquiring and processing data, whereas the second stage involves decision making (Cigolini et al. 2009). From chapter 2 it was learned that in practice there is still a lot unclear on how to approach stage one, and therefore also stage two is not yet understood. In what follows, the different aspects of designing a data acquisition and corresponding data processing approach will be introduced. See figure 33 for a schematic representation of a typical data flow structure for supervisory monitoring.

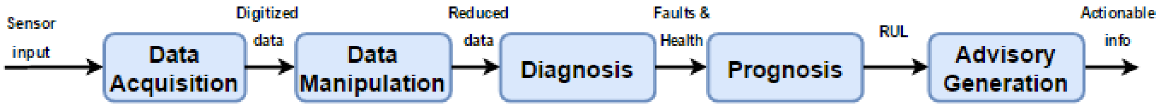


Figure 35. data flow structure for supervisory monitoring. Based on: (Isermann 2011)

The supporting electronics in technical systems generally are the first ones to fail (N. Vichare and Pecht 2006). A similar situation was described in the case of movable bridges. Classic failure prediction methods for electronics, such as those prescribed by NEN (2015), are proven to be flawed by N. M. Vichare and Pecht (2006). In section 3.2.1, a model based approach was therefore proposed. For many failure mechanisms in electronic products, there are so called *Physics of Failure (PoF)* models that can relate loads to the time of failure of the system. By monitoring the environment and operational loads over the systems' lifecycle, it is often possible to determine the accumulated damage and predict the moment of failure (Ramakrishnan and Pecht 2003). This approach is known as model based *life consumption monitoring*, and is known to have the following advantages (Pecht and Gu 2009):

- Advanced notification of incipient failures
- Minimizing unscheduled maintenance
- Reducing life cycle costs (inspection, downtime, inventory)
- Effective in supporting (re)design and logistic decisions

In high quality demanding sectors, such as the US Defense sector, integrated prognostics have become a requirement for electronics in the field (Pecht, Tuchband, and Pecht 2016). In a paper by Pecht and Gu (2009), an implementation procedure including Failure Mode, Mechanisms and Effect Analysis, (FMMEA), data reduction, feature extraction, damage accumulation and uncertainty assessment is presented (See figure 34). An extended version of this procedure is used in the remainder of this section to describe the main choices when implementing life consumption monitoring on electronics in movable bridges.

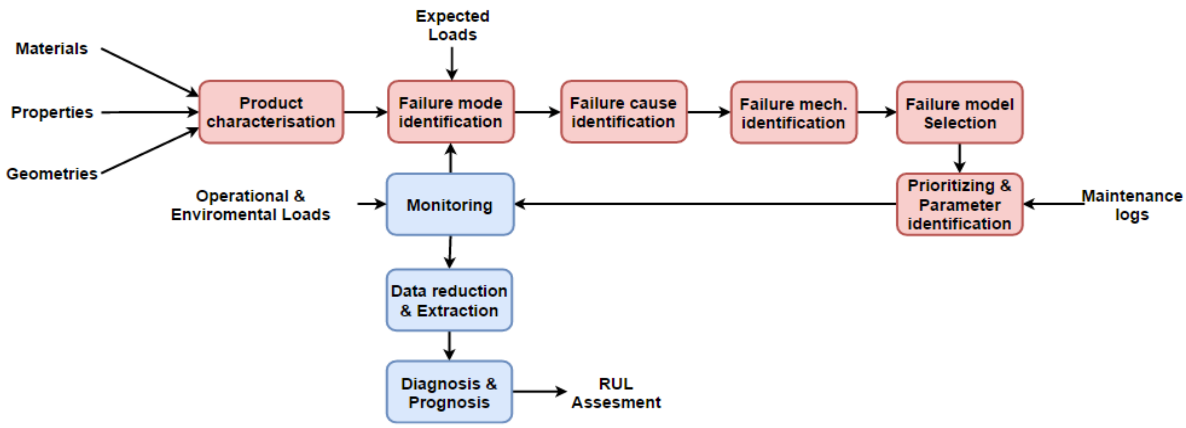


Figure 36. Predictive maintenance implementation procedure. Based on: (Pecht and Gu 2009)

System and failure mode selection

To determine on which system and on which failure mode to focus, a FMMEA analysis can be used. The steps generally comprising an FMMEA are depicted in red in figure 34. It should be noted that with the term *failure cause*, the specific process or condition is meant that initiates failure (e.g. a certain temperature). The *failure mechanism* is a physical, mechanical, chemical, etc. process that leads to a failure. The *failure mode* is the effect by which a failure is observed (See figure 35).

Figure 37. Failure terminology

A FMMEA involves the following steps (Pecht and Gu 2009):

- Characterization of the system on all levels (subsystems, components, interfaces). This involves collecting all information regarding the materials, their properties, and geometries to be able to generate a model.
- Identification of the failure modes by using Finite Element Modelling (FEM), Accelerated Life Testing (ALT), historical data, or expert judgement.
- Identification of an appropriate PoF model for the failure mechanism corresponding to the identified failure modes. See table 2.

Table 3. PoF model selection table. Source: (Pecht and Gu 2009)

Failure mechanisms	Failure sites	Relevant loads	Failure models
Fatigue	Die attach, Wirebond/TAB, solder leads, bond pads, traces, vias/PTHs, interfaces	ΔT, Tmean, dT/dt, dwell time, ΔH, ΔV	Nonlinear Power Law (Coffin–Manson)
Corrosion	Metallizations	M, ΔV, T	Eyring (Howard)
Electromigration	Metallization	T, J	Eyring (Black)
Conductive filament formation	Between metallization	M, ∇V	Power Law (Rudra)
Stress driven diffusion voiding	Metal traces	S, T	Eyring (Okabayashi)
Time dependent dielectric breakdown	Dielectric layers	V, T	Arrhenius (Fowler–Nordheim)

T, temperature; H, humidity; Δ, cyclic range; V, voltage; M, moisture; J, current density; ∇, gradient; S, stress.

Monitoring parameter selection

Although often multiple failure mechanisms are acting at the same time, generally only a few load parameters are responsible for most failures. Typical life cycle loads include:

- Thermal (ranges, cycles, gradients)
- Mechanical (pressure, vibration)
- Chemical (humidity, acidic)
- Physical (radiation, electromagnetic)
- Electrical (current, voltage)

Data reduction and feature extraction

To avoid the need for large storage capacities to cope with the quantity of monitoring data, data reduction methods are required. The sensor signals from monitoring typically are processed using load extraction algorithms. Further data reduction can be achieved by storing the results of this process appropriately, e.g. in histograms (See figure 36).

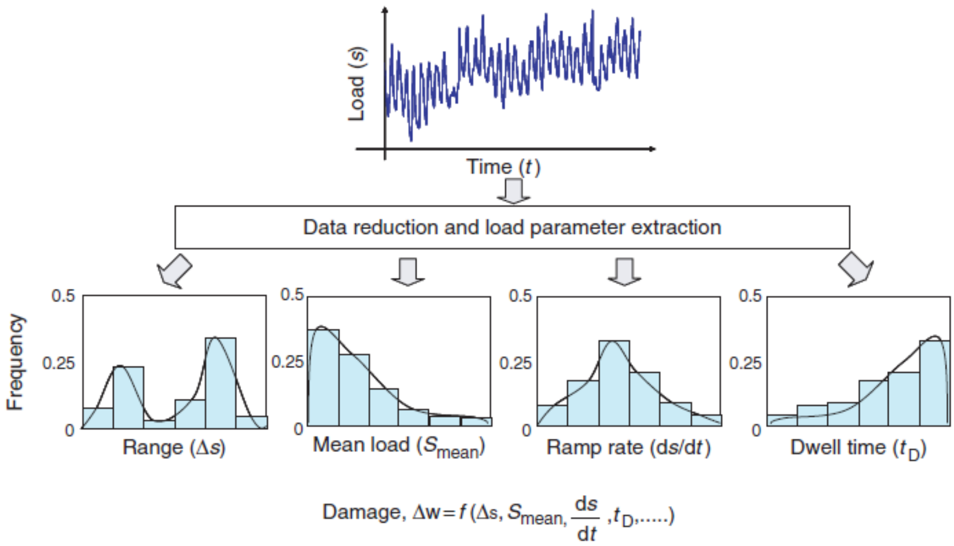


Figure 38. Load feature extraction. Source: (Pecht and Gu 2009)

Diagnosis, prognosis, and decision making

The extracted load features are, possibly after domain transformation, used as the input of PoF model to calculate the damage (See fig 37). Possibly, measurement data of multiple components is combined into a single index by using an approach as in (Ramuhalli et al. 2014). Finally, from the output of these models over time the 'accumulated damage' is determined. Based on these data points, a RUL prediction (remaining hours, cycles) can be made at which the system is expected to still function reliably. The prognostic approach will be further described in section 3.6.2. Finally, the failure prognoses are used for planning and scheduling of maintenance actions. Often this is performed semi-automatically using decision support systems (App. E, SP4, Q5).

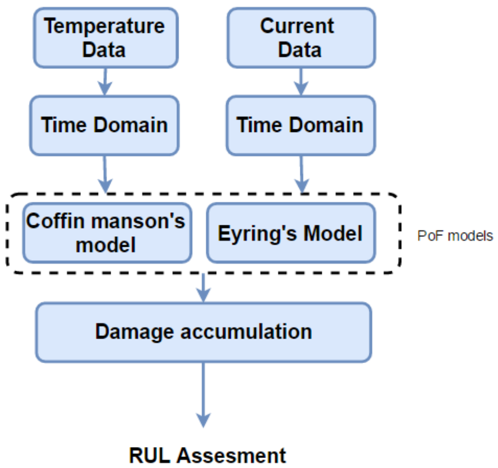


Figure 39. condition diagnosis process. Based on: (Pecht and Gu 2009)

Recovery process selection

Once maintenance has been executed, the replaced system should be recovered by choosing the right recovery process. Zhang et al. (2013) proposes an approach in which an estimation of the RUL is used in recovery process selection. The RUL is estimated and then compared to a threshold quantitatively to determine whether the component should be reused, recycled or remanufactured. To estimate the RUL, the author performs a Weibull analysis such as by Kraijema (2015) and Viswanath Dhanisetty (2014), and trains an Artificial Neural Network (ANN) model based on the characteristic indexes for degradation. Finally, Zhang et al. (2013) develop a decision support tool that stores and visualizes the results of the RUL estimation and recovery process selection. A similar module would need to be incorporated in the future state ISS.

The maintenance module, recovery module as described by Zhang et al. (2013), and for instance the finance module, all need to be compatible and firmly integrated. Tsang (2002) therefore pleas for an enterprise asset management system (EAP) (See figure 38).

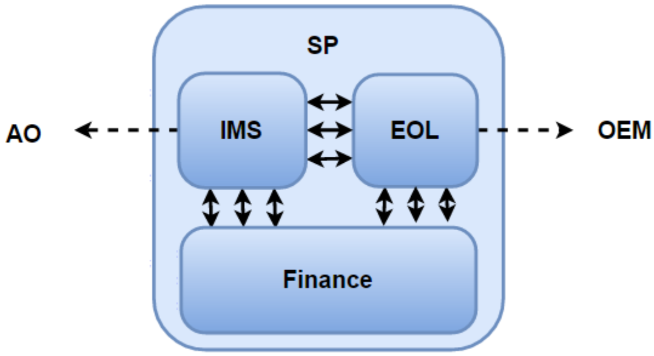


Figure 40. Enterprise Asset Management System at SP

To leverage the benefits of such a system, the author concludes that it should at least support:

- Analysis of life-time distributions, inspections, replacements and EOL decisions.
- Direct communication links with the corresponding modules of supply chain partners.

Being considered as the responsible and executing party within the proposed setup, the SP requires the support modules to be installed with all features as described. The AO, and OEM at least need to be able to access the results of the analyses to avoid information asymmetry.

3.4.3. Hardware requirements

As was described in chapter 2, there currently is no physical infrastructure capable of providing real-time remote monitoring of movable bridges. In practice, an AO operator calls the SP once ‘a failure’ has occurred. To implement the processes as described in the previous chapters, several improvements to the information infrastructure are required. In the rail sector, and even within the AO organisation, more advanced ISS’s are implemented. This section will be used to describe the hardware requirements by reviewing both practice and research.

System architecture

In large national infrastructures, such as rail, tunnels and roads, Supervisory Control and Data Acquisition (SCADA) systems are used for control. In practice, large SCADA systems are very like distributed control systems, in which there is distributed autonomous control but also geographically remote supervisory control. An important feature of such systems is their layered structure. On the ‘product’ layer, signals are measured and transformed, whilst at the central unit layer, the pre-processed data is sent for the diagnostic process. The diagnostics module provides an analysis of all the monitored products, allowing for complete view on systems needing maintenance. To be able to perform effective asset management on movable bridges (and other movable infra), it is assumed that a similar control infrastructure should be implemented. See figure x for a schematic representation of a layered control system.

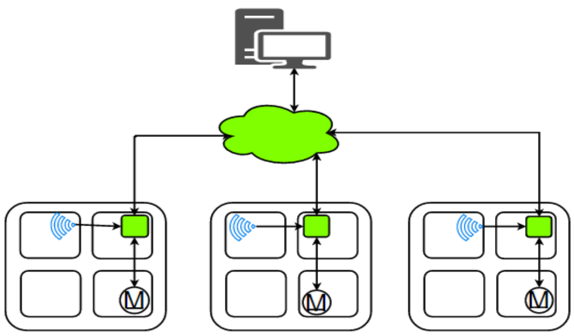


Figure 41. Scada/distributed control architecture

The data obtained from SCADA systems currently under management of the AO, are currently only being used for operational control. SP’s do not have access to the data because AO wants to avoid risks regarding cybercrime. In the rail sector, ProRail has advanced more on this subject. Real-time monitoring and decision making is currently being applied for the maintenance of critical railway switches all over the country (Lidén 2015). Also in sectors with more high tech electronic equipment, supervisory control is applied (App. E, SP4). A description of the state of the art technology regarding these systems will follow.

Decision making

The trend currently seen is that more decision capacity is available locally (Cassina et al. 2009). Vichare and Pecht (2006) expected that future electronic systems would be equipped with algorithm embedded sensors enabling fault detection, diagnostics and RUL prognostics that would ultimately drive the supply chain. The prognostics information will be linked wirelessly to web portals to acquire and deliver replacements on an as-needed basis. Indeed, applications of such technology are becoming visible (Morlet et al. 2016).

Recently, a Watchdog Agent IMS (hardware and software) has been developed from the vision of developing a systematic approach in advanced prognostics (Lee and Wang 2008). The platform facilitates decision support tools, data storage, and device-to-business (D2B) system level connectivity (See figure 40). It is assumed that a similar system, in which a Watchdog as depicted delivers the local decision power, is suitable in our case.

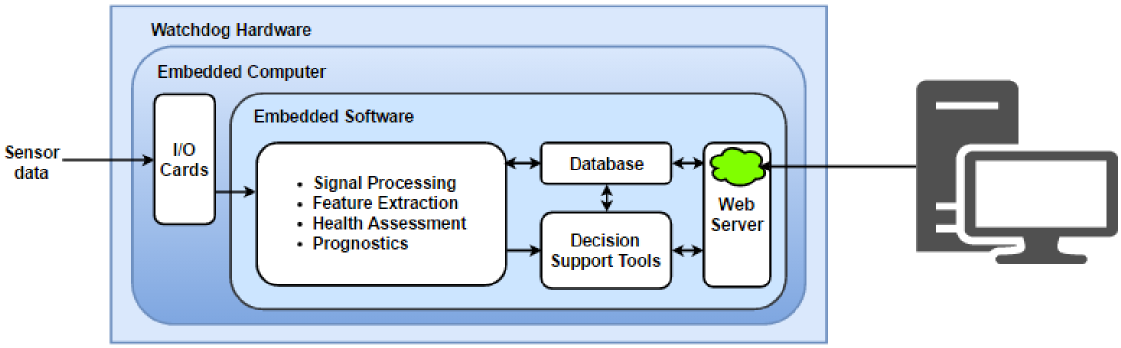


Figure 42. Watchdog systems. Based on: (Cigolini et al. 2009)

Data Acquisition

The Watchdog agent is embedded onto machines and converts multi-sensory data to machine condition information locally, by using the processes as described in section. In-situ data can be monitored from different sites (system, components, interconnections) using built-in or external sensors (N. Vichare and Pecht 2006). Because of the choice for load based maintenance, the required sensors will be relatively simple. It is assumed that just as in the paper by Ramakrishnan and Pecht (2003 and N. Vichare and Pecht (2006), simple integrated temperature and current sensors will be deployed.

Data transfer and communication

The extracted information is transferred wirelessly, automatically triggering service. N. Vichare and Pecht (2006) mention that RFID technologies are the most common method of achieving the communication and storage of information locally. RF technologies provide, amongst others, the following functionalities on which application scenarios can be based (Muller et al. 2009):

- Localisation and identification of systems
- Tracking and recording relevant data throughout lifecycle

Wan and Gonnuru (2013) propose to use these functionalities of RFID to support disassembly decisions for end-of-life products. A Bayesian classification method is used to translate the lifecycle data on the RFID into a quality index. A fuzzy logic model, solved with a genetic algorithm, synthesises the input variables (product usage, component usage and component condition) into a maximized profit disassembly plan. The authors claim to have verified the merits of applying RFID to improve disassembly decisions. For data transfer to and from remote control centers, most often a secure internet connection is used (Lee and Wang 2008; App. E, SP4, Qx). Recently, the AO has implemented similar technology for monitoring of dynamic road signs, using the network of the largest Dutch telecom provider (KPN) (Peelen 2016).

3.5. Intermediary Conclusions

3.5.1. Promising future practice

From the previous chapters, it was learned that the future demands a strategy resulting in less downtime, and a smaller carbon footprint. It has become clear that improved information on the state of the electronic systems is required to accomplish this. Due to a lack of knowledge on how to approach this both technically as organisationally, such innovations have yet failed to break through. Based on the practice research from chapter 2, and literature review in section 3.1 to 3.4, the following promising approach was identified:

- Between the AO, SP, and OEM, long term collaborative relations should be developed to improve the sharing of information, ensure a fair distribution of the costs and benefits, and thereby increase the performance of the supply chain. To enable these collaborative relations, the Ministry of Infrastructure and Mobility should develop laws and regulations that allow for the development of innovative contract forms between, and business models of the stakeholders.

- For non-strategically vulnerable electronic assets, such a change in collaboration could comprise a collaborative relationship between the OEM and SP on the one side, and a customer-supplier relation between the SP and AO on the other. In the collaborative agreement, the OEM would design and deliver technical systems according 'Eco-design' standards, whereas the SP would fulfil the role of contract remanufacturer under a credit-based, OEM certified, remanufacturing contract. Between the AO and SP, a long-term use based contract would be established in which the SP has an incentive to invest, environmental performance criteria are concretized, and there is improved communication between the AO and SP before, during and after the contracting process.

- The SP/OEM combination could adopt a 'remanufacturing-with-upgrade' product service system, by implementing product level monitoring, decision support systems, and consequently executing a load based predictive maintenance policy with complementary remanufacturing. A SCADA-like ISS with Watchdog functionality could fulfil the hardware requirements.

It should however be considered that in practice, the SP would only engage this scenario if the operational expenditure (OPEX) benefits weigh up to the required capital expenditure (CAPEX). A reduction of downtime and the carbon footprint will only be pursued when cost effective. For movable bridges, improving the quality of information is expected to primarily improve cost performance by reducing the workload caused by unexpected failures. It is not expected that remanufacturing activities itself will be profitable. It is expected that a regulatory incentive would be required at least on the short term. Clearly, more insight is required into the costs and benefits of implementing the future state as proposed.

Now that both practice and literature have been explored, a refined research objective can be defined as recommended by Dul and Hak (2008).

3.5.2. Refined objective

The refined objective is to quantify the trade-off between the cost performance, environmental performance, and operational performance of the future state as proposed, to identify a situation in which implementation becomes profitable within 10 years.

3.5.2. KPI's

In order to quantify the costs and benefits of the proposed changes, both current and future state will need to be assessed considering several Key Performance Indicators (KPI's). These KPI's can be derived from current practice and need to reflect the objective as good as possible. Tsang (2002) classifies maintenance related KPI's into cost performance (e.g. maintenance costs), process performance (e.g. eco-efficiency), and equipment performance (e.g. availability). From each of these classes, one KPI relevant to this research will be described.

Operational Expenditure (OPEX)

The cost performance is predominantly determined by personnel costs, which are incurred on an operational level. Hence, the focus will be on estimating these OPEX by generating operational schedules and routes. To assess the profitability of the future state scenario, the *Return on Investment* (RoI) is evaluated. The RoI is made up out of the following components:

- OPEX
- CAPEX
- Revenue

Both CAPEX and Revenue components are estimated based on examples from practice. When the RoI becomes 0%, the break-even point of the investment has been reached. More information can be found in section 3.6, 9.1 and appendix E.

Total Emissions (TEm)

As was described in the introduction, reducing the carbon footprint is an organisational target for the AO. Soon, this 'target' can become paramount for the AO as well as the SP, as governmental organisations are converging towards a CO_2 tax. Increasing recovery through remanufacturing directly affects the amount of virgin raw materials, and therefore the total CO_2 emissions, required for delivering an (as good as) new product. In section 3.6 there is elaborated on how the CO_2 emissions are modelled.

Total downtime (TDT)

The availability of movable objects and its technical installations is an important factor in the performance contract between AO and SP. This KPI reflects the amount of unplanned downtime, which is a large nuisance for the users of an object and the reputation of the AO.

It should be noted that the KPI values at which implementation of the future state becomes feasible differs per case. It is therefore that there is chosen to introduce these boundary conditions during the scenario description in chapter 6.

3.6. Theoretical framework

Now that the objective has been refined and KPI's are identified, it should be found out what kind of theoretic scope is suitable to test the hypothesis. The goal is to identify theories and techniques that can be used to model the relation between the KPI's and the factors or processes that were found to affect these KPI's.

The main issues for modelling the object of study (the maintenance and end-of-life policy for electronics) are that:

- There is no accurate data to model the current state
- The proposed future state is a fictive situation

These facts make that a lot of assumptions and estimations have to be made, which will result in high uncertainties. According to Carson and Maria (1997), a simulation modelling is a suitable approach to explore the effects of different courses of action in situations that do not yet exist. This requires the development of a mathematical model of the process under consideration, as well as an implementation that allows to show the behaviour of this model over time. Decision support tools can help in reducing uncertainty by experimenting with different values, and getting an impression of the importance of data. According Dekker (1996), decision support tools should be used in the area's where they yield most benefits. Because of the KPI scores are affected by processes that take place on an operational level (transport, servicing), the tool should consider operational decision making processes. The models describing this process would very much resemble the processes that would be executed on embedded software of a watchdog system. Though because of the focus on the cost-benefit trade-off over time rather that real time coordination of the crew, this resemblance is strongly simplified.

Regarding the above, the remainder of the research will focus on simulating the crew scheduling and routing processes, by building a simulation based decision support tool. This tool should provide the possibility to test the research hypothesis by:

- Allowing for an assessment of the effect of different levels of quality of information (QoI), resembling manual periodic inspections (current state) and automated monitoring (future state), on the KPI's (OPEX, TEm, TDT), over a certain time horizon

The expected relation between improved quality of information on the one hand, OPEX, TEm and TDT on the other, is depicted in figure x. Note that because the relation between CAPEX is not modelled, a dashed line is used to indicate the relation.

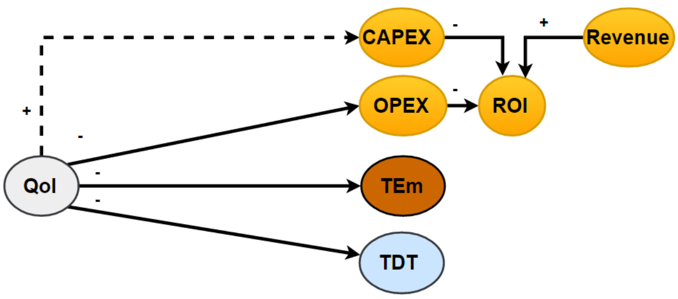


Figure 2

This hypothesized relation could be verified and quantified by modelling:

- The time framework that is relevant to the research hypothesis
- The degradation and failure behaviour of geographically dispersed electronic systems
- The process of using/not using the degradation data to schedule maintenance actions
- The transport movements of the SP maintenance crew according maintenance demand
- The recovery processes executed on replaced electronics transported back to the depot

In the following subsections, the modelling techniques that are used to this end are deducted and described.

3.6.1. Simulation

The tool model must consider degradative behavior information, obtained from prognostics, over a certain time horizon. The model within the tool should therefore be classified as dynamic. In a review of maintenance models by Dekker, Wildeman, and van der Duyn Schouten (1997), the authors conclude that a Rolling Horizon (RH) approach is very effective to this respect, because it combines the advantages of both finite and infinite horizon models. RH models progress incrementally through an infinite horizon by considering finite horizons along the way, thereby yielding more stable solutions and providing more insight in the actions that are taken. See figure 42 for a schematic representation of the rolling horizon procedure.

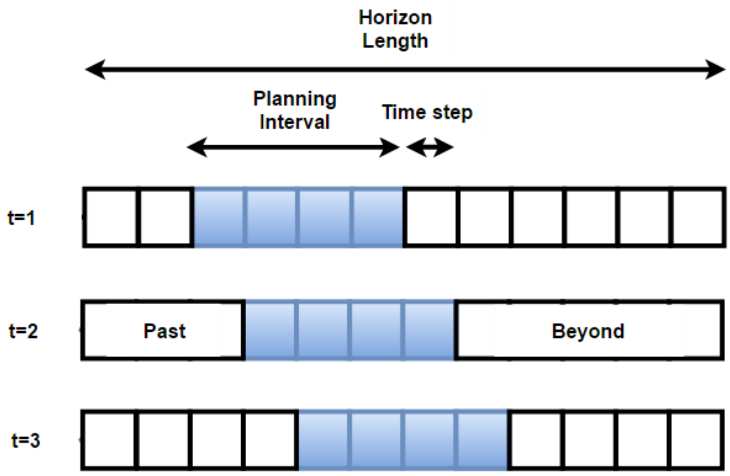


Figure 44. Rolling horizon procedure

The rolling horizon is characterised by the following parameters:

- Horizon Length (H) (total time span considered by the model)
- Time Step (t) (number of time steps the horizon is 'rolled' after each run)
- Planning Interval (T) (total time steps considered each 'roll' of the horizon)

The used parameter values will be described in chapter 9.

3.6.2. Mathematical Model

Next, an appropriate mathematical formulation for the object of study should be deducted. Murthy and Jack (2014) advocate that the systems approach is the most appropriate method to determine this. The systems approach as described in INCOSE (2015) involves system characterisation, building a mathematical model and analysing and optimising the model. In the previous, it was already listed which aspects should be included in the model. See figure 41 for a schematic representation of the model as intended. Note that the dashed lines depict transport distances between geographical locations (objects, SP depot), and the red dotted lines represent information flow.

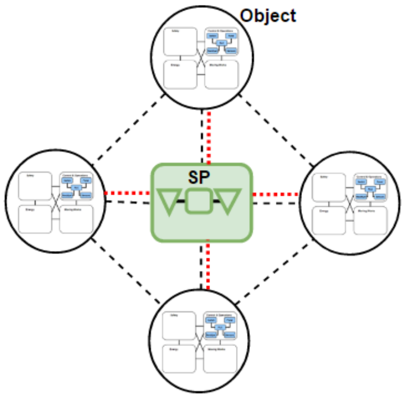


Figure 45. model outline

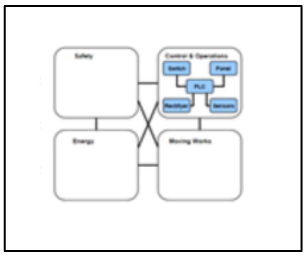
In the remainder of this subsection, the model as depicted in figure 41 is split into three sub models:

- A model on system level describing the electronic systems degradation and failure behavior
- A model on infrastructure level that links the geographically dispersed systems to OPEX, TEm and TDT, by modelling the maintenance logistics (prognostics, scheduling and routing).
- A model on depot level that links the replaced electronics to the CO_2 emissions by modelling the recovery processes.

This setup is used to enable easy adaption of the model in future research. Within our scope, the focus will mainly be on the infrastructure level model. The system level model and recovery model are significantly simplified and are left for further research. The following sections will be used to describe the sub models in more detail.

System level model

The model should link the effect of degradation and maintenance actions to the availability of the overall system. Maintenance optimization methods are the conventional approach in combining reliability with economics in a quantitative way, and are eminently suited to make scientifically justified statements to this regard. In general, maintenance optimization models cover four aspects (Dekker 1996):



- Description of the technical system (see 2.1)
- Modelling of the performance, deterioration, and failure of the system
- Analysis of the available information to the decision maker
- Formulating an objective function with corresponding optimization technique.

In this research, it is assumed that the physical structure of the technical installations is known and fixed, and that the maintenance policy is varied. In practice, the optimization of a predictive maintenance policy on multi-unit systems is done by dynamic grouping methods as in Van Horenbeek and Pintelon (2013), which perform both an individual optimization step as an additional grouping optimization. With the current focus on a single electrical system, such policy optimization is not considered because the savings are not expected to be representative. Alternatively, the two levels of information quality will be compared by means of a simulation scenario study. The modelling guidelines for MO as listed above are however used as a structured approach to identifying the cost-benefit trade-off the maintenance policies. The approach to modelling information will be described further in this section. More on the research methodology will follow in chapter 4.

Modelling performance

Every technical system is designed to perform to certain specifications. Performance measures are often expressed in term of *Reliability*. The definition of reliability is states as follows (Murthy and Jack 2014):

> *The ability of a system to perform a required function, under given environmental and operational conditions and for a stated period of time (ISO 8402 1986).*

Generally, reliability increases with increasing investment in the product development stage. Mathematically, the reliability R(t) of a technical system is expressed as the probability P(t) of not failing to perform its function for a given time period (See equation 1, figure 43).

Equation 1. $R(t) = P(t_f > t)$

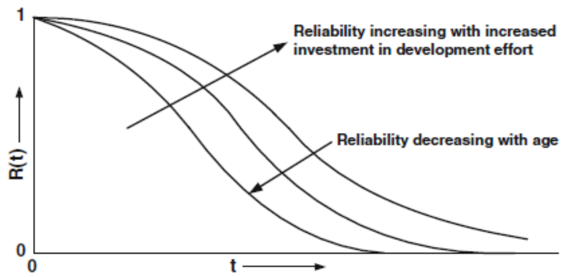


Figure 46. Reliability functions. Source: (Murthy and Jack 2014)

This research focuses on movable bridges, which are designed to provide passage traffic on water, road, or rail with some specified reliability. This reliability is a function of the system *condition* or *state*, which in turn depends on the condition or state of its elements. Maintenance modelling of these discrete elements is similar to that of ‘plants’ as discussed by Murthy and Jack (2014), who link the different system levels by using a reliability block diagram (RBD)

Reliability Block Diagram

In a RBD, each component is represented by two endpoints. When the component is in working state, there is a connection between these points. A system can then be represented as a network of such blocks, again with two endpoints. When a path exists between the network endpoints, the system is in working order. This method is applied on the system as depicted in figure 10, by assuming that all electronic subsystems are critical for a (safely) functioning movable bridge (see figure 44). This is confirmed by both SP3 (App. E, Q10) as the AO2 (App. E, Q1), who add to this that unavailability of critical systems is considered as unavailability in the penalizing process as described in 2.3.2.

From the RBD, a structure function can be derived. The structure function links the (binary) component states to the (binary) system state. The same can be done for component and system reliabilities. The level of complexity of this procedure is related to the dependency of component failures.

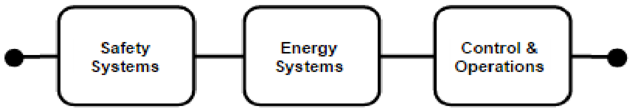


Figure 47. Reliability Block Diagram of Electronics in movable bridge

Multiple geographically dispersed movable bridges can be regarded as a fleet, which is characterised as a multi-unit system in which each unit operates independently, and a failure of a unit does not result in failure of the whole system. According to Murthy and Jack (2014), statistical dissimilarity because of differences in age, use pattern, etc. needs to be taken into account when considering fleet maintenance. For each system, the failure probability at model initialization will be randomized by using a uniform distribution between 0 and 1. Thus, a 'warm start' is assumed in which the initial failure probabilities approach the expected steady state.

Modelling Degradation and failures

The reliability of a technical system decreases with time and usage, as operational and environmental loads induce failure mechanisms. As was described in section 3.2.1, this degradation can be modelled as accumulated damage in the case of electronics. The variable X(t) is used to express this accumulated damage, where t=0 corresponds to a (as good as) new component that is being used for the first time. A higher value of X(t) thereby implies greater degradation (See curved line in figure 42). In practice, X(t) would change continuously and stochastically over time due to the variance in operational loads (current) and environmental loads (temperature). In the example of an integrated circuit board, degradation for instance occurs due to thermal cycling induced fatigue of the board connections.

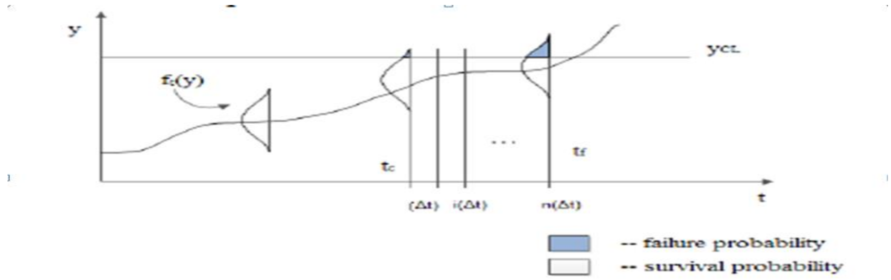


Figure 48. Degradation curve and corresponding failure probability. Source: (Hu et al. 2014)

The probabilistic complement of R(t) is the cumulative failure distribution F(t), which is expressed as the probability of failure before time t:

$$\text{Equation 2.} \quad F(t) = 1 - R(t)$$

Therefore, as the reliability of a technical system decreases due to degradation, the failure probability increases (see blue area in figure 42). The rate of this failure probability increase depends on several factors, such as the design, stresses, and/or previous maintenance actions. The failure behaviour of technical systems can be described by the *hazard function* or *failure rate function*, which is defined as follows:

Equation 3. $\lambda(t) = \frac{f(t)}{R(t)}$

For electronic systems throughout their in-service life, three different failure rate phases, or failure regimes, can be observed:

- Burn-in phase: infant mortality failures occur, e.g. due to factory defects
- Useful life: random failures (Rf) occur
- Aging: wear out failures (WOf) occur, due to accelerating degradation

The curve that describes this behaviour is often called the *bath tub curve*, which is a mixed distribution with subpopulations (See figure 46).

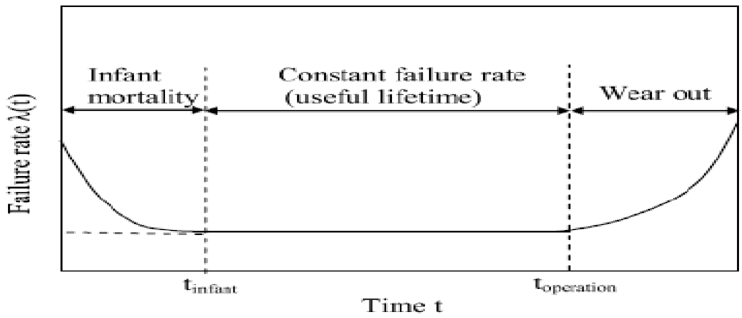


Figure 49. Bathtub curve

The Weibull function is often used to model these regimes, because it can take on the characteristics of different distribution functions by varying its parameters.

Weibull distribution

The Weibull probability density function (see eq. 4) can describe different failure behaviours by varying its shape parameter (β), scale parameter (η) and location parameter (γ).

Equation 4. $f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$

The effects of these parameters are defined as follows:

- The shape parameter (β), also known as the slope, reduces the probability density function of the Weibull function to that of other functions at certain values. When β has a value of 1, the pdf reduces to the negative exponential pdf, describing the behaviour of the constant failure rate regime as depicted in figure 46. When β ≈ 3.4, the pdf reduces to a normal distribution, resembling wear out (accelerated) failure. The effect of varying the shape parameter is depicted in figure 47.
- A change in the scale parameter (η), or characteristic life, has the same effect on the pdf as changing the x-axis scale. Since the area under the pdf remains unity, increasing η while keeping β constant stretches out the pdf on the x-axis and decreases the peak. In the constant failure rate regime (β = 1), eta is the time where 63.2% of failures have occurred, and is often used as the mean time that expires between failures (or MTBF)
- The location parameter (γ), or the failure free life, locates the pdf along the x-axis. Changing γ slides the pdf to the right (γ>0) or left (γ<0).

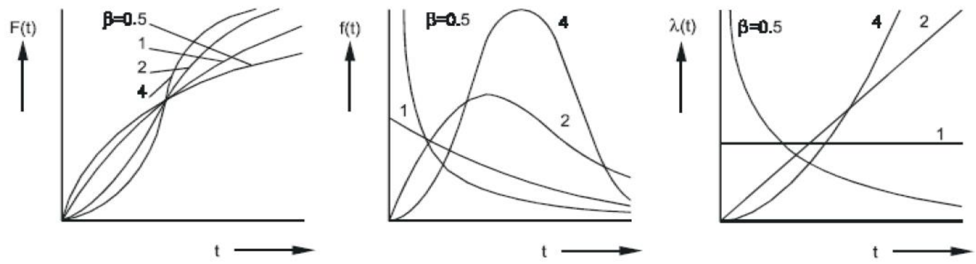


Figure 50. Effect of shape parameter on pdf, CDF, and hazard function

In this thesis, a 2-parameter Weibull distribution is adopted (β, η, 0). Normally, these parameters are estimated by using historical data as in (Haans 2016; Kraijema 2015). Because this data is not available, the failure behaviour will be modelled according the following assumptions:

- The electronic systems have undergone a burn-in procedure as in Kalgren et al. (2007), which is assumed to remove the possibility of infant mortality, and causing them to be installed in the useful life phase.
- The electronic systems are assumed to have a specified lifetime (L), whereof three-quarters is characterised by a random failure regime, and one-quarter is described by an increasing failure rate regime. This is modelled as a switch of β from 1 to 3.4. (see figure 45).
- Each time step, the failure probability increases with an amount that is derived from a linearization of the system CDF within its corresponding failure regime. The procedure and results of the previous bullets are described in appendix E for the system of focus.
- Each time step, the failure probability is used to simulate failure or survival by drawing a random number from a uniform distribution (see figure 46).

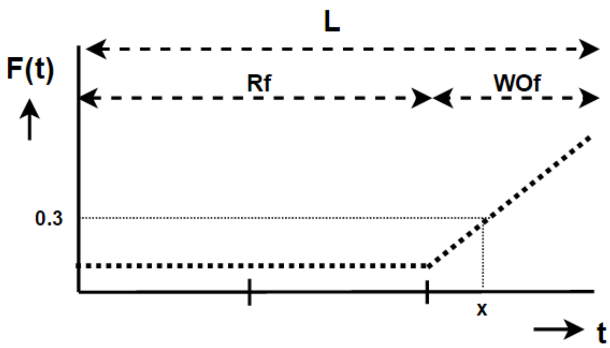


Figure 51. failure probability modelling

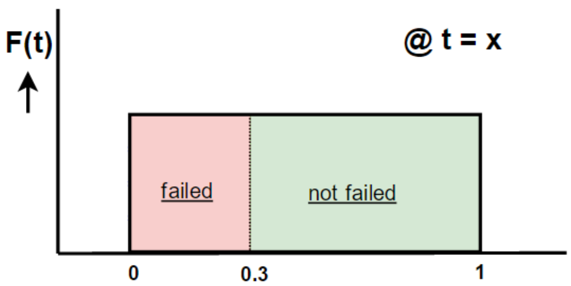
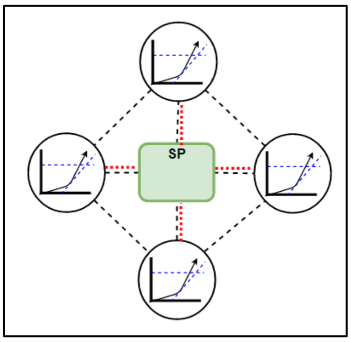


Figure 52. Simulation of survival or failure

Maintenance logistics model



During the scheduling of fleet maintenance actions, a forecast of the failure probability should be used. In examples found in literature, maintenance is often performed when the degradation reaches a certain threshold (Li, Guo, and Zhou 2016; Reimann and Kacprzynski 2009). Camci (2014) however, states that this is not sufficient for maintenance scheduling of geographically dispersed systems such as railway switches, offshore wind farms, etc. The author therefore proposes a method that considers both the forecasted failure probability and the travelling distances during scheduling. The model is called the Traveling Maintainer Problem (TMP), and is closely related to the Vehicle Routing Problem (VRP). The TMP aims to find the most cost-effective routing for the maintenance operator to visit assets that have not yet failed.

Camci (2015) uses a finite horizon formulation in which assigning tasks to days and ordering tasks per day are performed simultaneously. The TMP is less suited to model a dynamically deteriorating fleet on a longer horizon without becoming too large. It is therefore adapted to consider the 'task assignment to days' step and 'task ordering per day' alternatingly in a rolling horizon setting. At every time step, a locally optimized schedule is produced for the current planning interval. Subsequently, the ordering step is performed considering only those maintenance actions that where assigned to the current time step in a previous run. This latter step models the routing of the maintenance crew. The following subsections will consider respectively the forecasting model, scheduling model, and routing model in more detail.

Prognostics

In the models by Camci (2014, 2015), a known time-series prognostic curve is assumed. In practice, such failure probability curves are obtained through performing the data processing steps as described in 3.4.2. Guclu et al. (2010) for instance, use an Auto Regressive Moving Average Model to make a prognosis of the failure progression in railway turnout systems. Because the goal here is to estimate the cost and benefits of prognostics, a Simple Moving Average (SMA) forecasting approach adopted. The n-SMA model (see eq. 5), uses the realizations of the failure probability of n former time steps to forecast the expected failure probability for the time units within the PI. The prognostics module thus looks ahead several time steps equal to the length of the PI (see figure 47)

equation 5.
$$SMA = \frac{P_M + P_{M-1} + \cdots + P_{M-(n-1)}}{n} = \frac{1}{n}\sum_{i=0}^{n-1} P_{M-i}$$

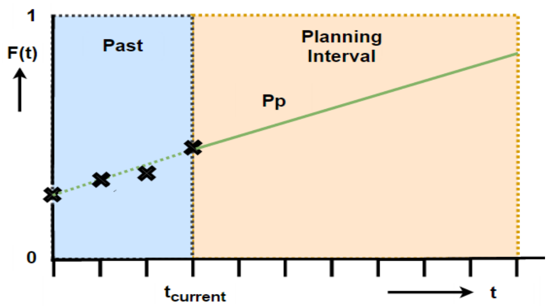


Figure 53. failure probability prognosis modelling

To deal with the uncertainty of prognostic approaches related to measurement errors, parameter estimation errors, and future use approximation errors, Pecht and Gu (2009) describe a combination of sensitivity analysis and Monte-Carlo approximations to identify confidence bounds. In this research, only a simple parametric sensitivity analysis will be performed to understand model behavior (see chapter 9).

Scheduling

Scheduling is adopted as the term for assigning maintenance tasks to days within the PI. During scheduling with prognostic information, a trade-off is made between costs of performing maintenance and the costs for not performing maintenance. Since hypothetical situations are considered during this process, expected failure probabilities are used during calculation. As in Camci (2015), the expected failure probability of a system at time t is obtained from prognostics (P_p) if no maintenance is scheduled before t, and obtained from reliability analysis (P_R) when maintenance is scheduled before t. See figure 47.

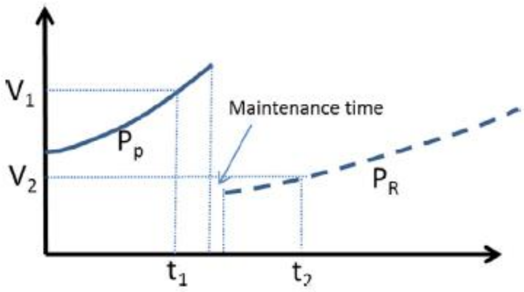


Figure 54. Expected Failure Probability curves. Source: (Camci 2015)

This can be explained by considering that after a system is replaced, there is no link between the forecasted failure probability and the new system. In order to take this effect into account during scheduling, Camci (2015) introduces a variable that describes the cumulative failure probability of a system on a certain day ($P_{i,t}$) (see eq. 6)

$$\text{equation 6.}\ P_{i,t} = P_{P,t} * \left(1 - \min\left(\sum_{k=1}^{t} x_{i,k}\,, 1\right)\right) + P_{R,t-LM_i} * min\left(\sum_{k=1}^{t} x_{i,k}\,, 1\right)$$

Where:

- $P_{P,t}$ is the failure probability of asset i at time t obtained from prognostics
- $P_{R,t}$ is the failure probability of asset i at time t obtained from replacement specs
- LM is the time of last maintenance, if no maintenance is scheduled LM = PI+1
- $X_{i,k}$ = 1 if asset i is scheduled for maintenance at time k, 0 otherwise
- $Min(\sum x_{i,k}, 1)$ is the Heaviside function, representing a variable that does not change again after changing from 0 to 1 after a specified time

This variable considers both the prognostics curve as the replacement curve, and the parameter $x_{i,t}$ is used during optimization to determine the optimal time unit for scheduling a maintenance task on a system. This process is depicted in figure x for a single system and single PI.

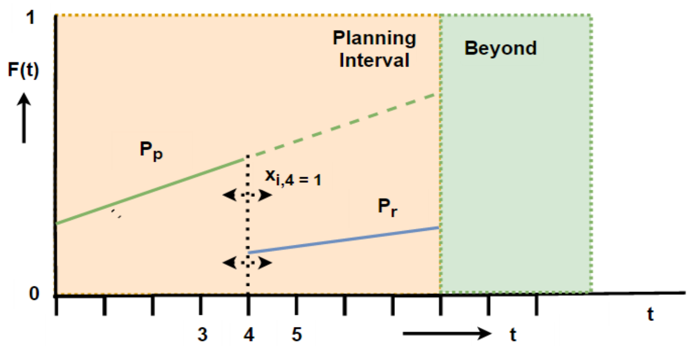


Figure 55. Schedule optimization procedure

During scheduling, equation 7 is minimized by considering all solutions (summation over days in schedule and assets in service area).

$$equation\ 7.\ \min \mathrm{z} = (C^f + C^M)$$

Where:

- C^f are the total expected failure costs
- C^M are the total expected maintenance costs

The solution algorithm thereby finds the time for maintenance at which the aggregated (expected) failure costs and maintenance costs for each asset are minimal. The following subsections will describe the modelling of the respective cost components. The solution algorithm will further be described in section 7.3.

Failure Costs

The costs of failure (C^f) typically consist of direct failure costs and indirect failure costs (Murthy and Jack 2014). Similar to Camci (2015), the costs for carrying out a CM action are considered as direct failure costs, whereas the indirect failure costs consider costs of downtime. Because of the focus on a single electronic system, and replacements are considered a routine job, the costs for carrying out a CM action are modelled into a single deterministic parameter C_{CM} (direct failure costs). The indirect failure costs are calculated by multiplying the expected duration of downtime (DT) during failure, by the costs per unit downtime (δ). The total expected failure costs are then obtained by multiplying $P_{i,t}$ with the total failure costs. See eq. 8.

$$\text{equation 8.}\ C^f = \sum_{i=1}^{n}\sum_{t=1}^{T}\left(P_{i,t} * F_i + DT_i * \delta_i * P_{i,t}\right)$$

Maintenance Costs

The maintenance costs (C^M) are the sum of the scheduled maintenance costs within the planning interval. However, if the system fails before scheduled maintenance, then the maintenance is not performed (Camci 2014). The expected maintenance costs are therefore determined by multiplying the costs for a PM action (C_{PM}) by the probability of performing a scheduled maintenance action (See eq. 9).

$$\text{equation 9.}\ C^f = \sum_{t=1}^{T}\sum_{i=1}^{n}\left((1 - P_{i,t}) * (x_{i,t} * \gamma_i)\right)$$

Like C_{CM}, C_{PM} is modelled as a single deterministic parameter. C_{CM} is considered larger than C_{PM} because CM actions do not allow for efficient planning.

Information

To differentiate between the current state and future during the simulation experiments, different levels of information should be considered. This is done by assuming that in the current state, a forecast of the failure probability is not considered and failure is more likely to take place as degradation continues. This eventually ends in failure, resembling the run-to-failure approach. In the future state, prognostic information is used during scheduling, thereby allowing for scheduling maintenance actions before failure. The differences in cost-benefits incurred during both scenarios is considered the value of information.

Routing

The maintenance crew performs the daily schedule by ordering the tasks on importance and executing them accordingly. The crew drives along the assets in the determined order and performs the replacements. During the execution of scheduled tasks however, unexpected failures can occur. Typically, such unscheduled tasks have priority over the remaining scheduled tasks since these they add to the overall downtime. The modelling of the crew routing will be described in the next subsection. Incorporating maintenance actions on the performance of the physical systems will be described in the subsection thereafter.

Crew routing

One of the most well-known network problems is the traveling salesman problem (TSP). The TSP is an NP-hard combinatorial optimization problem that aims find the shortest possible route (Hamiltonian path) that visits all 'customers' exactly once and returns to the origin city. The TSP is a special case of the VRP, which aims to minimize the total routing costs of K vehicles to n destinations. In a paper by Pillac et al. (2011), a VRP is used for modelling maintenance operations. Both the TSP and VRP essentially boil down to minimizing the transportation costs (time, distance). In a use-based business model as proposed however, a more 'customer-centric' model is required. Blum (1994) describes the TSP related Minimum Latency Problem (MLP), which aims to minimize the sum of path lengths (or waiting times) to all locations in the network. A special case of the MLP is the Traveling Repairman Problem (TRP) such as defined by Ezzine, Semet, and Chabchoub (2010). Here, the locations of assets that have already failed are known, and the objective is to find a route that minimizes the total downtime. The model considers both the travelling times and repair times up until arrival. The TMP by Camci (2015) considers the other extreme, in which the aim is to find the most cost effective routing of a maintenance crew performing maintenance actions on geographically dispersed assets that have not yet failed. The author assumes that the failure probabilities do not vary within a time unit and assets are visited based on travelling convenience. The routing is thereby affected by the RUL obtained from prognostics, and the distance of each asset.

In the current case, the model should consider the distinction between assets that have not yet failed (as in the TMP), and those that failed unexpectedly (as in the TRP). This requires the incorporation of their priorities within the optimization model. Balcik, Beamon, and Smilowitz (2008) considered visit priorities during routing by minimizing artificial penalty costs. The amount of the penalty costs of a location is weighted by the locations priority. Here, the priority factors corresponding to a certain location will be used within a constraint that forces the locations with the highest priority factors to be visited first. By randomly assigning priority factors to corrective maintenance tasks, the occurrence of unexpected failures across the day are mimicked (See figure 49 and 50).

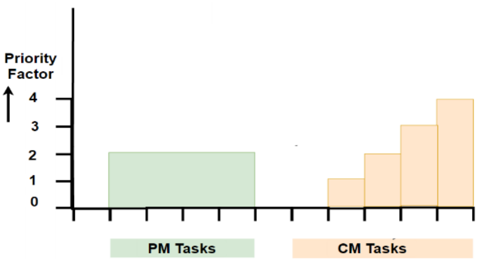


Figure 56. Priority factor distributions

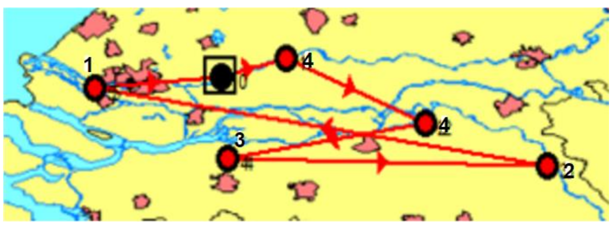


Figure 57. Network plot with priority constrained route

It will furthermore be assumed that each visit resembles the ‘collection’ of ‘supply’ to be transported to the depot after visiting all locations as in Rommert Dekker et al. (2003). A reformulation of the TRP by Angel-bello, Alvarez, and García (2012) will be used in chapter 7 as the base-model for crew routing. A multilevel network representation of this model, where the levels resemble the visit order or a location within the route, is depicted in figure 51.

Because of the rolling horizon setup adopted in this research, each time step the single period (adapted) TRP is solved based on the task list which was obtained from prognostic based scheduling and failure simulation. In practice, a dynamic TRP would be required to deal with real-time dynamic information from communication between the vehicles and supervisory system. This was researched by Borenstein et al. (2010) and is out of scope here.

Maintenance actions

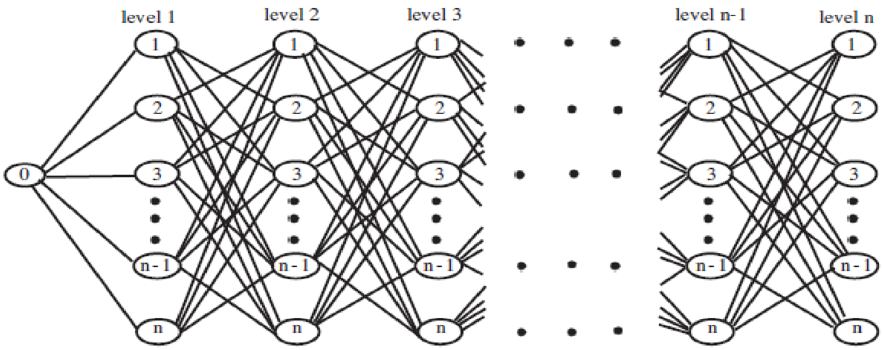


Figure 58. multilevel network represenation of TRP. Source: (Angel-bello, Alvarez, and García 2012)

Technical systems can be repairable or non-repairable. Non-repairable systems can only be replaced whereas repairable systems can either be replaced by new or repaired (minimal, imperfect). Electronic systems suffering a wear out failure are assumed to be non-repairable and therefore only on-site replacements are considered. Replacements can be performed unplanned (CM) or planned (PM), which are modelled as a restoration factor and a downtime.

Restoration factor

The effect of replacements on the performance of an asset is modelled by using a restoration factor. In the current state, such replacements involve new systems. In a future state with remanufacturing, as-good-as-new replacements are assumed. In both cases, the failure probability of the object is reset to ‘as new’ value by assuming a ‘perfect repair’ of the object as depicted in figure 52.

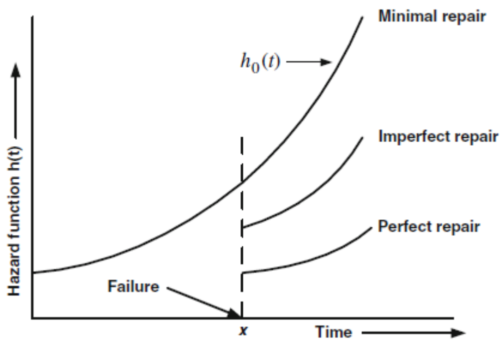


Figure 59. Restoration factor. Source: (Murthy and Jack 2014)

Downtime

Downtime is characterised by two events, namely the failure of the system and the system being put back into operation after replacement. The time in between these two events is usually larger than the repair time only, as depicted in figure 53.

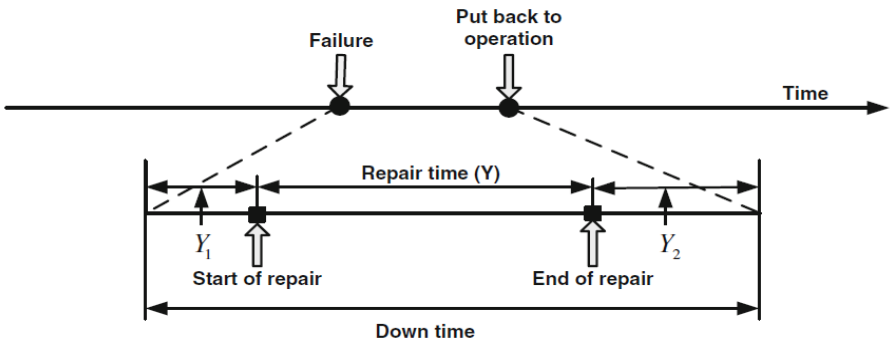


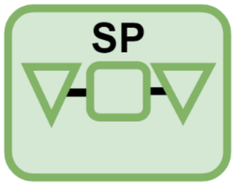
Figure 60. Downtime and repair time. Source: (Murthy and Jack 2014)

When, as in this case, maintenance is carried out on site, the downtime is equal to the repair time (Y) plus the travel time (Y1). In practice, the dominant repair time factors for electronics are the investigation time (detection, response), and diagnosis time. The time for carrying out the actual replacement is often negligible (App. E, CON3, Q2). The repair time factors are aggregated into one deterministic variable. The effect of improved information will be modelled by decreasing the investigation and diagnosis times, thereby decreasing the downtime due to a failure. PM actions are assumed to result in less downtime than CM actions. The travel times are modelled by using a symmetric distance matrix between objects and constant vehicle speeds (See Eq. 10).

equation 10. $DT = RT + TT$

$$DT = \left(t_{detect} + t_{response} + t_{diagnose} + t_{replace}\right) + \sum \frac{dist}{v}$$

Recovery



In the future state, a remanufacturing recovery network is added to increase the EOL value recovery of electronic assets. The electronics that are transported back to the depot are put in stock before a batch of replaced systems is reprocessed. Based on input from SP3 (App. E, Qx), it is assumed here that the recovery processes are performed monthly.

Because the 'inspection' of the collected systems have been performed decentral through monitoring while in-service, the recovery processes (ordering spares, scheduling personnel) can be planned beforehand. As was mentioned before, the RUL values of replaced systems can be used for process selection. Here it is assumed that all preventively replaced systems (RUL>0) are remanufactured whereas correctively replaced systems (without RUL<0) will be sold off to (low grade) recyclers (see figure 51). This is assumed as a 'purge' of value from the supply chain as in Fleischmann (2001). See figure 54 for a schematic representation of this process.

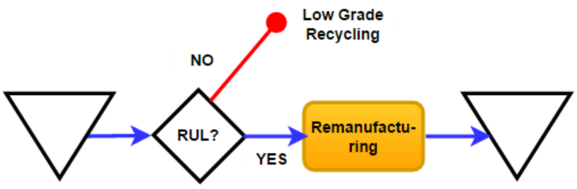


Figure 61. Recovery process modelling

A distinction will hereby be made between the amount of CO_2 emitted per correctively replaced system (which induces the production of a 'new' replacement), and the amount of CO_2 emitted per preventively replaced system (which induces the production of the 'worn' component to remanufacture the replaced asset into a AGAN replacement).

4. Mathematical Model

This chapter presents the results of applying the theoretical framework: the decision support tool to test the hypothesis with. In the remainder of this chapter, further assumptions regarding the situation to be modelled are listed in section 4.1. In section 4.2 the conceptual model is presented, consisting of the symbolic representation of all sets, parameters, and decision variables. The solving approach for the combined model, including the software implementation, will be described in section 4.3

4.1.Assumptions

To arrive at the conceptual model presented in section 4.2, the following assumptions were made:

- Every day a maintenance schedule is performed by a single crew that starts and ends at the depot, sequentially visiting all systems in the task list. The daily workload of the crew is not directly constrained by a maximum shift length.
- Assets degrade during operation (discretized for problem formulation), causing their failure probability to increase. Maintenance is scheduled when the assets have failed or when the expected failure costs outweigh the costs for maintenance.
- Degradation within a time unit is ignored and scheduling within the time unit is performed based on priority factors. It can thus be said that maintenance in the morning is considered the same as maintenance in the afternoon of the same day when the expected failure probability is concerned.
- Because electronic assemblies are often relatively small, it is assumed that the replaced electronics as well as the replacement parts will always fit into the crew vehicle. Vehicle capacities are therefore not considered.
- The relation between planned and unplanned maintenance on one hand, and CO_2 emissions on the other, are modelled by a simple counter. The costs for remanufacturing are not considered
- Inventories are not considered, because the collected volumes are expected to be modest compared the average service provider depot size.

4.2.Formulation

In the following subsections, the mathematical formulation decision support tool is presented. Note that the formulation is split up into different sections that, apart from the general parameters, resembles the setup of the maintenance logistics model as described in section 3.6.2.

4.2.1. General

Sets & Indices

H	$Set\ of\ time\ units\ in\ Horizon$	$index$	t	$\in H$
PI	$Set\ of\ time\ units\ in\ Planning\ Interval$	$index$	t	$\subset H$
L	$Set\ of\ locations$	$index$	l	$\in L$
A	$Set\ of\ assets$	$index$	a	$\in A \subset L$
D	$Set\ of\ depots$	$index$	d	$\in L - A$

Parameters

h	$number\ of\ time\ units\ in\ H$	
T	$number\ of\ time\ units\ in\ PI$	
ts	$number\ of\ time\ units\ the\ PI\ advances\ each\ roll$	
m	$number\ of\ locations\ in\ L$	
n	$number\ of\ assets\ in\ A$	
o	$number\ of\ depots\ in\ D$	
Xco_l	$X\ Coordinate\ of\ location\ l$	
Yco_l	$Y\ Coordinate\ of\ location\ l$	
$Dist_{l,l2}$	$Distance\ between\ location\ l\ and\ l2$	$(l \neq l2)$
$v^{vehicle}$	$Average\ vehicle\ speed$	
$t_{l,l2}^{travel}$	$Travel\ time\ between\ location\ l\ and\ l2$	$(l \neq l2)$
C_{invest}^{obj}	$Investment\ cost\ for\ upgrading\ asset$	
Rev^{obj}	$Annual\ Revenue\ from\ service\ fee\ per\ system$	
C_{pers}^{u}	$Personnel\ costs\ per\ work\ hour$	
C_{CM}^{u}	$Execution\ costs\ per\ CM\ action$	$(direct\ \ failure\ costs)$
C_{DT}^{u}	$Downtime\ costs\ per\ failure$	$(inderect\ failure\ costs$
C_{PM}^{u}	$Execution\ costs\ per\ PM\ action$	$(maintenance\ costs)$
E_{prod}^{u}	$CO_2\ emissions\ per\ asset\ produced$	
E_{reman}^{u}	$CO_2\ emissions\ per\ asset\ remanufactured$	
E_{travel}^{u}	$CO_2\ emissions\ per\ km\ driven$	
$t_{CM}^{service}$	$time\ required\ to\ perform\ a\ corrective\ replacement$	
$t_{PM}^{service}$	$time\ required\ to\ perform\ a\ preventive\ replacement$	
$Stock_d^{rec}$	$Stock\ of\ recoverable\ (RUL > 0)\ systems\ at\ Depot$	
$Stock_d^{disp}$	$Stock\ of\ disposable\ \ (RUL = 0)\ systems\ at\ Depot$	

4.2.2. Prognostics

$t_{assetlife}^{spec}$	$Asset\ lifetime\ (total\ health)\ specified\ by\ OEM$
$t_{assetlife,a}^{init}$	$Health\ of\ asset\ a\ at\ the\ start\ of\ the\ horizon$
$t_{assetlife,a}$	$Health\ of\ asset\ a\ at\ certain\ point\ in\ horizon$
F_a^{init}	$Failure\ probability\ of\ asset\ a\ at\ start\ of\ the\ horizon$
F_a^{init}	$Failure\ probability\ of\ asset\ a\ at\ start\ of\ the\ horizon$
$Incr_F^{useful}$	$Increase\ of\ failure\ probability\ per\ unit\ time\ during\ useful\ life$
$Incr_F^{wearout}$	$Increase\ of\ failure\ probability\ per\ unit\ time\ during\ wearout\ phase$
$F_{a,t}$	$Failure\ probability\ of\ asset\ a\ at\ time\ t\ \ = First(t, PI))$
$\Delta F_{a,t}$	$Increase\ of\ failure\ probability\ of\ asset\ a\ on\ time\ t\ compared\ to\ t-1$
$zSMA_a^{\Delta F},_t$	$Simple\ Moving\ Average\ of\ z\ past\ increases\ in\ failure\ probability\ of\ asset\ a$
P_a^P	$Prognosed\ failure\ probability\ progression\ without\ maintenance$
Rd_a	$Random\ number\ to\ simulate\ survival\ or\ failure\ of\ asset\ a$
$y_a^{hl} \in \{0,1\}$	$1\ if\ \ a\ is\ past\ its\ ^3/_4\ life\ point$ $0\ otherwise$
$y_a^{fl} \in \{0,1\}$	$1\ if\ \ a\ has\ failed\ a\ a\ certain\ point\ in\ time$ $0\ otherwise$

4.2.3. Scheduling

Parameters

LM_a	$Time\ of\ last\ maintenance\ for\ asset\ a$
DT_a	$Expected\ downtime\ when\ asset\ a\ fails$
$P^P_{a,t}$	$Expected\ failure\ probability\ from\ prognostics\ of\ asset\ a\ \ at\ time\ t$
P^R	$Expected\ failure\ probability\ progression\ after\ maintenance$
P^R_{t-LM}	$Failure\ probability\ obtained\ from\ (OEM)\ reliability\ specs$ $t-LM\ time\ units\ after\ maintenance$

Decision Variables

$P^{cum}_{a,t} \in (0,1)$	$Cumulative\ failure\ probability\ of\ asset\ a\ at\ time\ t\ (see\ eq\ x.)$
$x_{a,t} \quad \in \{0,1\}$	$1\ if\ asset\ \ a\ is\ scheduled\ for\ maintenance\ at\ time\ t$ $0\ otherwise$

Objective function

$$minimize\ z = \sum_{t=1}^{T}\sum_{a=1}^{n}(P^{cum}_{a,t} * (C^u_{CM} + DT_a * C^u_{DT}) + (1 - P^{cum}_{a,t}) * (x_{a,t} * C^u_{PM}))$$

Constraints

$$\text{constraint 1.} \quad \sum_{t=1}^{T} x_{a,t} \leq 1 \qquad (a = 1,2, \dots, m)$$

$$\text{constraint 2.} \quad x_{a,t} \quad \in \{0,1\} \qquad (a = 1,2, \dots, m; t = 1,2, \dots, T)$$

$$\text{constraint 3.} \quad P^{cum}_{a,t} \in (0,1) \qquad (a = 1,2, \dots, m; t = 1,2, \dots, T)$$

Constraint 1 ensures that for a single asset a, at most 1 maintenance action is scheduled in the PI. **Constraint 2** and **constraint 3** define $x_{a,t}$ as a binary variable and $P^{cum}_{a,t}$ as a continuous variable between 0 and 1 respectively.

4.2.4. Routing

Sets & Indices

PA	$Set\ of\ assets\ planned\ for\ maintenance$	$index\ \ pa$	$\subset A$
FA	$Set\ of\ assets\ failed\ unexpectedly$	$index\ \ fa$	$\subset A$
VA	$Set\ of\ assets\ to\ be\ visited$	$index\ \ va$	$\in PA + FA$
K	$Set\ of\ assets\ on\ tasklist\ by\ visiting\ order$	$index\ \ k$	$\in\ K$

Parameters

f_{va}^{prio}	$Priority\ factor\ for\ visiting\ asset\ va$
$f^{restore}$	$Restoration\ factor\ upon\ maintenance\ for\ asset\ a$
$t_{l,l2}^{arc}$	$Total\ of\ travel\ time\ between\ l\ and\ l2\ and\ repairtime\ at\ l2$
p	$number\ of\ assets\ planned\ for\ maintenance$
q	$number\ of\ assest\ failed\ unexpectedly$
r	$number\ of\ assets\ on\ tasklist\ (p+q)$

Decision Variables

$x_a^{(k)} \quad \in \{0,1\} \quad 1\ if\ asset\ \ a\ is\ visited\ in\ k^{th}\ order\ on\ hamiltonian\ path$

$\qquad\qquad\qquad 0\ otherwise$

$Y_{a,a2_{a\neq a2}}^{(k)} \in \{0,1\} \quad 1\ if\ asset\ \ a\ is\ visited\ in\ k^{th}\ order\ and\ a2\ in\ (k+1)^{th}\ order$

$\qquad\qquad\qquad 0\ otherwise$

Objective function

$$minimize\ z = \ r\sum_{va=1}^{r} t_{d,va}^{arc} * x_{va}^{1} + \sum_{k=1}^{r-1}\sum_{va=1}^{r}\sum_{va2=1}^{r}(r-k) * t_{va,va2}^{arc} * Y_{va,va2}^{(k)}$$

Constraints

constraint 1. $\sum_{k=1}^{r} x_a^{(k)} \quad = \quad 1 \qquad\qquad (va = 1,2,\dots,r)$

constraint 2. $\sum_{va=1}^{r} x_{va}^{(k)} \quad = \quad 1 \qquad\qquad (k = 1,2,\dots,r)$

constraint 3. $\sum_{va2=1}^{r} Y_{va,va2}^{(k)} \quad = \quad x_{va}^{(k)} \qquad\qquad (va = 1,2,\dots,r; k = 1,2,\dots,r-1)$

constraint 4. $\sum_{va2=1}^{r} Y_{va,va2}^{(k)} \quad = x_{va}^{(k+1)} \qquad\qquad (k = 1,2,\dots,r)$

constraint 5. $\sum_{va2=1}^{r} x_{va2}^{(k+1)} * f_{va2}^{prio} \quad \leq \quad \sum_{va=1}^{r} x_{va}^{(k)} * f_{va}^{prio} \qquad\qquad (k = 1,2,\dots,r)$

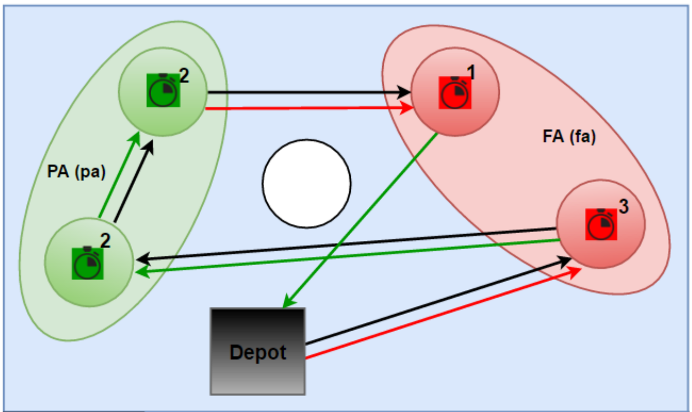
Constraint 1 ensures that each node occupies exactly one position in the Hamiltonian path, whereas **Constraint 2** ensures that each position is occupied by a single node. **Constraint 3** prescribes that in a feasible solution, only one arc can leave a position (level, see figure 52) k in the tour, namely from the visited node at that level. Similarly, **constraint 4** induces that only a single arc enters level k+1, namely at the node that is visited. Finally, **constraint 5** is used to ensure that in the daily tour, the assets are visited in order of descending priority factor.

4.2.6. KPI's

The KPI scores are determined by daily accumulating the following cost factors:

- **OPEX** **Operational Expenditure**
  - TSC Total Service Costs $(\sum_{va=1}^{r} \sum_{k=1}^{q} x_{va}^{(k)} * t_{va}^{service}) * C_{pers}^{u}$
  - TTC Total Transport Costs $(\sum_{va=1}^{r} \sum_{va2}^{r} \sum_{k=1}^{r} Y_{va,va2}^{(k)}) * t_{va,va2}^{travel} * C_{pers}^{u}$
- **TEm** **Total Emissions**
  - TPE Total Production Emissions $Stock_{d}^{disp} * E_{prod}^{u}$
  - TRE Total Reman Emissions $Stock_{d}^{rec} * E_{reman}^{u}$
  - TTE Total Transport Emissions $Stock_{d}^{rec} * E_{reman}^{u}$
- **TDT** **Total Downtime**
  - TTDT Total Transport Downtime $\sum_{l=1}^{m} \sum_{fa=1}^{q} \sum_{k=1}^{q} t_{l,fa}^{travel}$
  - TSDT Total Service Downtime $q * t_{CM}^{replace}$

See figure 60 for a schematic representation of the calculation of the KPI scores. Note that although the actual 'costs' (personnel, emissions, downtime) are incurred during routing, the scheduling efficacy affects the KPI scores by reducing the number of CM actions. See appendix F, figure x for a more abstract representation of this relation.



Component	Driver	Legend
		Service Time
OPEX	#	Failed
TEm	#	Scheduled Priority Factor
TDT	#	Minimum Latency Route

Figure 62. KPI cost drivers

4.3.Solving approach

The approach to solving the joint model should provide a means to couple the different aspects of the model (diagnosis, prognosis, scheduling, routing, and recovery) in a rolling horizon setting. This coupling should furthermore be made visible and allow for manually changing certain input parameters. Software packages that are built around an Algebraic Modelling Language (AML) have proven to provide this flexibility. AML's are high-level programming languages that are typically used for describing and solving complex large scale mathematical problems. Instead of solving those problems directly, AML's provide the possibility to call external algorithms (solvers) to obtain a solution. See figure 61 for a typical outline of the core AML processes.

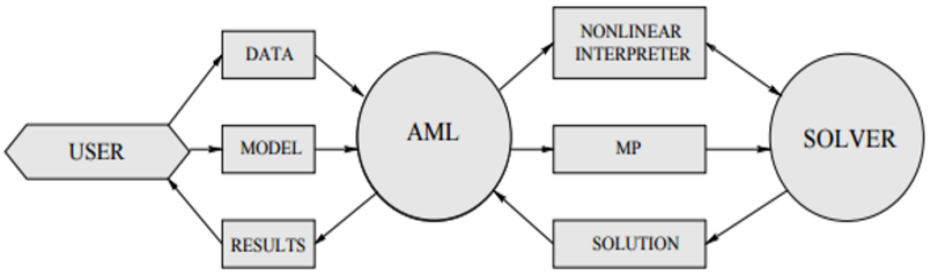


Figure 63. Typical AML outline

Several examples of AML's are AIMMS, AMPL and GAMS, which all have large similarity in the syntax used. Because of the special focus on decision support tool design, AIMMS is selected as modelling software.

Scheduling

The shape of the scheduling objective function can be characterised as $ax2 + bx + c$. The presence of this non-linear term makes solving more challenging since there may by many (local) optima. In highly dynamic scheduling environments such as the one considered here, often global optimization is not cost effective (Balcik, Beamon, and Smilowitz 2008). It is therefore assumed here that locally optimized maintenance schedules are sufficient. AIMMS offers the possibility to approach the problem using an Outer Approximation (OA) algorithm. The AIMMS AO (AOA) is a local nonlinear solver that applies two solvers alternatingly, namely one for the linear sub model and one for the nonlinear sub model. The textual outline of the algorithm is as follows (Duran and Grossmann 1986):

- The entire model is solved with the integer variables relaxed as continuous between its bounds.
- Linearizations are carried out at the optimal solution, of which the results are added to the original linear constraints. The new model is the 'master MIP model'.
- The master MIP is solved.
- The integer part of the optimal solution is fixed, and the nonlinear sub model is solved with fixed integer variables.
- Linearizations at the optimal solution are constructed and new linear constraints are added to the master MIP. Previously found integer solutions are cut off.
- Step 3 to 5 are repeated until the termination criteria are satisfied. Upon termination, the know best solution (not necessarily optimal) is the final solution.

See figure 62 for a schematic representation of the algorithm.

To avoid the locally optimized schedule from changing abruptly due to small input changes, each time the solver is initialized by using the previous solution from the in-program repository. Hence, an iteration limit of 10 is used as termination criteria since it is expected that a good solution will be found during the first few iterations. Furthermore, this keeps computational times low.

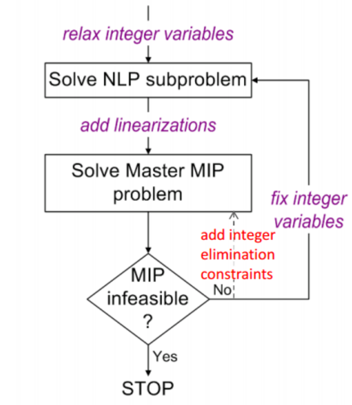


Figure 64. AOA algorithm

To summarize, the term Outer Approximation refers to a linear approximation at selected points on nonlinear constraints, which are used to form an outer approximation of the solution region. This approximate solution region is used to replace the nonlinear constraints. As linearizations are added, the model becomes an improved approximation of its original. The solvers standardly provided by AIMMS, namely the CPLEX 16.3.2 solver (MIP) and the CONOPT 3.14V solver (NLP), are used during optimization. Further algorithmic details are out of scope.

Routing

The TRP by Angel-bello, Alvarez, and García (2012) is a genuine NP-hard MIP. Such problems are notoriously difficult computationally. Commercial solvers such as those supplied by AIMMS often apply heuristics to prevent real world problems from becoming too large to solve. Here, CPLEX 16.3.2 is chosen because of its versatility and efficiency.

Software implementation

The implementation of the models in AIMMS essentially is built up out of the following aspects:

- Declarations of identifiers that are used throughout the entire model (Sets, parameters, variables, constraints, etc.)
- Mathematical programs that represent a subset of the identifiers used during optimization (objective, decision variables, constraints)
- Internal and declared procedures and functions that allow for solver execution and manipulation of in and/or output data.
- A Graphical User Interface (GUI) that allows for the representation of results and changing of (certain) model parameters.

The declarations and MP's to be used are as declared in section 7.2. The outline and linkage of the different parts of the model are depicted in figure 63, which represents a single simulation step over a single planning interval. Here, it can clearly be seen that both scheduling and routing models are part of the simulation procedure.

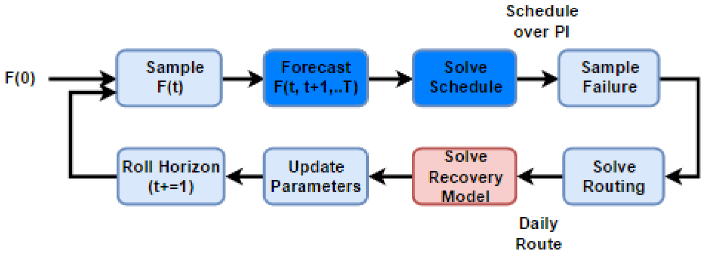


Figure 65. Simulation flow scheme

The flow as depicted in figure 62 is realized by executing the procedures as listed below. Note that the procedures that mimic an actual real life process are depicted in green. The other procedures are used inside the model to prepare in or output data.

- MainInitialization
- InitializeLengthOfPlanningInterval
- MovePlanningIntervalToStartOfCalendar
- RollHorizonToEnd
  - RollHorizonOnce
    - LinkHorizonToCalendar
    - SampleFailureProbability
    - DetermineForecast
    - SolveSchedule
    - SampleFailure
    - RegisterInOverallPlanning
    - SolveRouting
    - SolveRecoveryModel
    - PrepareForNextDataRoll

More details regarding the procedures, as well as their verification can be found in the Appendix. The GUI screenshot of the model is depicted in figure 64, where:

- RED: Model input
- ORANGE: Diagnosis and prognosis
- YELLOW: Maintenance Schedule
- GREEN: (daily) Routing network
- BLUE: Systems recovered
- PURPLE: KPI outputs

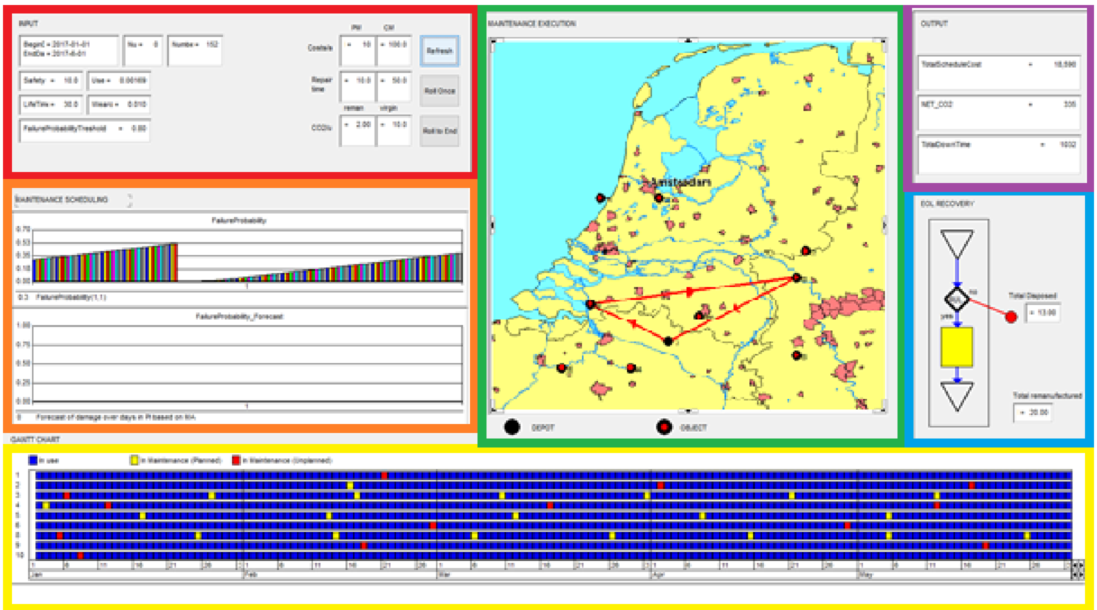


Figure 66. Decision support tool Graphical User Interface

5. Methodology

This chapter forms the bridge between the practical and theoretical basis of the research on one hand, and the results and conclusions on the other. Therefore, classifying the research and selecting a corresponding research strategy is required.

Clearly, this is a practice oriented research as defined by Verschuuren and Doorewaard (2010). The main objective has been to determine which improvements to the maintenance and recovery strategy would have a positive effect on the performance of the maintenance supply chain. To this end, a hypothesis has been formulated. It is now key to test this hypothesis by quantifying the relation between improved information and the KPI's. A confirmation of the hypothesis could inform the stakeholders on how to approach the future strategically. According to Dul and Hak (2008), a comparative simulation case study is a suitable approach in this case. The case study methodology from these authors was used to provide a structured approach, consisting of:

- Case selection
- Measurement
- Data Analysis

5.1.Case selection

The case(s) considered should be from the practice under consideration, or a comparable practice. Because the window of opportunity to implement the future state is greatly determined by the type of electronic system, the case selection procedure starts off with an analysis of the system of focus (see chapter 5). Based on this system, a current state and future state scenario will be formulated between which the quality of information available to the decision maker is varied. Due to the lack of examples from practice that have implemented the complete set of processes as proposed in chapter 3, the future state scenario has been developed by combining several examples from practice from the system of focus. The required data and information has been gathered by following the approach as listed in section 1.6, namely applying a combined desk research and a field research strategy (literature research, practice research, stakeholder interviews, expert meetings). The scenarios are presented in chapter 6.

5.2.Measurement

To extract evidence supporting the hypothesis, the simulation based decision support tool developed in chapter 4 will be applied. Before application, the tool is verified and validated in chapter 8 by considering data quality, internal validity, and external validity. Subsequently, a comparative simulation case study is performed, for which the input data is presented in chapter 9. Regarding the experimental plan, the following choices were made:

- 2 scenarios ((1) without and (2) with predictive maintenance) are compared
- For scenario 2, a scale up variant (2b) is tested to improve the economies of scale
- For each scenario, three sub runs are performed with a different random seed
- A 'warm start' is applied by randomizing asset failure probabilities as described in 3.6.2.
- Because of the strategic perspective, a run length of several years is chosen.
- The results are split up into multiple experiments because of the limited lifetimes of assets
- The simulations are terminated at a well-defined end time.

5.3.Data analysis

After the experiments, the result data is exported into Excel for processing. Because of the large number of experiment replications, it is assumed that the result data mean is normally distributed. The hypothesis is assumed confirmed when there is a 'significant' improvement in the expected direction. To determine if this is the case, the following steps are taken:

- The mean and standard deviations are calculated
- For each KPI and each scenario, the 95 % confidence bounds are determined
- When for a certain KPI between scenario 1 and 2, the results mean has changed in the direction as hypothesized and there is no overlap in the confidence interval, the hypothesis regarding that KPI is considered not to be falsified.
- When for a certain KPI between scenario 1 and 2, the results mean has changed in the direction as hypothesized and there is overlap in the confidence interval, a 2 sided 95% t-test with unequal variance is applied to confirm or reject the hypothesis.

For each scenario, the results will be visualized as follows in chapter 10:

- The averaged KPI scores are visualized into a three-dimensional graph, each dimension resembling the KPI/scenario score.
- For each KPI, the averaged cost breakdown is depicted to be used in the discussion of the results.

To aid the process of drawing conclusions and formulating recommendations in chapter 11, a sensitivity analysis is performed regarding the importance of model parameters. With the results of this sensitivity study, possibly the most promising approach for profitably implementing the future state in this exact case can be identified. The boundary condition that determine this profitability are described in chapter 6.

6. Case Selection

6.1. System selection

Applying the improvements as proposed in the previous chapters requires the availability and selection of a suitable system of focus. In the following, the electronic systems within a movable bridge will be subjected to a series of selection criteria that were deduced from the previous chapters.

6.1.1. Selection criteria

Apart from the FMMEA analysis that was introduced in 3.4.2, the system selection is also dependent on the extent to which the selected system is suitable for recovery. For an electronic assembly to be promising in terms of predictive maintenance and remanufacturing, it should:

- Be critical for the objects function
- Represent sufficient value to be recovered
- Allow for an early detection of failure

6.1.2. Analysis

These selection criteria will now be applied on the electronic system groups and corresponding assemblies that were depicted in section 2.1, figure 10.

System criticality

Electronics cause the most downtime by frequent failures, long investigation times and long fault diagnosis times (App. E, CON3, Q3). It is even estimated that malfunctioning electronics cause 90 % of unexpected failures (SP2, Q1). In practice, a FMECA analysis is applied to rank systems on criticality. Since criticality is only one of four criteria, here it is chosen to use maintenance logs for quantification. When reviewing a printout of the CMMS module of a renowned SP, the following figures could be deduced regarding the occurrence of unexpected failures (see figure 55:

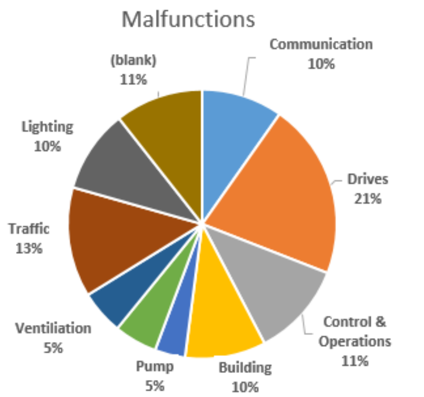


Figure 67. system malfunction piechart

- 11 % is caused by the C&O systems group, of which:
  - 80 % is caused by relay switches

- 33 % is caused by the Safety systems group, of which:
  - 40 % is caused by the traffic control subsystem
  - 30% is cause by the lighting subsystem
  - 30 % is caused by the communications subsystem

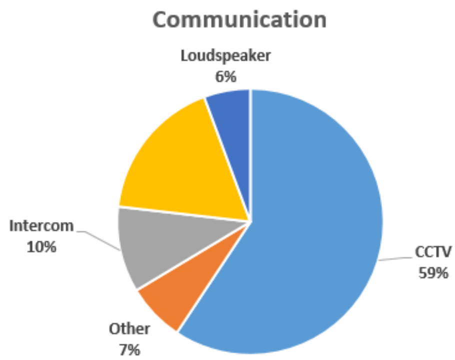


Figure 68. Communication related malfunctions piechart

While many different assemblies and components cause both the traffic control and lighting subsystem failures, 60 % of communication related failures can be accounted to the Closed-Circuit Television (CCTV) subsystem (see figure 56).

Value recoverable

Sufficient volumes (quantities, masses) of identical valuable electronic components need be become available for remanufacturing to be economically feasible. The AO under consideration owns a total of 176 movable bridges, of which roughly 85 % (≈ 150) is not located in the main road and water network.

Relay Switches

For the electronics in the C&O systems group, mainly relay switches are replaced relatively often (SP2, Q1). When it is assumed that on average a movable bridge contains 30 relay switches (W+B 2015), the total number of switches in the installed base is roughly 4500 switches. Considered that a modern solid state relay switches only contain a couple of grams of precious metals, silicon, and plastic with a material value of 7 euro/kg (App. E, CON1, Q1), it can easily be understood that this will not cover the investments in a reasonable timespan nor would it provide significant environmental benefits.

It should also be noted that there generally is a large diversity regarding system type, generation, and manufacturer between electronic systems in the installed based (App. E, SP1, Q5). Moreover, statistic dissimilarity between the components of different systems cause them to display different failure behaviour. Combined, these facts cause the recoverable value to be even lower than estimated above and it is reasonable to assume that this would not be much better for other electronic systems.

CCTV systems

In the last decade's technologies that enable remote control as well as remote surveillance have developed substantially. Modern movable bridges too, are these days equipped with CCTV systems to reduce the amount of personnel required for safe, often remote operation (Gemeente Delft 2010). Modern CCTV systems contain a lot of high tech components. In a book about the developments in CCTV surveillance, Kruegle (2006) lists the following:

- Control panels
- Monitors
- Switchers
- Cables and connectors
- Cameras

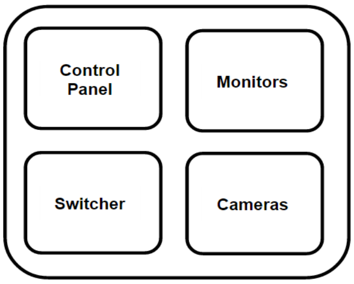


Figure 69. CCTV subsystem

See figure 57 for a schematic representation of a CCTV sub-subsystem. When looking at failure behaviour, it is seen that 20 % of the CCTV related failures are solved by performing replacements (figure 58). Most of which are confirmed to be camera replacements (App. E, SP1, Q10). Besides movable bridges, many CCTV systems have also been installed in other objects, or along spatially distributed infrastructure such as roads, rails, and waterways. This trend is expected to continue in the future, making especially camera assemblies an interesting system to focus the analysis on. See figure 59 for a schematic representation of a CCTV camera assembly (Kruegle 2006).

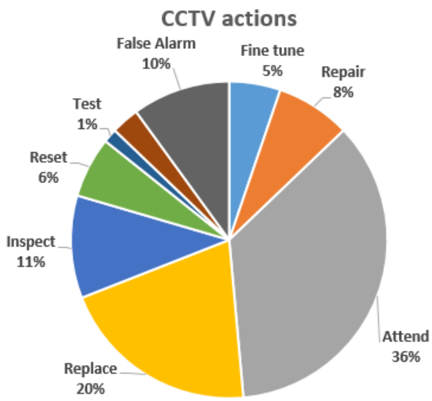


Figure 70. CCTV maintenance actions

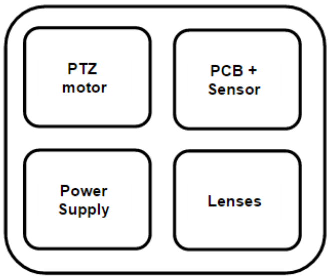


Figure 71. Camera Assembly

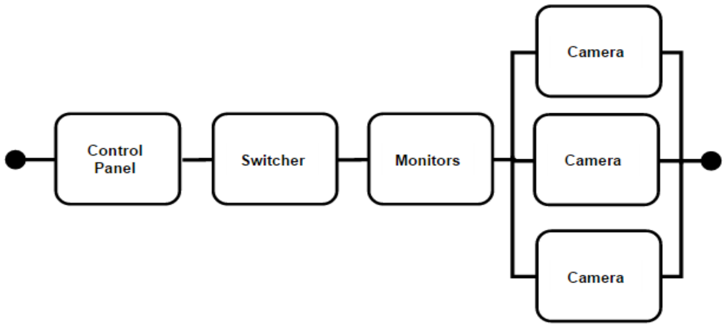


Figure 72. CCTV subsystem RBD

When viewing figure 59, it is seen that the reliability of the CCTV subsystem is dependent on a camera by a parallel relation. Failing of a single camera, technically thus does not reduce the functionality of the subsystem (and therefore the object) to zero. However, camera downtime does add to the total subsystem downtime which is used for penalizing (W+B 2014c). This can be accounted to the ‘Safety’ criticality aspect in RAMS, which is expected to increase in the future because of a larger reliance on non-human control. It is therefore assumed that downtime is directly dependent on the camera assemblies (see figure 61), and that the focus on a single assembly is justified. See figure 63 for a picture of a typical pan-tilt-zoom camera assembly.

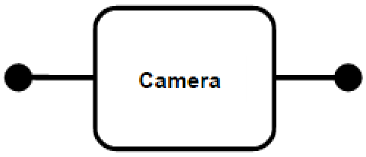


Figure 73. Object level RBD considering CCTV camera assemblies

Figure 74. Typical CCTV camera assembly

Prognostics potential

What remains now, is verifying the prognostics potential for CCTV camera’s. According to (Damjanovski 2014), the Pan-Tilt-Zoom (PTZ) motors are the most critical component. For electric motors in the offshore sector, approximately 20 % of failures occur during start up, for which the incipient failure is overheating (OREDA 2015). This overheating is most often caused by degradation of the motor insulation, which in turn has been caused by electrical (current) and thermal (heat) loads as a result of wind, ice, and/or excessive temperature (Kruegle 2006). As was described in section 3.4.2 and 3.4.3, these loads can be monitored by integrating sensors into the assembly. By using PoF models, the monitored loads could be used for diagnosis, and subsequently for prognosis. For the PCB units, spurious operation is the critical failure mode (OREDA 2015), accounting to 50% of total failures.

A similar, but more data driven approach has been employed by SP4, who is specialized in safety systems. The SP offers predictive maintenance services for, amongst others, CCTV systems. This particular SP’s service is supported by monitoring contamination (lens), start-stops (motor), current load (power supply), and temperature load (PCB).

6.2. Scenarios

In this chapter, the current state and future state scenarios are described for the system of focus: CCTV camera assemblies. As was mentioned earlier, the scenario's will differ in the quality of information available during decision making. Regarding the quality of information, two extreme cases, namely manual periodic inspections vs. automated continuous monitoring are considered. For each of the scenarios, the expected cost breakdown will be depicted to indicate the expected difference in KPI performance.

6.2.1. Scenario 1: Run-to-failure and low grade recycling

The baseline scenario resembles the current state supply chain processes as described in chapter 2. CCTV cameras are inspected manually once a year, and replaced using a run-to-failure approach. All replacements are therefore performed correctively and transported back to the depot for low grade recycling. See fig 59 for a schematic representation of the baseline scenario, see equation 11, 12 and 13 for the cost breakdown per object.

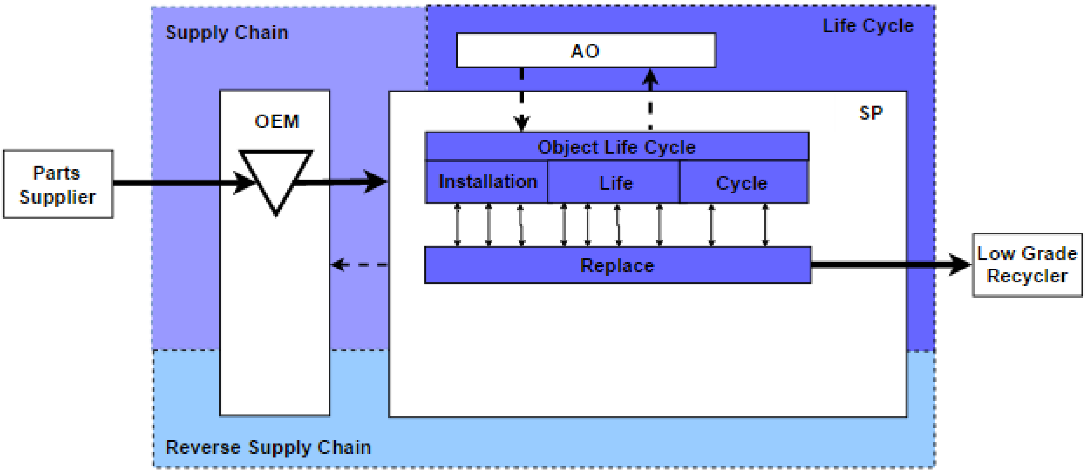


Figure 75. Scenario 1 (Current state)

eq. 11: $OPEX$	$= TSC + TTC$	$[€]$
eq. 12: TEm	$= TPE + TRE + TTE$	$[kg\ CO_2]$
eq. 13: TDT	$= TTD + TSD$	$[hr]$

6.2.2. Scenario 2a: Predictive maintenance and remanufacturing

In the future state scenario, the improvements as described in chapter 3 are implemented. For this case specifically, this could be approached as follows:

- The CCTV cameras are equipped with integrated sensors as described by SP4 (Qx). Both the currents and temperatures of the PTZ motor and PCB unit (see figure 52) are continuously monitored. It is assumed that an FEM analysis, combined with a and ALT analysis as in Sonnenfeld, Goebel, and Celaya (2008) is used to determine the correct sensor configuration.
- A Coffin-Manson and Eyring PoF model could be used to process the monitored currents and temperatures respectively (see figure x). The overall RUL could be estimated by using a Bayesian

approach as in (Ramuhalli et al. 2014). Diagnosis as well as prognosis is performed locally on watchdog modules, and communicated wirelessly to the SP's supervisory computer.

- When an incipient wear-out failure is detected, the failure probability prognosis is used to schedule a maintenance action. Subsequently, the maintenance crew daily executes both the preventive and corrective replacements.
- The RUL characteristics at the time of replacement are stored on an RFID chip on the camera, similar to Wan and Gonnuru (2013).
- A routinized version of the remanufacturing activities mentioned by SP3 is assumed. Preventively replaced systems (with RUL) are put in stock for remanufacturing whereas correctively replaced systems (without RUL) are sold off to a low-grade recycler. Remanufacturing is performed by replacing the failed PTZ motor with a replacement that has been newly ordered from the OEM.

For this specific case, the following boundary conditions for 'success' could be deducted from practice:

- BEP should be less than 10 years (SP3, Latten 1991; Slichter 1992)
- TDT (unexpected) should not exceed 2h per asset per year (Gooijer and Noortwijk 2001)
- TEm should be reduced by 40% (CivieleTechniek 2016b; Schippers 2012)
- The future state should be realistic in terms of operational loads on the current state organisation

See figure 60 for a schematic representation of the scenario. Please note that the dotted lines indicate the physical flow, the dashed lines indicate information flow, and that the difference in thickness of the arrows compared to figure 59 indicates the expected change in physical flow volumes. The expected cost breakdown per object is as formulated in equation 14, 15 and 16. Compared to the current state, (⇧) represents an expected increase, (⇩) a decrease.

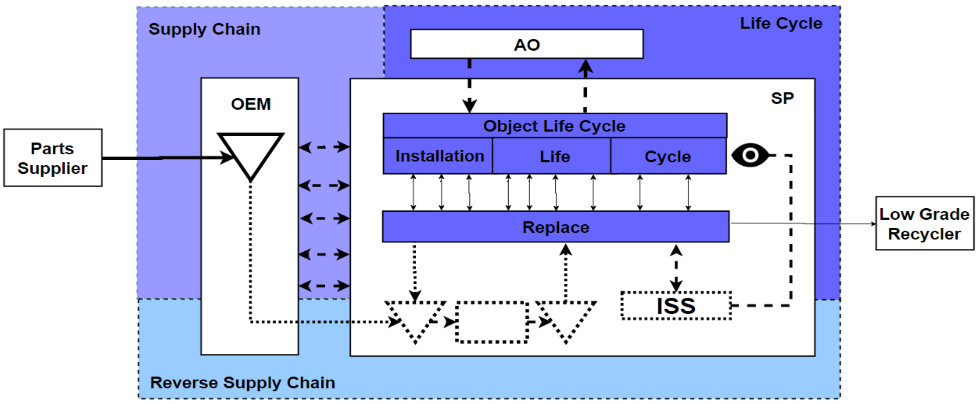


Figure 76. Scenario 2a (Future state)

$$\text{eq. 14: } OPEX = TSC\ (⇩) + TTC\ (⇩) \qquad [€]$$

$$(BEP \Rightarrow \frac{TRev\ (⇧) - OPEX(⇩)\ -\ CAPEX\ (⇧) +}{CAPEX(⇧)} * 100 = 0\% \qquad [yrs]$$

$$\text{eq. 15: } TEm = TPE\ (⇩) + TRE\ (⇩) + TTE(⇩) \qquad [kg\ CO_2]$$

$$\text{eq. 16: } TDT = TTD\ (⇩) + TSD\ (⇩) \qquad [hr]$$

6.2.3. Scenario 2b: Scale up

To provide insight into benefit of an increased service area, a scale-up variant of scenario 2a is considered. Compared to scenario 2a, this is expected to affect the cost breakdown as depicted in equation 17, 18 and 19.

$$\text{eq. 17: } OPEX \;=\; TSC + TTC\,(⇩) \qquad [€]$$

$$(BEP \;=> \frac{TRev - OPEX(⇩) - CAPEX\,(⇩) +}{CAPEX(⇩)} * 100 \;= 0\% \qquad [yrs]$$

$$\text{eq. 18: } TEm \;=\; TPE + TRE + TTE(⇩) \qquad [kg\ CO_2]$$

$$\text{eq. 19: } TDT \;=\; TTD\,(⇩) + TSD \qquad [hr]$$

7. Verification & Validation

To assess whether the model performs according specifications, and whether it is the right model to answer real world questions, the framework by Sargent (2010) is used. The author recommends certain best practices that will be used as a guideline throughout this section. Firstly, it is recommended to specify the required model accuracy with respect to the intended purpose. As followed from the hypothesis statement as well as the refined objective, the main purpose here is to confirm or reject potential of the future state by providing insight into the cost-benefit trade-off. To this end, it was assumed in chapter 5 that the comparative case study should show statistically significant improvements regarding the model KPI's. To thoroughly understand model behaviour, and gain confidence on the research quality, Sargent (2010) recommends considering data validation, conceptual model validation, computerized model verification and operational validation. The results of these assessments are depicted in table x. A detailed description can be found in appendix X.

Table 4. verification and validation summary

Aspect	Item	Technique(s) Used		Conclusion	Conf.
Data	• Modelling • Validation • Input	• Semi structured interviews • Desk Research		• Not sufficiently available	**Low**
Conceptual Model	• Simulation • Scheduling • Routing	• Comparison with other models • Expert Validation		• Proven principles • Confirmed reasoning	**High**
Computer Model	• Simulation • Scheduling • Routing	• Structured walkthrough • Trace/counters		• Adequate functionality	**High**
Operational	• Simulation • Scheduling • Routing	• Internal Validity Check • Parametric sensitivity analysis • Subjective judgement		• Not quantifiable • Directions and order of magnitudes as expected	**Medium**

8. Comparative Case study

In this chapter, the model is applied to both scenarios by using input data that was obtained from both literature and practice. In the absence of data, expert opinions are used as much as possible.

Input data

In table x., the input parameters that were used during simulation are depicted. It should be noted that not all parameters from section 7.2 are listed here, since some not used as 'input' but determined by the model. The remainder of this section will explain shortly how some of the parameter values where obtained.

The value of **Parameter 1 through 3** define the rolling horizon in the model. Firstly, the time unit of one days was chosen since this allows for both a 'look ahead' period and assigning tasks to days. A horizon length ($\mathbf{1}$: h) of 3650 days (10 years) was chosen because this is sufficiently long to encounter multiple 'life cycles' during simulation (see **Parameter 14)**. Furthermore, strategies as the one proposed are typically continued for (several) decades. For scenario 2, the number of time units in the PI ($\mathbf{2}$: T) (i.e. the look ahead period) was set at 14 days. Such a prognostic distance was found to be technically feasible for electronics in other sectors, and is expected to be sufficient for maintenance and recovery planning. The PI advances one day at every time step ($\mathbf{3}$: ts) to mimic the effect of real-time scheduling as much as possible. The number of objects present within the service area (**Parameter 4),** is primarily kept at 10 in both scenario 1 and 2 resembling the size of SP2. To research the effect of economies of scale, scenario2b considers an increasing service area of 100 objects. This increase in the number of objects is expected to be accompanied by a decrease in the investment costs per object, as is displayed by **parameter 5.** Several cost components are modelled by **Parameter 6 through 11.** The values for **Parameter 6 and 7** were deduced from an internal SP document (W+B 2014b). **Parameters 8 and 9**, which are not considered in scenario 1 due to the absence of PM tasks, were estimated by assuming that they should be significantly lower than the direct failure costs. **Parameters 10 and 11** represent the amount of CO2 emitted when producing a CCTV camera assembly from virgin raw materials and remanufacturing a CCTV camera assembly by replacing the PTZ motor respectively. These values where estimated by using a paper on waste electronics recycling by Lakhan (2016). To put it in perspective, the production of a cellular phone approximately accounts for 50 kg's of CO2. The average time for performing both a CM and PM action (**Parameter 12 and 13)** in the current state, was estimated by using the maintenance logs from SP2 as well as expect judgement from SP4 (App. E, Q6). For the scenarios with predictive maintenance it is assumed that the time durations for these tasks are halved and equal, because of the reduced investigation times (see section 3.6.2). **Parameter 14** depicts the expected lifetime of a CCTV camera before a PTZ wear out occurs. This expected lifetime was estimated by averaging the amount of camera replacements in a single year by the number of objects in the service area of SP2. It is striking that this lifetime is rather low, which could be explained by the application of the wrong type of camera for the circumstances. Nevertheless, this value is used during simulation due to the absence of better data. **Parameters 15 through 18** and **20 through 23** are assumed to speak for themselves. **Parameter 19** was deducted from a maintenance log.

Table 5. Model input for comparative case study

	Parameter	Unit	Scenario 1	Scenario 2a	Scenario 2b		
						Conf.	**Source.**
1	h	$[days]$	3650	3650	3650	**n/a**	n/a
2	T	$[days]$	-	14	14	**M**	(Pecht 2006)
3	ts	$[days]$	1	1	1	**n/a**	
4	m		10	10	100	**n/a**	
5	C^u_{invest}	$[€/\mathrm{Obj.}]$	-	15000	12000	**M**	App.E
6	$Rev^u_{service}$	$[€/\mathrm{Obj.}]$	-	100	100	**M**	App.E
7	C^u_{pers}	$[€/hr]$	100	100	100	**H**	(W+B 2014b)
8	C^u_{CM}	$[€/act.]$	400	400	400	**H**	(W+B 2013)
9	C^u_{DT}	$[€/hr]$	-	100	100	**M**	
10	C^u_{PM}	$[€/act.]$	-	100	100	**M**	
11	E^u_{prod}	$[\frac{kgCO_2}{syst}]$	100	100	100	**M**	
12	E^u_{reman}	$[\frac{kgCO_2}{syst}]$	-	15	15	**M**	
13	$E^u_{transport}$	$[\frac{kgCO_2}{km}]$	0.1	0.1	0.1	**H**	www.anwb.nl
14	$t^{replace}_{CM}$	$[hr]$	2	1	1	**M**	SP4
15	$t^{replace}_{PM}$	$[hr]$	-	1	1	**M**	SP4
16							
17	$t^{spec}_{assetlife}$	$[days]$	365	365	365	**L**	App.E
18	$t^{init}_{assetlife}$	$[days]$	Rnd(Uni(0,365	Idem	idem		
19	$Incr^{useful}_F$		1E-8	1E-8	1E-8	**M**	App.E
20	$Incr^{wearou}_F$		0.005	0.005	0.005	**L**	App.E
21	Z		-	6	6	**n/a**	App.E
22	Rd_a		U (0,1)	U (0,1)	U (0,1)	**n/a**	
23	DT_a	$[hr]$	2	2	2	**M**	App.E
24	f^{prio}_a (PM)		-	2	2	**n/a**	App.E
25	f^{prio}_a (CM)		Rnd(Uni.(0,4))	idem	idem	**n/a**	App.E
26	$f^{restore}$		1 (100%)	1 (100%)	1 (100%)	**L**	
27	$v^{vehicle}$	$[km/hr]$	60	60	60	**H**	www.anwb.nl

During route optimization, there is made use of a distance matrix ($Dist_{l,l2}$), containing the distance between each location. These distances where calculated by using a google geocoding API script integrated in excel, which calculates the actual driving distance (by road) given the 'from' (Xco_l, Yco_l) and 'to' (Xco_{l2}, Yco_{l2}) coordinates. This matrix is automatically read into AIMMS upon initialization, making it very easy to extend and adapt the matrix to incorporate other object locations. A snapshot of this matrix is depicted in Appendix E.

9. Results & Discussion

In this chapter, the case study results are presented and discussed. After presenting the KPI scores in section 9.1, section 9.2 will be used interpret the results by means of a sensitivity analysis. Besides, several promising sub-scenarios will be evaluated here to identify promising improvements to the future state, as well as their implications. Finally, section 9.3 will discuss the findings by considering the research limitations and relating the findings to practice.

9.1.KPI scores

For each scenario, KPI scores were calculated based on the model input as listed in the previous chapter (see figure x). Please note that the results are normalized to account for the number of objects considered. Regarding the research objective, an ideal scenario would have minimal OPEX, CO_2 emissions, and total downtime, and should therefore be as near to the origin in figure x as possible. See appendix b for separate plots of the KPI scores.

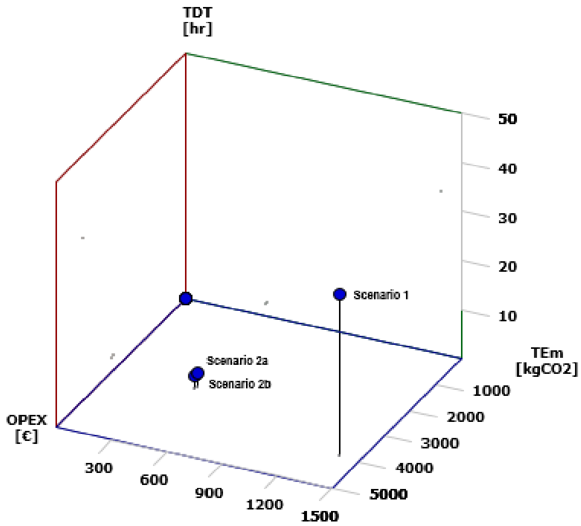


Figure 77. KPI scores for scenario 1 and 2

Operational Expenditure

Considering figure 68, it is shown that the both improvement scenarios result in lower OPEX than the baseline scenario. For scenario 2a, a 29% reduction is achieved, whereas for scenario 2b, the decrease in OPEX amounts to a 31% % decrease compared to the baseline. It can be clearly seen that the OPEX savings are caused by a reduction of the service costs, induced by less unexpected failures. The reduction in transport costs between scenario 2a and scenario 2b is negligible. This indicates that a significant 'scale of economies' does not (yet) apply here.

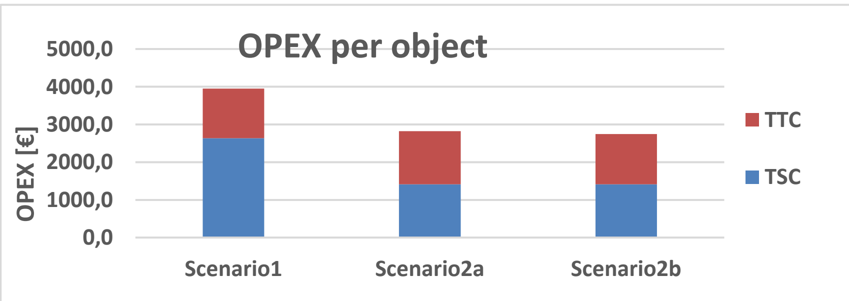


Figure 78. OPEX results

BEP

It was determined that the CAPEX investments required to implement predictive maintenance, should at least be earned back within 10 years. Within the horizon considered during simulation therefore, the ROI should become 0% (see section 3.5.2). When considering table x however, it can clearly be seen that this is not the case for scenario 2a, nor scenario 2b. At the current cost rates, an additional 3 respectively 2 years is required to earn back the capital investments.

Table 6. Break-even points

Scenarios	CAPEX	OPEX	Revenue	ROI
Scenario 2a	150000	28209	120000	-38.8%
Scenario 2b	1200000	274160	1200000	-22.8%

Total Emissions

Like the cost performance, both improvement scenarios outperform the baseline regarding the CO_2 emissions. The fact that more systems are replaced preventively, and therefore remanufactured rather than disposed, accounts for a 70% decrease in emissions (see figure x.). Clearly this is sufficient to meet the 40% reduction goal. The savings due to an increased transport efficiency are marginal.

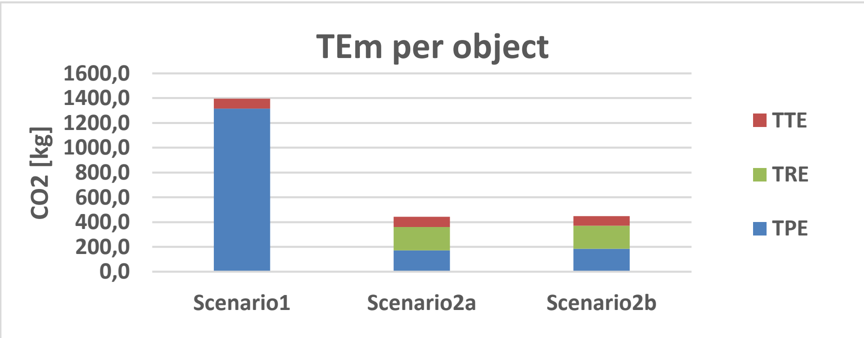


Figure 79. TEm Results

Total Downtime

Finally, for equipment availability too, it can be said that the improvement scenarios perform the best. Due to shorter service times, as well as the decrease in unexpected failures, total downtime is reduced by roughly 90%. See figure x for the cost breakdown.

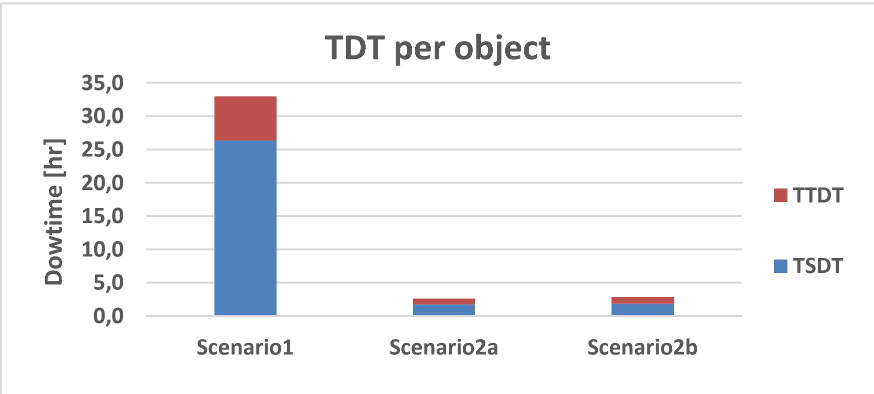


Figure 80. TDT results

Maximum Downtime

For the CCTV systems under consideration here, it was deducted that the yearly downtime should be below 2 hours per object. In table x below, the downtimes for each of the scenarios are normalized to account for a single object for a single year. While the current state scenario does not meet the specified limit, both improvement scenario's do.

Table 7. downtime per object per year

Scenarios	TDT [hr]	# objects	# years	TDT/object/year
Scenario 1	329	10	10	3.29
Scenario 2a	26	10	10	0.26
Scenario 2b	284	100	10	0.28

9.2.Interpretation

Regarding the results of the case study, it is verified that under the current assumptions, implementing predictive maintenance would result in a significant decrease of the OPEX, emissions, and downtime. Furthermore, it was shown that the profitability of neither improvement scenario meets the profitability constraints. However, to cope with the effect of missing input data, several simplifications and estimations were made. Before drawing conclusions therefore, the robustness of the results should be tested to account for these uncertainties. Furthermore, a better insight into the effect of parameters could assist in formulating conclusions and recommendations.

Sensitivity analysis

To be complete without becoming exhaustive, a selection of those parameters is made that are both prone to uncertainty and are expected to affect the KPI's significantly. The effect of varying the following parameters on the results will be evaluated:

- CAPEX [ROI]
- Revenue [ROI]
- OPEX [ROI]
- Service time (PM) [ROI, TDT]
- Reman Emissions [TEm]

See table x for a summary of the results. Here, the black sections indicate whether a parameter affects a certain KPI score. Furthermore, the second and third column indicate respectively whether a parameter works towards or opposed the feasibility of the case study, together with the percentage it should or should not change compared to scenario 2b. Of course, this change can work both ways. It is however assumed here that the parameters 'requiring' change are in practice more likely to be improved, whereas the parameters that are 'allowed' to change are an optimistic estimate already. It should also be noted that the figures as indicated in table x were determined separately, whereas compromises between several parameters could also create feasible scenarios.

Table 8. sensitivity overview

			Affects KPI:		
Parameters	**Required change**	**Allowable change**	**ROI**	**TEm**	**TDT**
C_{invest}^{obj}	-25%		■		
Rev^{obj}	+30%		■		
OPEX	-110%		■		
$t_{CM,PM}^{service}$		+0%	■		■
E_{reman}^{u}		+40%		■	

Predictive policy variants

Considering table x, it can be said that the most urgent factor to focus on is the OPEX performance. It is expected that especially the transport cost component can be improved. Due to (a combination of) the following factors namely, no significant transport cost savings where achieved during the experiments:

- The focus on single-unit assets with a single failure mode
- A relatively small number of assets
- Statistic dissimilarity regarding failure probability
- No grouping optimization for replacements within the planning interval

All these factors reduce the probability of replacements being scheduled on the same day, resulting in many inefficient single trips. In the following, three simplified predictive sub-policies (two of which were introduced in section 3.2.1), are compared to scenario 2b. It is expected that with these policies, the OPEX performance of the future state will be improved. See figure x for a graphical representation of the maintenance policy deployed in scenario 2b. Note that each square denotes a single system, red indicates a system to be maintained (@t=1), and green indicates when an asset has been replaced (@t=2)).

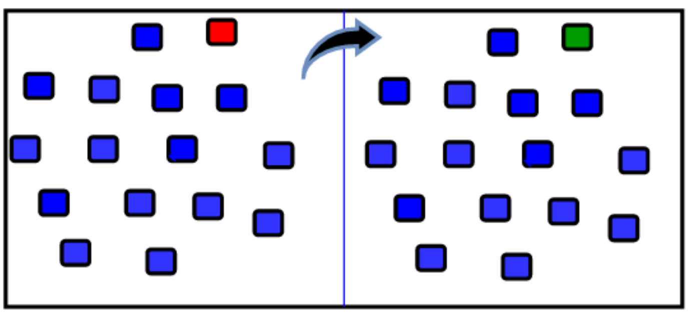


Figure 81. Predictive maintenance policy (2a)

Scenario 2c: Multi-Unit systems

In practice, often multiple CCTV cameras are installed at a single location. A first variant of scenario 2b is therefore proposed to be a multi-unit scale up, meaning that at every location, multiple systems are positioned. It is assumed here that each system is monitored and serviced separately. Because of the increased number of assets in the service area, this scenario is expected to improve the transport performance. Furthermore, the 20% unit-CAPEX reduction rule is assumed still to apply here. See figure x for a graphic representation of the scenario.

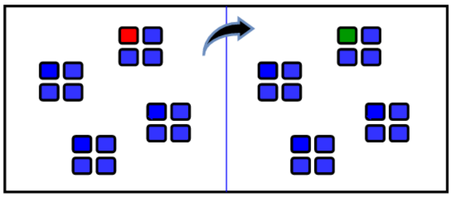


Figure 82. Predictive maintenance policy 2c: multi-unit systems

Scenario 2d: Multi-Unit systems, grouping

Further cost reduction could be attained when instead of servicing each unit separately, group replacements are performed. This policy entails that whenever a single unit requires maintenance, all units at that location are replaced. As for scenario 2c, this is expected to improve OPEX performance. The main difference with scenario 2c is that far less trips are required at the cost of having a higher risk of excessive crew workloads and vehicle loads. See figure x for a schematic representation of this scenario.

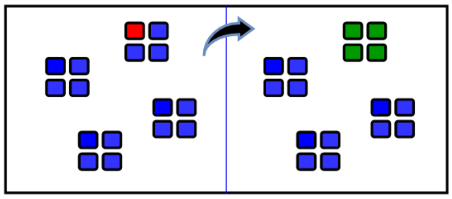


Figure 83. Predictive maintenance policy 2d: multi-unit systems + grouping

Scenario 2e: Single-Unit systems, clustering

Finally, scenario 2e proposes to reduce the transport costs by enabling a clustering policy. The service area is now clustered into geographical areas in which the (single-unit) systems have relatively little statistic dissimilarity. This increases both the chance of having replacements being scheduled on the same day, as well as the chance that these replacements are located near to each other. It is expected that this would decrease the transportation costs significantly, without increasing the crew and vehicle loads excessively.

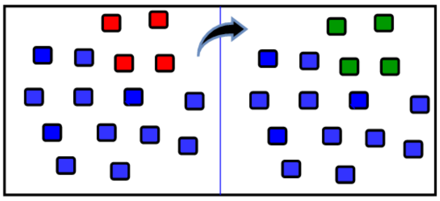


Figure 84. Predictive maintenance policy 2e: clustering

See appendix b for the input parameters used during the simulation of scenario 2c, 2d, and 2e. Note here that parameter y is added here to account for the number of units present at an asset location. See figure x for the OPEX output of the sub-policy scenarios as compared to scenario 2b. It can be clearly seen that for each sub-policy, the total transport cost decrease significantly. When increasing the total number of assets in the service area, by servicing 10 units instead of single units at each location, the total transport costs per object decreases as much as 35%. When these assets are now replaced in groups rather than independently, a reduction of even 90% of transport costs is shown. Finally, when comparing the clustering scenario (2e) to the original 'scale-up' (2b) scenario, a reduction of approximately 20% per object is achieved.

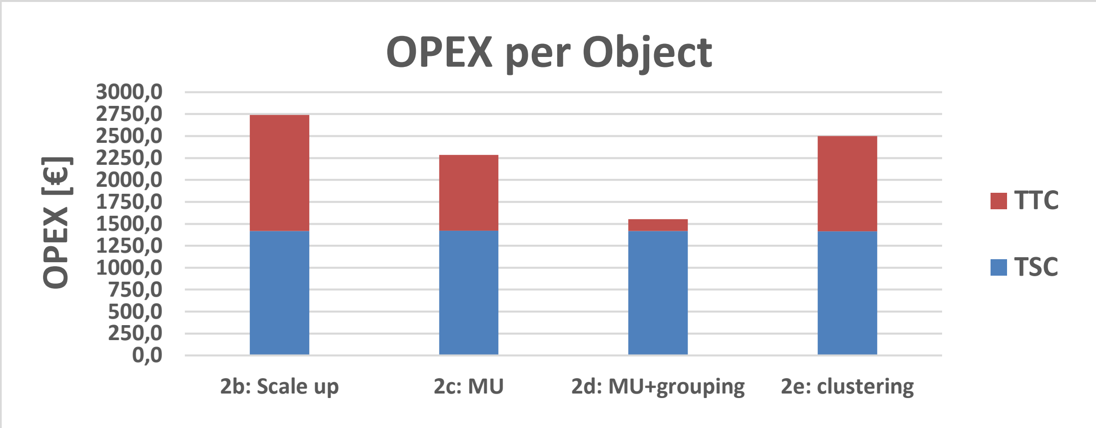


Figure 85. OPEX results per sub-policy

From the point of view from normalized OPEX therefore, scenario 2d performs by far the best. A similar conclusion can be drawn from the performance regarding the emissions per object, and the downtime per object (see appendix b). When reviewing the ROI for scenario 2c and 2d, it can be seen that the BEP lies within the 10-year time frame. Scenario 2e has no ROI within 10 years, but does show a halving of the ROI deficit compared to scenario 2b.

Table 9. break even points: sub policies

Scenarios	CAPEX	OPEX	Revenue	ROI
Scenario 2b	$12^{E}5$	$27.5^{E}4$	$12^{E}5$	- 22.8%
Scenario 2c	$96^{E}5$	$22.9^{E}5$	$12^{E}6$	+1.2%
Scenario 2d	$96^{E}5$	$14.2^{E}5$	$12^{E}6$	+10.2%
Scenario 2e	$12^{E}5$	14.1E4	$12^{E}5$	- 11.7%

It should be noted that in table x, it is assumed that servicing a 10-unit system generates 10 times as much revenue as a single unit system. In practice this may very well be not the case. In table x it becomes clear that when this assumption is wrong by 10%, the profitability of scenario 2c quickly decreases to below an acceptable limit. The same is true for scenario 2d.

Table 10. break-even point 2c and 2d: sensitivity

OPEX	CAPEX	Revenue	Rev.factor	ROI
2,29E+06	9,60E+06	1,20E+07	1	1,2%
2,29E+06	9,60E+06	1,08E+07	0,9	-11,3%
2,29E+06	9,60E+06	9,60E+06	0,8	-23,8%
2,29E+06	9,60E+06	8,40E+06	0,7	-36,3%

Furthermore, it should be noted that scenario 2c and 2d will have severe implications for the organization. Instead of increasing the service area tenfold (2b vs. 2a), now a hundred times as many units need to be serviced. Besides having to remanufacture all these replacements, this fact causes to expect that the single crew, unlimited vehicle capacity, and no stock assumptions must be revised.

Table x shows the results for scenario 2b through 2e, regarding vehicle load (VL), crew load (CL), monthly stock and monthly remanufacturing loads. Here, the following was assumed:

- A single camera assembly occupies a volume of 0.5m*0.5m*0.5m = 0.125 m^3
- The vehicle capacity (VC) is 3.5 m^3 (VW transporter)
- The crew takes exactly the right amount of (AGA) new units on a tour, and transports the replaced units to the depot on the way back
- The service time for replacing 10 units requires ten times the time for a single unit
- A single day consists of 8 working hours (WH)
- In the calculation of the average vehicle and crew loads, only active days were considered

Table 11. capacity constraints

Scenarios	Avg VL [%]	P (VL>VC)	Avg CL [hr]	P (CL>WH)	Stock per mth (Avg) [#]	Reman per mth (Avg) [#]
Scenario 2b	4%	≈0	2.4	≈0	11,8	10,3
Scenario 2c	32%	≈0	6.4	0.28	118,4	102,7
Scenario 2d	85%	0.14	13	0.95	118,2	103,2
Scenario 2e	11%	≈0	2.7	≈0	11,8	10,3

When reviewing table x, it can clearly be seen that scenario 2c and 2d will not always comply with both the vehicle load and crew load constraints. Where in scenario 2c, a 32% vehicle load is still acceptable, there is an almost 30% probability of exceeding the daily work hours. For scenario 2d, the chance of exceeding the vehicle capacity and the crew work hours are 14% and 95% respectively. This implies that in these scenarios, additional CAPEX investments are required regarding vehicles and personnel. Furthermore, the average stock per month and the average number of cameras to remanufacture in scenario 2c and 2d are quite high. At the end of the month, the amount of stock built up at the SP facility would on average be 15 m^3. Also here therefore, The SP would most likely have to make additional investments in the form of stock facilities and workforce.

On the contrary, for scenario 2e there would still be time left for the existing crew to perform other activities. When considering table x, the crew would on average have 5.3 hours left to perform the remanufacturing activities within the same day. Considering the cluster size of 5 assets used here, and assuming that the crew focuses on CCTV cameras on specific days, the crew would have approximately one hour per asset. Besides seeming quite reasonable workload-wise under the eco-design assumption, it can be imagined that such a variation of tasks could add to the employee satisfaction.

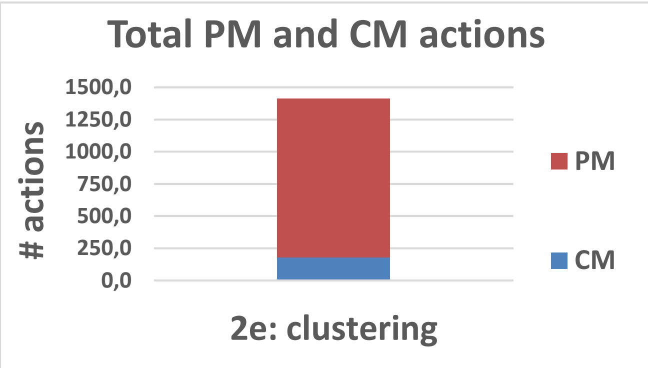
Conclusion

From the previous it could be concluded that although increasing the scale of implementation improves the business case, it does so to a certain limit. Considering the modest size of the current state SP, it does not seem reasonable nor wanted to expand the service area more than tenfold, since this would have large implications for capacity demands. Considering the case study therefore, a conservative trade-off between the proposed sub-policies is more suitable. When scenario 2e would be implemented in the service area under consideration, the BEP could be reduced to 10 years by either increasing the service revenue per asset per month from €100 to €115, by reducing the CAPEX per asset from €12000 to €10000, or a trade-off in between (see table x, appendix B). In this situation, the future state would comply with all constraints regarding OPEX, ROI, TEm and TDT. It should go without saying that the performance could be improved more by continuing in this direction, and that when the SP party would be more wealthy and flexible, pursuing a more progressive combination of scenario 2c, 2d and 2e could be justified.

Feasibility of remanufacturing

An important fact to consider however, is that the bulk of CO_2 emission reductions stands and falls with the assumption that remanufacturing will be executed. It was already explained before that unless cost effective, remanufacturing will not be pursued. Because of the decreasing trend in equipment costs, and the increasing trend in costs for labor, it is not expected that significant cost benefits will be achieved directly through remanufacturing. Some kind of incentive, such as the CO_2 tax, is therefore required to realize the predicted reduction in emissions in the future.

In a situation where the CO_2 – tax has been implemented, remanufacturing could become profitable by relating the cost savings due to reduced emissions to the costs for remanufacturing. Considering scenario 2e from before, a total of approximately 1400 cameras are replaced during 10 years, of which approximately 85% qualify for remanufacturing (see figure x). In total this amounts to approximately 1200 cameras, or 102 ton of CO_2 saved. Although currently roughly €5 per ton, scientists at Stanford university have estimated that when considering the negative effects of CO_2, a 'fair' price would be around €220 per ton (Stanford 2015).



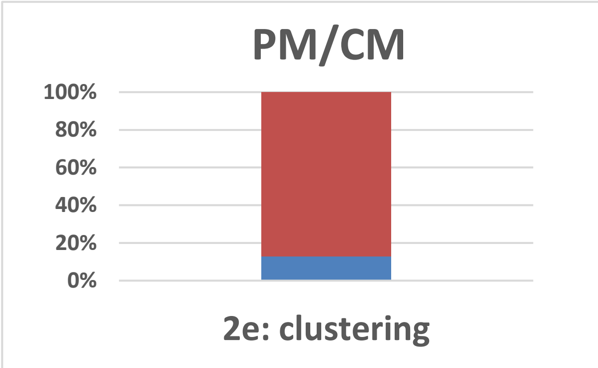


Figure 86. Total number of actions for scenario 2e

In table x, an overview has been made of several cost/workload combinations for remanufacturing the cameras from the entire service area over the course of 10 years. When taking the price per ton of €220 as a best-case scenario, no realistic workload/hourly rate configurations are feasible. Even in the highly questionable case of being able to remanufacture one asset per hour at an hourly rate of €50, the price per ton of CO_2 would still have to almost triple as compared to the best case considered.

Table 12. remanufacturing costs versus cost per ton of CO2

WorkLoad [hr]	Hourly rate [€]	Reman. Costs per asset [€]	# Assets [10yr]	Total Reman Costs [€]	CO2 savings [ton]	Break-Even tax [€/ton]
1	50	50	1200	60000	102	600
2	50	100	1200	120000	102	1200
3	50	150	1200	180000	102	1800
4	50	200	1200	240000	102	2400

9.3.Limitations

The reader should bear in mind that several limitations have been encountered during this research, some of which have already been made clear in other parts of the thesis. For instance, there was a general lack of data because this data was non-existent, or not made available. Furthermore, the data that was acquired often only was based on a single stakeholder, and could therefore not be compared to ‘common’ practice. An obvious result of this given, is that the results of this thesis cannot be generalized. A consequence of this lack of data was that several aspects of the analysis were strongly simplified, or assumed based on a similar practice. When similar practices were not available, several aspects where assumed. Some of these assumptions have intentionally been made on the optimistic side to simplify the analysis. For instance, focusing on a single failure mode of a single system, while assuming remanufacturing to as-good-as-new when replaced preventively, gives reason to believe that things may well not be that easy in reality.

Another fact to consider is that the directions that were identified as improving the business case, are in practice not realistic. Scaling up the business operations focusing on CCTV systems is not considered feasible for many current state SP’s. Only for SP4, the results of the case study could provide recommendations on which they could act. It is however unlikely that they would apply this to movable bridges on a large scale. For other electronics comprising movable bridges, is can be said that they have performed less on the selection criteria from chapter 6. It can therefore be said that although the absolute values of the results presented are highly uncertain, it is expected that in practice, implementing predictive maintenance for electronics in movable bridges is not viable.

On the positive side, the frameworks applied during the determination of the future state, as well as the governing principles that were used during modelling have all been accepted in the academic world. Furthermore, the direction and order of magnitude of the results have quite well met the general expectations that were formed during the literature review. It is therefore believed that the model presented is suitable to provide insight into the relative effect of the model parameters that are relevant to the hypothesis. Even though the profitability of the future state cannot be confirmed nor falsified with certainty, the method and tool developed in this thesis have provided a means to assess the costs and benefits of implementing several maintenance and end-of-life recovery policies. The direction of change to the overall policy that were identified as improving the KPI scores, can therefore be used to make recommendations.

10. Conclusions

The objective of this research was to investigate promising changes to the maintenance and recovery strategy for electronics within Dutch movable bridges, due to which the maintenance supply chain's cost performance, operational performance, and environmental performance would improve, while complying with the boundary conditions set by the AO, SP, and OEM. The following was hypothesized:

> *Implementing monitoring based maintenance with recovery is preferred over the current manual inspection based maintenance strategy without recovery, regarding OPEX, CO_2 emissions and equipment downtime, and becomes profitable within 10 years.*

Based on research of both practice and literature, the following could be concluded regarding the prerequisites for a future state strategy:

- The AO should keep full ownership of strategically vulnerable objects and its critical systems. Furthermore, the OPEX for maintenance should be reduced, a reduction of the CO2 emissions should be realized, and the maximum yearly unexpected downtime should not be exceeded. For both the SP and OEM, it can be said that at a future state should at least be profitable.

- A future state strategy should be accompanied by improved electronic system (eco-) design, improved component level information, and improved stakeholder coordination mechanisms such as contracts and business models. Such changes require clear and committing regulations from governmental organisations that explicitly demand sustainable practices.

Within these boundaries, the potential of a predictive maintenance and remanufacturing policy has been identified for electronic systems in movable bridges that are not part of the main road and waterway networks. The following was concluded:

- A promising fulfilment of stakeholder roles involves a collaborative relationship between the OEM and SP on the one side, and a customer-supplier relation between the SP and AO on the other. In the collaborative agreement, the OEM would design and deliver technical systems according 'Eco-design' standards, whereas the SP would fulfil the role of OEM certified contract remanufacturer. Between the AO and SP, a long-term use based contract would be established in which the SP retains ownership, environmental performance criteria are concretized, and there is improved communication between the AO and SP before, during and after contract establishment.

- The SP/OEM combination could adopt a remanufacturing-with-upgrade based value proposition, by investing in component level monitoring systems, real time remote data analysis and decision support systems. The hardware requirements could be fulfilled by implementing a distributed control information support system with local decision making functionality and a corresponding predictive policy.

At the cost of capital investments, these changes were expected to decrease OPEX, unexpected downtime, and CO_2 emissions. To quantify this trade-off, a SP centred decision support tool has been built using AIMMS to perform a comparative simulation case study. By knowledge of the author, it is the first simulation based tool for this sector that quantifies the costs and benefits of implementing CE practices.

Within the tool, the following aspects were modelled:

- A discrete network with a SP depot and a geographically distributed 'fleet' of electronic assets at known locations and transport distances.
- A rolling horizon simulation setting, considering a daily increase of failure probability, a corresponding Simple Moving Average failure probability prognosis, and a random simulation of failure at each time step.
- Based on the prognostic curve, maintenance tasks are scheduled for future days by minimizing the expected costs over the planning interval. To this end, an Outer Approximation algorithm combining a CONOPT V13.4 algorithm and a IBM CPLEX 12.6.3 algorithm was used to obtain locally optimized schedules.
- Based on the set of tasks from scheduling and tasks from failure simulation, a minimum latency route is obtained for the maintenance crew while considering visiting priorities. Here, IBM CPLEX 12.6.3 was used for solving.
- Systems that are replaced preventively are assumed to be remanufactured at the depot whereas correctively replaced systems are assumed to be sold off to material recyclers.

After verification and validation, the tool was applied to a fictive, practice based case, with CCTV camera assemblies as the system of focus. The cameras were assumed to be remanufacturable by replacing their pan-tilt-zoom motor once an incipient failure has been detected. It was deducted that a 40% reduction in emissions, a yearly downtime of less than 2 hours per asset, and a break-even point of less than 10 years should be achieved. The future state should furthermore be realistic in terms of operational load on the current state SP organization. Both the current state *run-to-failure* policy without recovery (scenario 1), a future state predictive maintenance policy with remanufacturing (scenario 2a), and a scale-up (scenario 2b) have been simulated. The following was concluded:

- Both predictive scenarios outperform the current state sufficiently regarding CO_2 emissions and unexpected downtime.
- Scaling up from 10 to 100 assets while independently servicing each asset does not improve the cost performance of the future state sufficiently to become profitable within 10 years.

Subsequently, several variants of scenario 2a have been analyzed to investigate the economies-of-scale effect on the model KPI's, namely a multi-unit asset expansion (2c), a group-maintenance sub-policy (2d), and a cluster maintenance sub-policy (2e). The following could be concluded:

- Scaling up from 100 single-unit assets to 100 10-unit assets while independently servicing each unit results in acceptable profitability, but exceeds the vehicle, personnel, and stock capacity constraints of the SP. Applying group maintenance exacerbates this situation.
- Applying clustering together with an increase of the monthly service fee per asset from €100 to €115, while reducing the CAPEX per asset from €12000 to €10000, would result in a situation that complies with all constraints considered.
- Implementing remanufacturing is however not feasible soon, while laws and regulations are not in place nor will they be sufficient without substantial additional subsidization.

It can thus be concluded that implementing a predictive maintenance policy is preferred considering OPEX, CO2 emissions, and equipment downtime, and that in an ideal case, this could become profitable within 10 years. In the practice of movable bridges however, this ideal case is far from realistic. Furthermore, the hypothesized CO_2 emission reductions are highly uncertain because remanufacturing does not improve the business case by a long shot.

11. Recommendations

Recommendations to practice

By knowledge, this is the first time that the concepts of CE are being assessed quantitatively in a simulation setting within this sector. Despite several 'what-if' assumptions, implementation of the proposed changes was not deemed feasible. To further increase the feasibility of the future state on the long term, the following measures can be recommended:

Policy makers

- Further develop law and regulations that enforce the development of eco-design measures, sustainable business models, and stakeholder collaboration. Improved versions of the CO_2 – tax plan, as well as additional subsidization would qualify for this. Care should be taken in avoiding a mere top-down approach while devising these laws and regulations, to reduce the current mismatch between policy makers (top level AO) and the daily responsible (district level AO).

AO, SP, and OEM

- Identify a common ground regarding the respective organisational drivers, and propose a corresponding subsidizing scheme to policy makers.
- Develop contracts that stimulate a better cooperation between the responsible, executing and facilitating stakeholder parties, with the goal of improving the supply chain performance regarding costs, eco-efficiency, and equipment availability. This should involve attracting more specialty knowledge, and enabling more knowledge transfer.
- Investigate the possibility of setting up a predictive maintenance and remanufacturing pilot program for a specific system in a specific geographical area by one or more specialized stakeholders. Such a program could give valuable insights into the financial, technical, and organisational implications for the involved stakeholders, while providing a better source of operational validation for the tool presented in this thesis.
- Improve the data gathering regarding the operational reliability of equipment. This data could be processed into a form that allows a more accurate repetition of the analysis presented in this thesis. The results of this refined analysis could provide better insight into the profitability of the future state.

<u>Regarding eventual implementation</u>:

- Work towards scaling up operations in promising service areas, while standardizing equipment and applying phased rejuvenation, to enable the implementation of a clustering policy.
- Actively pursue the minimization of capital investments required to implement the policy as proposed, while looking for possibilities to increase the service level experienced by Object Owner and the corresponding service fee.

Recommendations to science

Considering the literature that was researched as a part of this thesis, the model developed in chapter 4 is the first attempt to incorporate both prognostics based scheduling, minimum latency routing with visit priorities, and end-of-life recovery in a rolling horizon setting. For further details regarding the scientific aspect of this thesis, the reader is referred to appendix A. Regarding the scope and corresponding research limitations of this study, the following directions for further research are recommended:

Application to other cases

- Investigate the possibility of applying the model on other system types (e.g. mechanical), system levels, time scales, and possibly on other sectors. This should be accompanied with a revision of the assumptions regarding equipment reliability, capacity constraints and the potential for recovery.

Model development

- ***Diagnosis & Prognosis***
    - Further develop the model to account for different levels of prognostic efficiency, by allowing to vary the frequency and accuracy of performance assessment.
    - Develop a proper failure model and a corresponding data analysis approach to couple real monitoring signals to performance degradation. Probably a coupling with other software, such as MATLAB, would be required here.
- ***Scheduling***
    - Establish a coupling of scheduling and routing cost factors, possibly by applying simulation based optimization methods as described in (Carson and Maria 1997).
    - Further develop the scheduling model to account for an additional grouping optimization as in (Van Horenbeek and Pintelon 2013).
    - Optimize both costs and CO_2 by considering them in a single objective function.
- ***Routing***
    - Investigate the implications of expanding to a multi-crew operation by formulating a k-TRP with corresponding solution methods such as in (Jothi and Raghavachari 2007).
    - Investigate the merits of implementing clustering and sweeping algorithms on routing model outputs.
    - Expand the simulation capabilities of the model to enable an efficiency comparison of different routing strategies to the optimized routes.
- ***Recovery***
    - Improve the modelling of recovery process by coupling the actual RUL at time of replacement to remanufacturability as in (Hu et al. 2014; Hua, Liu, and Zhang 2015)

References

Alonso, Stephane. 2016. “Vervuilen Is Nu Spotgoedkoop.” *NRC next*.

Andrew-munot, Magdalene, Raafat N Ibrahim, and Ervina Junaidi. 2015. “An Overview of Used-Products Remanufacturing.” 5(1): 12–23.

Andrews, John, Darren Prescott, and Florian De Rozières. 2014. “A Stochastic Model for Railway Track Asset Management.” *Reliability Engineering and System Safety* 130: 76–84.

Angel-bello, Francisco, Ada Alvarez, and Irma García. 2012. “Two Improved Formulations for the Minimum Latency Problem.” *Applied Mathematical Modelling* 37(4): 2257–66.

Arnold, Jens M., Beata S. Javorcik, and Aaditya Mattoo. 2011. “Does Services Liberalization Benefit Manufacturing Firms?. Evidence from the Czech Republic.” *Journal of International Economics* 85(1): 136–46.

Ashraf, Labib. 2008. “Computerised Maintenance Management Systems.” In *Complex System Maintenance Handbook*,.

Balcik, Burcu, Benita Beamon, and Karen Smilowitz. 2008. “Last Mile Distribution in Humanitarian Relief.” *Journal of Intelligent Transportation Systems* 12(April): 51–63.

Berger, I., D. Healy, and M. Tilley. 2015. 2 *Movable Span Bridge Study Volume 2 : Bascule and Swing Span Bridges*.

Besnard, François. 2013. “On Maintenance Optimization for Offshore Wind Farms.” Chalmers University of Technology.

Bigum, Marianne, and Thomas H Christensen. 2010. *Waste Electrical and Electronic Equipment*.

Blum, Avrim et al. 1994. “The Minimum Latency Problem.” *Computers and Operations Research*: 5–94.

Borenstein, Y et al. 2010. “On the Partitioning of Dynamic Workforce Scheduling Problems.” *European Journal of Operational Research*.

Bouvard, K., S. Artus, C. Bérenguer, and V. Cocquempot. 2011. “Condition-Based Dynamic Maintenance Operations Planning & Grouping. Application to Commercial Heavy Vehicles.” *Reliability Engineering and System Safety* 96(6): 601–10.

Brito, Marisa P De, Rommert Dekker, and Simme Douwe P Flapper. 2004. “Reverse Logistics : A Review of Case Studies.” *Learning* (1998): 0–35.

Van den Broek, Ton. 2014. “Cost - Sensitivity Analyses for Gearbox Condition Monitoring Systems Offshore.” Delft University of Technology, Eindhoven University of Technology.

Camci, Fatih. 2014. “The Travelling Maintainer Problem: Integration of Condition-Based Maintenance with the Travelling Salesman Problem.” *Journal of the Operational Research Society* 65(9): 1423–36.

———. 2015. “Maintenance Scheduling of Geographically Distributed Assets with Prognostics Information.” *European Journal of Operational Research* 245(2): 506–16.

Carson, Yolanda, and Anu Maria. 1997. “Simulation Optimization: Methods and Applications.” *Proceedings of the 29th conference on Winter simulation (1997)*: 118–26.

Cassina, Jacopo, Marco Taisch, Matteo Zanotto, and Marco Gerosa. 2009. “Proposal for a Methodology for the Development of Predictive Maintenance Decision Support Systems.” In *Recent Advances for Maintenance and Infrastructure Management*,.

Chierici, Elisabetta, and Giacomo Copani. 2016. “Remanufacturing with Upgrade PSS for New Sustainable Business Models.” *Procedia CIRP* 47: 531–36.

Cigolini, Roberto D., Abhijit V. Desmukh, Lorenzo Fedele, and Sara A. McComb. 2009. 1 *Recent Advances in Maintenance and Infrastructure Management*. eds. Roberto D. Cigolini, Abhijit V. Desmukh, Lorenzo Fedele, and Sara A. McComb. Springer.

CivieleTechniek. 2016a. “Risico’s En Kosten Uitstel Onderhoud in Beeld, Het Meest Kosteneffectieve Onderhoudsmoment.”

———. 2016b. “Stappenplan Voor CO2 Reductie Bij Beheer En Onderhoud.”

Coelman, B.H. 2001. *Beweegbare Bruggen En Hun Levensduur*. Matrijs.

Cost Engineers. 1992. *Electrotechnisch Begroten*.

Council for the Environment and Infrastructure. 2015. *Circular Economy*.

Cramer, Jacqueline. 2014. *Moving Towards a Circular Economy in the Netheralnds: Challenges and Directions*.

Damjanovski, Vlado. 2014. *CCTV: Networking and Digital Technology*. 3rd ed. Elsevier.

Debo, Laurens, R. Canan Savaskan, and Luk N. Van Wassenhove. 2003. “Coordination in Closed-Loop Supply Chains.” In *Reverse Logistics*, eds. Rommert Dekker, Moritz Fleischmann, Karl Inderfurth, and Luk N. Van Wassenhove. Rotterdam: Springer, 205–311.

Dekker, Rommert. 1996. “Applications of Maintenance Optimization Models : A Review and Analysis.” *Reliability Engineering and System Safety* 51: 229–40.

Dekker, Rommert, Moritz Fleischmann, Karl Inderfurth, and Luk N. Van Wassenhove. 2003. “Quantitative Models for Reverse Logistics Decision Making.” In *Reverse Logistics*, eds. Rommert Dekker, Moritz Fleischmann, Karl Inderfurth, and Luk N. Van Wassenhove. Rotterdam: Springer, 29–41.

———. 2004. *Reverse Logistics, Quantitative Models for Closed-Loop Supply Chains*. Rotterdam: Springer.

Dekker, Rommert, Ralph E. Wildeman, and Frank A. van der Duyn Schouten. 1997. “A Review of Multi-Component Maintenance Models with Economic Dependence.” *Mathematical Methods of Operations Research* 45(3): 411–35.

Doodeman, M. 2013. “PGGM Koopt Snelweg Utrecht-Veenendaal.” http://www.cobouw.nl/artikel/977601-pggm-koopt-snelweg-utrecht-veenendaal.

Duran, Marco A., and Ignacio E. Grossmann. 1986. “An Outer-Approximation Algorithm for a Class of Mixed-Integer Nonlinear Programs.” *Mathematical Programming* 36(3): 307–39.

Eker, O F, F Camci, and I K Jennions. 2012. “Major Challenges in Prognostics : Study on Benchmarking Prognostics Datasets.” *European Conference of Prognostics and Health Management Society*: 1–

Ellen MacArthur Foundation. 2015. *Towards a Circular Economy: Business Rationale for an*

Accelerated Transition.

Ellram, Lisa M, Wendy L Tate, Corey Billington, and C. Ellram, L. M., Tate, W. L., & Billington. 2004. “Understanding and Managing the Services Supply Chain.” *Journal of Supply Chain Management* 40(4): 17–32.

European Parliament and Council. 2008. EC directives 2008 *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Waste Framework*.

Ezzine, Io, F Semet, and H Chabchoub. 2010. “New Formulations for the Traveling Repairman Problem.” In *8th International Conference of Modeling and Simulation*, Hammamet, 8–13.

Fleischmann, Moritz. 2001. *Quantitative Models for Reverse Logistics*.

Gemeente Delft. 2010. *Beheerplan Kunstwerken Delft*.

Gooijer, Kees De, and Jan Van Noortwijk. 2001. *Module Levensduur Verlengend Onderhoud*.

Guclu, Adem, H. Yilboga, O.F. Eker, and Fatih Camci. 2010. “Prognostics with Autoregressive Moving Average for Railway Turnouts.” *Annual Conference of the Prognostics and Health Management Society*: 1–6.

Haans, Robin. 2016. “Optimization of Maintenance Strategy for Production Equipment on TEPNL Assets.” Delft University of Technology.

Hastings, Nicholas A.J. 2010. *Physical Asset Management*. Brisbane: Springer.

Hieminga, Gerben. 2015. ING Economics Department *Rethinking Finance in a Circular Economy*.

Hilberink, A. 2009. “Generating Knowledge with a Software Model ‘A Knowledge-Based Expert System for Condition Monitoring of an Hydraulic Brake System.’” Delft University of Technology.

Van Horenbeek, Adriaan, and Liliane Pintelon. 2013. “A Dynamic Predictive Maintenance Policy for Complex Multi-Component Systems.” *Reliability Engineering and System Safety* 120: 39–50.

Hu, Yawei, Shujie Liu, Huitian Lu, and Hongchao Zhang. 2014. “Remaining Useful Life Assessment and Its Application in the Decision for Remanufacturing.” *Procedia CIRP* 15: 212–17.

Hua, Yawei, Shujie Liu, and Hongchao Zhang. 2015. “Remanufacturing Decision Based on RUL Assessment.” *Procedia CIRP* 29: 764–68.

IMaintain. 2016. “ProBo, LCC En SLA Zijn Radertjes in Dezelfde Keten.”

INCOSE. 2015a. *Systems Engineering Handbook 4E*.

Isermann, Rolf. 2011. *Fault-Diagnosis Applications: Model-Based Condition Monitoring: Actuators, Drives, Machinery, Plants, Sensors, and Fault-Tolerant Systems*.

Jothi, Raja, and Balaji Raghavachari. 2007. “Approximating the K-Traveling Repairman Problem with Repairtimes.” *Journal of Discrete Algorithms* 5(2 SPEC. ISS.): 293–303.

Kalgren, Patrick W et al. 2007. *Digital Electronic Systems*.

Kobbacy, Khairy A.H., and D.N.Prabhakar Murthy. 2008. 1 *Complex System Maintenance Handbook*. eds. Khairy A.H. Kobbacy and D.N.Prabhakar Murthy. London: Springer.

Kokkinaki, Angelika, Rob Zuidwijk, Jo van Nunen, and Rommert Dekker. 2003. “ICT for Enabling Reverse Logistics.” In *Reverse Logistics*, Rotterdam: Springer.

Kraijema, S. 2015. “Optimizing the Maintenance Policy for Light Rail Rolling Stock at HTM.” Delft University of Technology.

Kruegle, Herman. 2006. *CCTV Surveillance*. 2nd ed. Springer.

Kuo, Tsai C. 2013. “Waste Electronics and Electrical Equipment Disassembly and Recycling Using Petri Net Analysis: Considering the Economic Value and Environmental Impacts.” *Computers and Industrial Engineering* 65(1): 54–64.

Lacy, Peter. 2015. “Using Digital Tech to Spin the Circular Economy.” : 5.

Lakhan, Calvin. 2016. “Calculating the Emissions Impacts of Waste Electronics Recycling in Ontario, Canada.” *C* 2(2): 11.

Lee, Jay, and Haixia Wang. 2008. “New Technologies for Maintenance.” In *Complex System Maintenance Handbook*,.

Li, Zhaojun, Jian Guo, and Ruolin Zhou. 2016. “Maintenance Scheduling Optimization Based on Reliability and Prognostics Information.” *2016 Annual Reliability and Maintainability Symposium (RAMS)*: 1–5.

Lidén, Tomas. 2015. “Railway Infrastructure Maintenance - A Survey of Planning Problems and Conducted Research.” *Transportation Research Procedia* 10(July): 574–83.

Matsumoto, M.a, S.b Yang, K.c Martinsen, and Y.d Kainuma. 2016. “Trends and Research Challenges in Remanufacturing.” *International Journal of Precision Engineering and Manufacturing - Green Technology* 3(1): 129–42.

Morlet, Andrew et al. 2016. “Intelligent Assets: Unlocking the Circular Economy Potential.” *Ellen MacArthur Foundation*: 1–25.

Muller, Gerhard, Klaus Richter, Cathrin Plate, and Johannes Mandelartz. 2009. “Optimizing Maintenance Processes With RFID.” In *Recent Advances for Maintenance and Infrastructure Management*,.

Murthy, D. N. Prabhakar, and Nat Jack. 2014. *Extended Warranties,Maintenance Service and Lease Contracts*.

Nijhof, Drs. P., and Ir. G.J. Arends. 2004. *Historische Sluizen En Stuwen; Waardering En Instandhouding*. Matrijs.

OREDA. 2015. *OREDA*. 6th ed.

Pecht, Michael, and Jie Gu. 2009. “Physics-of-Failure-Based Prognostics for Electronic Products.” *Transactions of the Institute of Measurement and Control* 4(31): 309–22.

Pecht, Michael, Brian A Tuchband, and Michael G Pecht. 2016. *The Use of Prognostics in Military Electronic Systems The Use of Prognostics in Military Electronic Systems*.

Peelen, W. 2016. “Infra Slimmer Instandhouden Met Data.” *LichtKogel*.

Pillac, Victor, Michel Gendreau, Christelle Guéret, and Andrés L Medaglia. 2011. “A Review of Dynamic Vehicle Routing Problems.” *Cirrelt-2011-62*: 0–28.

Pintelon, R, and A Parodi-Herz. 2008. “Maintenance Management: An Evolutionary Perspective.” In *Complex System Maintenance Handbook*,.

Ramakrishnan, Arun, and Michael G. Pecht. 2003. “A Life Consumption Monitoring Methodology for Electronic Systems.” *IEEE Transactions on Components and Packaging Technologies* 26(3): 625–

Ramuhalli, P et al. 2014. *Local-Level Prognostics Health Management Systems Framework for Passive AdvSMR Components - Interim Report*.

Reimann, Johan, and Greg Kacprzynski. 2009. “Using Condition Based Maintenance to Improve the Profitability of Performance Based Logistic Contracts.” *Annual Conference of …*: 1–9.

de Ridder, H.A.J. 2017. “Rijkswaterstaat Wéét Niks Meer.” *NRC next*.

Rijkswaterstaat. 2008. *Waterhuishouding En Waterverdeling in Nederland*.

Sargent, Robert G. 2010. “Verification and Validation of Simulation Models.” *Proceedings of the 42nd Winter simulation conference*: 166–83.

Schippers, Edith. 2012. *Rijksbrede Programma Circulaire Economie*.

Simchi-Levi, David, Xin Chen, and Julien Bramel. 2005. *The Logic of Logistics*. 2nd ed. ed. Stephen Robinson Peter Glynn. Springer.

Smith, David J. 2013. “Power-by-the-Hour: The Role of Technology in Reshaping Business Strategy at Rolls-Royce.” *Technology Analysis & Strategic Management* 25(8): 987–1007.

Sonnenfeld, Greg, Kai Goebel, and Jose R. Celaya. 2008. “An Agile Accelerated Aging, Characterization and Scenario Simulation System for Gate Controlled Power Transistors.” *AUTOTESTCON (Proceedings)*: 208–15.

Spit, Wim et al. 2012. “Ronde-Tafel Bijeenkomst Kosten-Batenanalyse En Beheer En Onderhoud.”1–8

Srinivasan, Rengarajan, and Ajith Kumar Parlikad. 2013. “Value of Condition Monitoring in Infrastructure Maintenance.” *Computers and Industrial Engineering* 66(2): 233–41.

Stanford. 2015. “The Social Costs of Carbon.” http://news.stanford.edu/2015/01/12/emissions-social-costs-011215/.

Tinga, Tiedo. 2010. “Application of Physical Failure Models to Enable Usage and Load Based Maintenance.” *Reliability Engineering and System Safety* 95(10): 1061–75.

Toktay, Beril L., Erwin A. van der Laan, and Marisa P. de Brito. 2003. “Managing Product Returns.” In *Reverse Logistics*, eds. Rommert Dekker, Moritz Fleischmann, Karl Inderfurth, and Luk N. Van Wassenhove. Rotterdam: Springer, 45–64.

Tsang, Albert H.C. 2002. 8 Journal of Quality in Maintenance Engineering *Strategic Dimensions of Maintenance Management*.

Tweede kamer. 2016. “Notulen Tweede Kamer.”

Tweede Kamer. 2013. *Notulen Tweede Kamer*.

Veeke, Hans P.M., Jaap A Ottjes, and Gabriel Lodewijks. 2008. *The Delft Systems Approach*. Delft: Springer.

Verkeerskunde. 2016a. “Ons Vaarwegennet Staat Op Een Kruispunt.”

———. 2016b. "Transitie Naar Nieuwe Infrastructuren En Nieuw Mobiliteitsgedrag."

Vichare, Nikhil M, and Michael G Pecht. 2006. "Prognostics and Health Management of Electronics." *COMPONENTS AND PACKAGING TECHNOLOGIES* 29(1): 222–29.

Vichare, Nikhil, and Michael Pecht. 2006. "Enabling Electronic Prognostics Using Thermal Data." *Electronic Products and Systems* (September): 27–29.

Viswanath Dhanisetty, V.S. 2014. "Weibull Distribution Based Multi-Objective Maintenance Interval Optimisation for Cross-Industrial Application." TU Delft.

W+B. 2013. 1 *Renovatie Brug En Sluis Te Blokzijl*.

———. 2014a. *Hoogheemraadschap van Delfland*.

———. 2014b. *Oplegnotitie Onderhoudsplanning*.

———. 2014c. *Werkomschrijving Keersluis Maassluis*.

———. 2015. *Rapportage Conditiemeting NEN 2767-4*.

Wan, Hung Da, and Venkata Krishna Gonnuru. 2013. "Disassembly Planning and Sequencing for End-of-Life Products with RFID Enriched Information." *Robotics and Computer-Integrated Manufacturing* 29(3): 112–18.

Wang, Yulan, Stein W Wallace, Bin Shen, and Tsan-Ming Choi. 2015. "Service Supply Chain Management: A Review of Operational Models." *European Journal of Operational Research* 247(3): 685–98.

Williams, J.H. 1994. *Condition-Based Maintenance and Machine Diagnostics*. Kluwer Academic Publishers.

Witjes, Sjors, and Rodrigo Lozano. 2016. "Resources , Conservation and Recycling Towards a More Circular Economy : Proposing a Framework Linking Sustainable Public Procurement and Sustainable Business Models." *Resources, Conservation & Recycling* 112: 37–44.

Yuan, Zengwei, Jun Bi, and Yuichi Moriguichi. 2006. "The Circular Economy." *Journal of Industrial Ecology* 10(1).

Zeegers, I. 2016a. "Asset Management Ontmoet Circulaire Economie." *LichtKogel*.

———. 2016b. "Onze Infrastructuur Toekomstbestendig Vervangen." *LichtKogel*.

Zhang, Xugang, Hua Zhang, Zhigang Jiang, and Yanhong Wang. 2013. "A Decision-Making Approach for End-of-Life Strategies Selection of Used Parts." *International Journal of Advanced Manufacturing Technology*: 1–8.

Appendices

Appendix A. Research Paper

Appendix B. Results

Contents

1. List of figures

2. List of Tables

3. Comparative Case Study Results

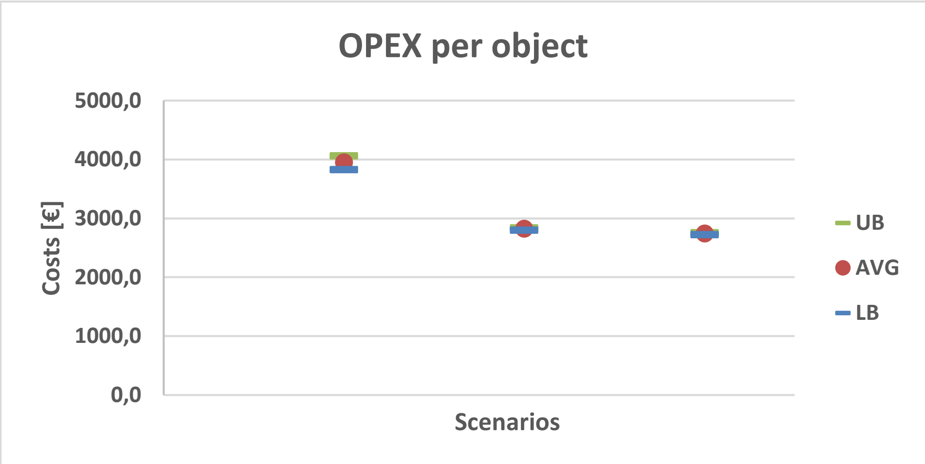


Figure B1. Total OPEX Per object Result

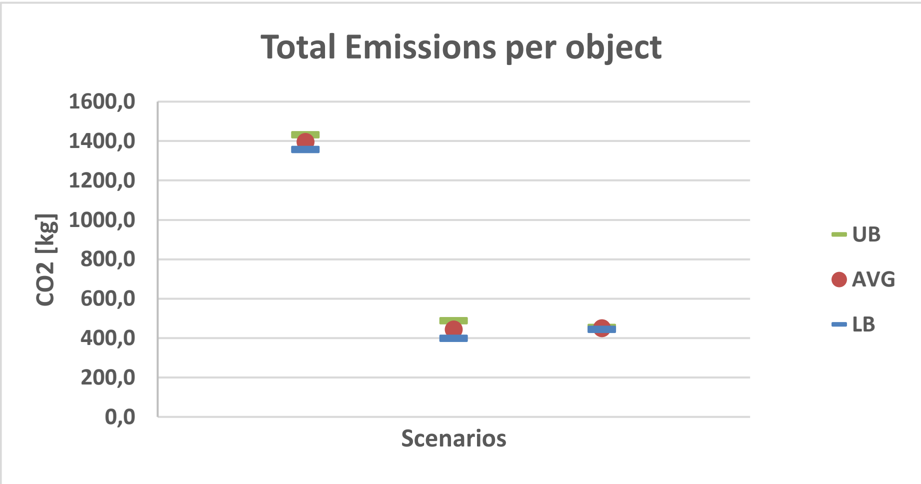


Figure B2. Total Emissions Per object Result

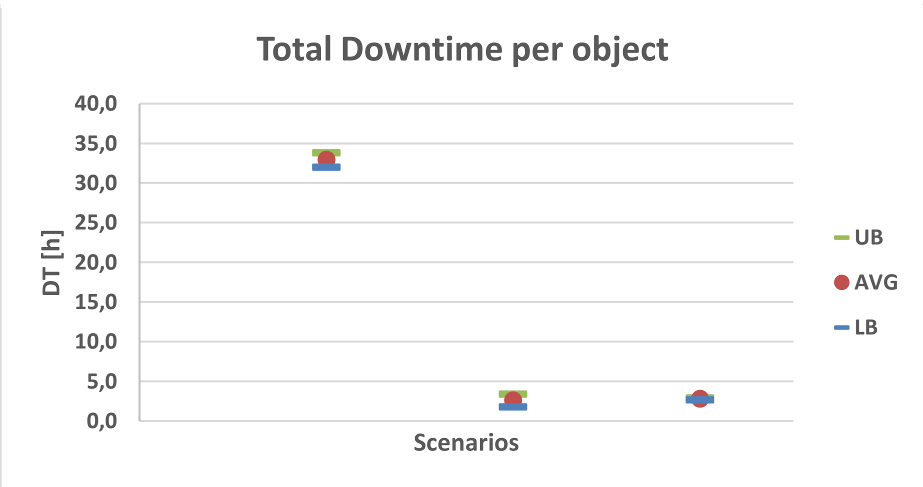


Figure B3. Total Downtime Per object Result

4. Sensitivity Analysis

CAPEX

One of the main determining factors for meeting the profitability constraint, is the CAPEX of implementation. In appendix E, it was estimated what a reasonable CAPEX per object would be, and what kind of scale effect could be expected when increasing the scale of implementation. Table x depicts the BEP for scenario 2b for several unit CAPEX values. It can be seen here that for a capital investment per object of €9000, the BEP drops to less than 10 years.

Table B1. CAPEX sensitivity (ROI)

OPEX per obj. [€]	Total OPEX [€]	CAPEX per obj. [€]	Total CAPEX [€]	REVENU per obj. [€]	Total REVENU [€]	ROI [%]
2741,6	274160	$12^{e}3$	$12^{e}5$	100	$12^{E}5$	-23
2741,6	274160	11e3	11e5	100	$12^{E}5$	-16
2741,6	274160	10e3	10e5	100	$12^{E}5$	-7
2741,6	274160	9e3	9e5	100	$12^{E}5$	3

Service Revenue

Similarly, the service revenue affects profitability. In table x, the service revenue for scenario 2b is varied. For a service revenue of 130 [€] per month, scenario 2b becomes profitable.

Table B2. Service Revenue Sensitivity (ROI)

OPEX per obj [€]	TotalOPEX [€]	CAPEX per obj [€]	TotalCAPEX [€]	REVENU per obj [€]	Total REVENU [€]	ROI [%]
2741,6	274160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-22,8
2741,6	274160	$12^{E}3$	$12^{E}5$	110	$13.2^{E}5$	-12,8
2741,6	274160	$12^{E}3$	$12^{E}5$	120	$14.4^{E}5$	-2,8
2741,6	274160	$12^{E}3$	$12^{E}5$	130	$15.6^{E}5$	7,2

OPEX

The final cost factor to consider is the OPEX. See table x for the value at which scenario 2b becomes profitable, by changing the OPEX per object. To become profitable, a negative OPEX is required.

Table B3. OPEX sensitivity (ROI)

OPEX per obj [€]	TotalOPEX [€]	CAPEX per obj [€]	TotalCAPEX [€]	REVENU per obj [€]	Total REVENU [€]	ROI [%]
2741,6	274160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-22,8
2241,6	224160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-18,7
1741,6	174160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-14,5
1241,6	124160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-10,3
741,6	74160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-6,2
241,6	24160	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	-2,0
-258,4	-25840	$12^{E}3$	$12^{E}5$	100	$12^{E}5$	2,2

Service Times

Regarding service times, it can be said that it has a linear effect on the model KPI's. See figure x. Every increase of the service time by 1 hour, results in an approximate increase of the OPEX by approximately €7000 per object, and an increase of the TDT by approximately 9 hours per object respectively. Compared to scenario 2b, this still results in an acceptable total downtime per object per year (0.28 + 9/10 ≈ 1.2 <2). For the OPEX however, and therefore for the profitability of the implementation, this is a showstopper. In the eventual design of a predictive maintenance policy therefore, sufficient effort should be put in designing product and processes that minimize the repair time.

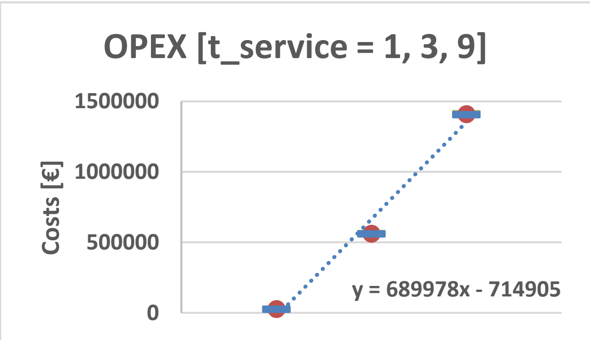


Figure B4. Service time sensitivity (OPEX)

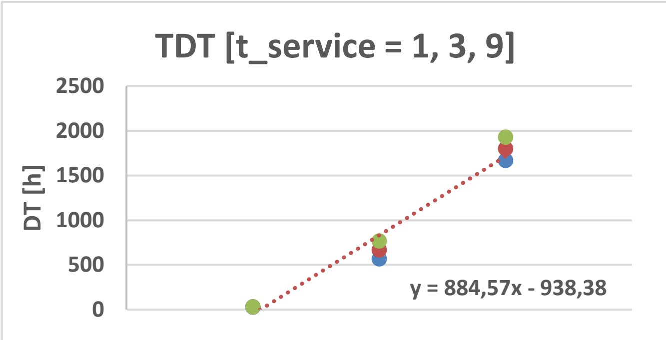


Figure B5. Service time sensitivity (TDT)

Remanufacturing Emissions (E^{u}_{reman})

The dominant parameter in the reduction of the total emissions, is the 'remanufacturing emissions' factor. Here, this amount resembles the expected amount of CO_2 emitted for producing a new PTZ motor to be used as replacement. In practice, this estimation may be wrong for a variety of reasons. By varying this factor, the importance of 'remanufacturability' on the environmental performance (TEm) can be assessed. See figure x for a graphical representation of sensitivity of TEm for changes in E^{u}_{reman}. Approximately for every additional kg of CO_2 emitted during PTZ motor production, roughly 65 kg of additional CO_2 is emitted per object. When considering the target of reducing the baseline emittance per object of 1400 kgCO_2 by 40%, E^{u}_{reman} is only allowed to increase:

- $(TEm_{target} – TEm_{scenario\ 2b})$/gradient = ((0.6*1400)- 450) / 65 = 6 kg CO_2 per unit. (=40%)

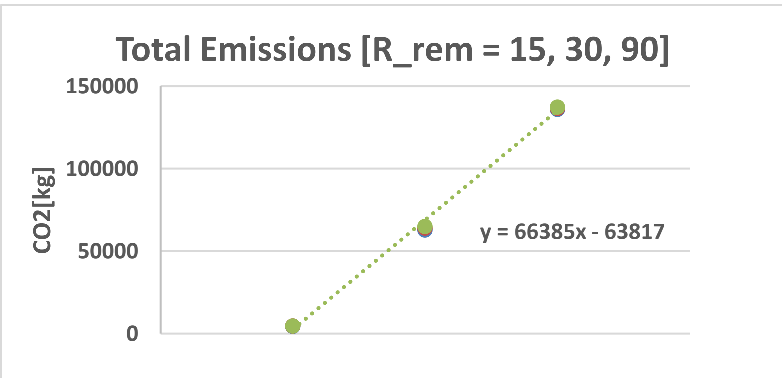


Figure B6. Reman emissions sensitivity (TEm)

5. Predictive policy variants

Table B4. changed input parameters per scenario, compared to chapter 8

	Parameter	Unit	Scenario 2b	Scenario 2c	Scenario 2d	Scenario 2d	
	m		100	100	100	100	
	y		1	10	10	1	
	C_{invest}^{u}	[€ /Obj.]	12000	9600	9600	1200	
	$Rev_{service}^{u}$	[€ /Obj.]	-	100	100		
	$t_{assetlife}^{init}$	$[days]$					See figures below

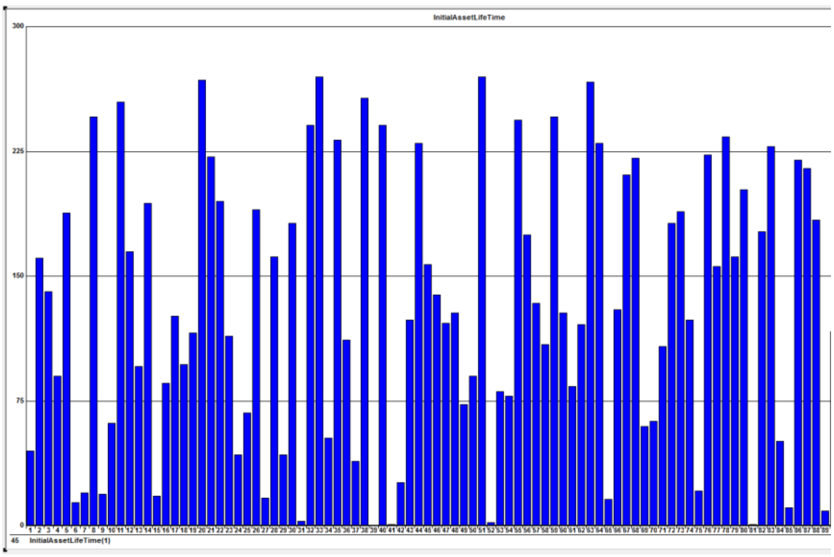


Figure B7. initial asset lifetime in scenario 1 through 2d

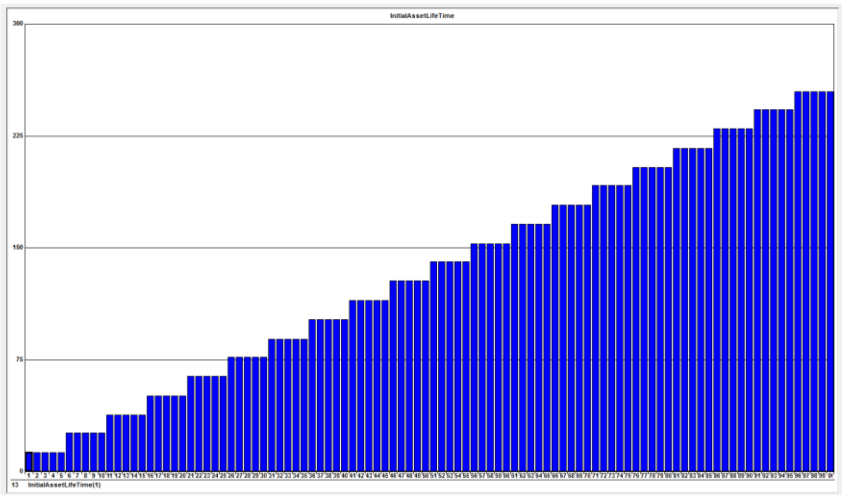


Figure B8. initial asset lifetime for scenario 2e

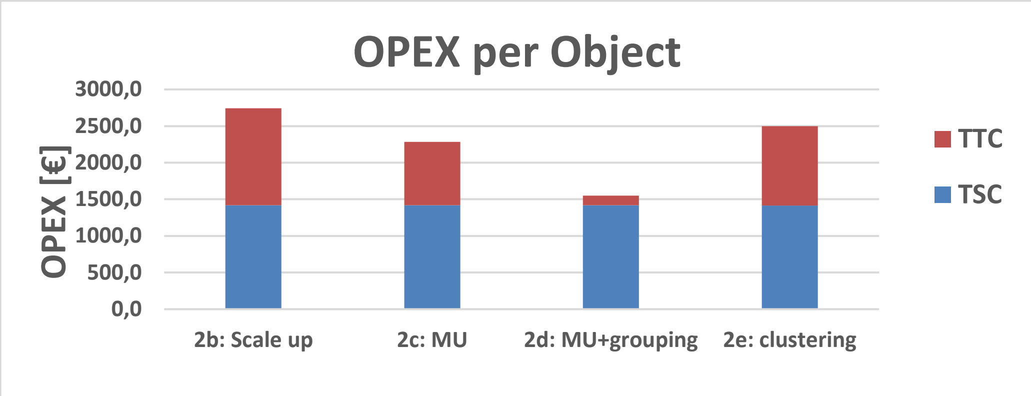


Figure B9

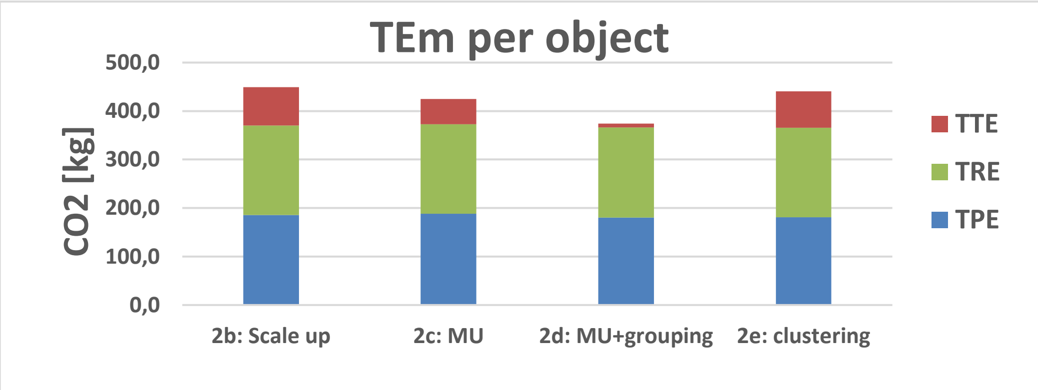


Figure B10

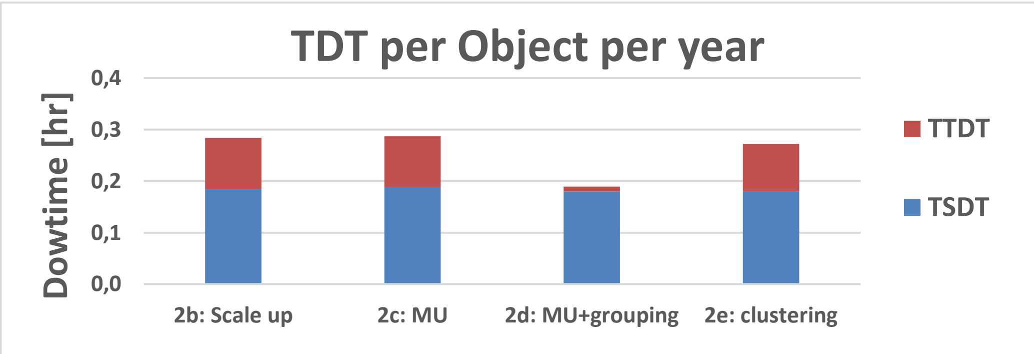


Figure B 11

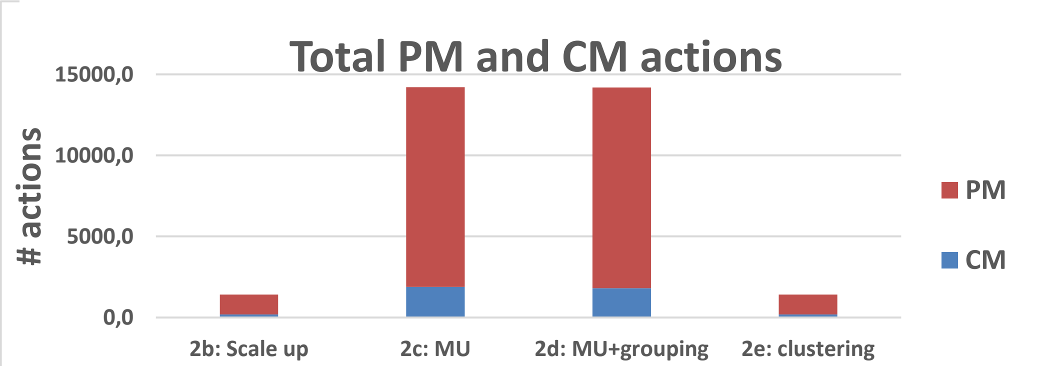


Figure B12

Appendix C. Input parameters

Contents

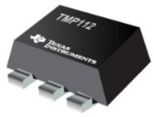
1. List of figures

2. List of tables

3. Investment Costs

The future state as proposed requires the implementation of certain hard - and software components. Here, it is estimated how large the CAPEX for such an implementation for CCTV systems would be. See table x for an estimation of the costs per asset:

Table C2. CAPEX estimations

Cost Factor	Qty [#]	Cost [€]		Source
Sensors	2	200		www.ti.com
	2	200		www.ti.com
Watchdog module	1	1000		www.siemems.com
RFID tag	1	100		www.omni-id.com
Ethernet I/O module	1	500		https://www.icpdas-usa.com
Supervisory Workstation	1/nth	1000		www.abb.com
	Subtotal	3000		
Design	200 %	5000		(Cost Engineers 1992)
Installation	300 %	5000		(Cost Engineers 2003)
	Total	15000		

Besides lower operating costs, it is expected that increasing the scale of operation of scenario 2 would lead to lower normalized CAPEX. Here, it is assumed that the capital investments reduce with 25% when the scale of implementation increases tenfold. This relation is similar to that of public cash withdrawal machines (Struben 2011).

4. Service Revenue

The SP service revenue in the future state is an important factor when determining the BEP. From reviewing an example online (see figure x, http://www.hallandalebeachfl.gov), it could be deducted that for 29 service locations (left), a yearly price of 55000/12/29 ≈ € 150 per asset is a reasonable estimate for a yearly CCTV maintenance service contract. Because we are considering long term contracts, a monthly service revenue of € 100 is assumed.

Appendix - List of covered COHB Properties

Count	Name	
1	Ansin (Municipal Parking Facility)	34
2	B.F. James Park	77
3	City Beach Park (North)	A1
4	City Beach Park (South)	A1 Co
5	City Hall	40
6	City Marina	10
7	Cultural Community Center	41
8	Department of Public Works	63
9	Fire Beach	A1
10	Fire Main	12
11	Foster Community Building	60
12	Foster Park	60
13	Golden Isles Tennis Court	42
14	Golden Isles Kiddie Park	42
15	Hallandale Elementary School	90
16	Hepburn Center	75
17	Historic Village	40
18	Ingalls Park	73
19	Joseph Scavo Park	90
20	Oreste Blake Johnson Park	90
21	Peter Bluesten Park	50
22	Police Department	40
23	Safe Neighborhood, Golden Isles	42
24	Safe Neighborhood, Three Islands	18
25	Sunrise Park	80
26	Sunset Park	81
27	Three Islands Fire	10
28	Foster Corridor, 4th st	Fo
29	Foster Corridor, 7th st	Fo

SOLD TO:
City of Hallandale Beach
400 South Federal Highway
Hallandale Beach, FL 33009
Maylin Aleman

SHIPPED TO:
Same

QUOTE NUMBER	AT0100814-01
QUOTE DATE	October 8, 2014
OUR ORDER NO	
PO NUMBER	
TERMS	Net 30
SALES REP	L. Zerne
SHIPPED VIA	N/A
F.O.B.	City, State
PREPAID or COLLECT	COLL

SERVICE LEVEL MAINTENANCE AGREEMENT

QUANTITY	DESCRIPTION	QUARTLY PRICE	ANNUAL AMOUNT
	COHB - CCTV Surveillance and Access Control		
Quarterly Rate	**City of Hallandale Beach: Monthly Maintenance Agreement**	13,750.00	$55,000.00
	CCTV Surveillance System Maintenance Access Control System Maintenance		
	Agreement duration: October 1st, 2014 thru September 30th, 2015		
	Payment Stage: Quarterly Payment Invoiced 1st of the Month		
		SUBTOTAL	$55,000.00
		TAX	$ -
		FREIGHT	$ -
			$ 55,000.00 **PAY THIS AMOUNT**

Figure C4. Service revenu example

5. Failure probability curve estimation

For the determination of the failure probability curve, the following sources where used:

- The Offshore and Onshore Reliability Database (OREDA 2015)
- A thesis from the TU Delft in cooperation with the World Class Maintenance (WCM) organisation on cross industrial application of Weibull analyses (Viswanath Dhanisetty 2014).
- Maintenance event log from SP2.
- OEM CCTV camera brochure (JVC 2011).

Specified asset lifetime

- In the OEM brochure, an expected CCTV lifetime of 3 years is specified (≈ 1000 days)
- From the maintenance event log of 10 objects over the course of a year, it could be deducted that in the year 2014, 16 CCTV camera assemblies had failed due to a failure of the PTZ. (≈ 0.625 year ≈ 250 days)

Based on these numbers, a specified lifetime of 365 days is assumed (of which 3/4th (= 275 days) is assumed to be 'useful life').

Increment estimation

See figure x and y for the assumed Weibull pdf and CDF respectively. Note that the wear out increment is estimated by linearizing the wear out cumulative failure probability curve. During simulation, a scale parameter (eta) of 100 is assumed, resulting in a wear out increment of ±0.005. The resulting Weibull pdf (Weib.(3,100)) is similar to the one deduced by Viswanath Dhanisetty (2014) for a wearing boom-drive unit in the rail sector. Because of the focus on PTZ wear out failures, the initial failure probability is assumed very low, and useful life increment is assumed to be very small. This is done to prevent a large random failure effect during simulation.

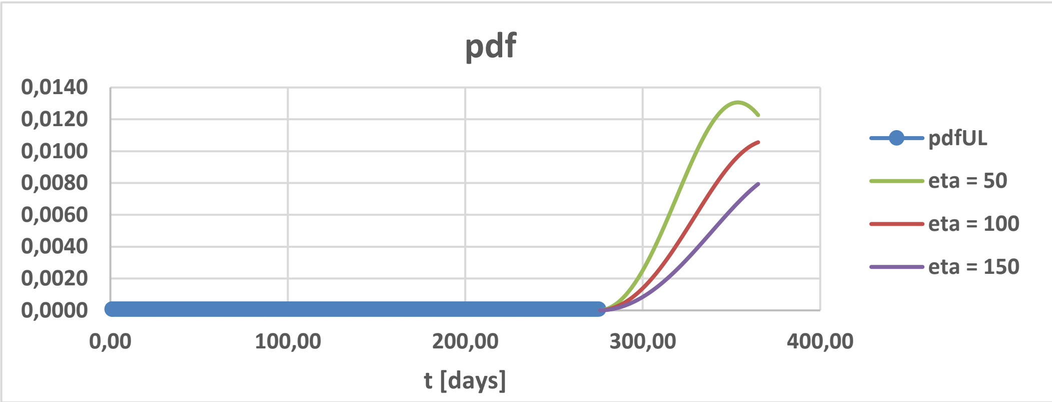


Figure C2. weibull pdf plot

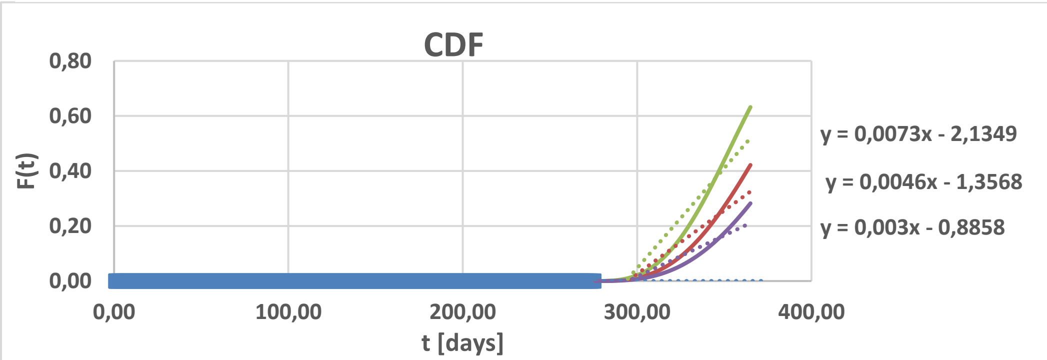


Figure C3. weibull CDF plot + linearized increments

6. Expected Downtime

The expected downtime factor that is used during scheduling, is assumed to be 2 hours. This was deducted from the 'average response time' metrics from the SP maintenance log.

7. SMA sample size

The sample size of the SMA model has a significant effect on the model output (see App.D). Considering the wear out increment of 0.005, and table 4 in appendix D, a moving average sample size of 6 units is chosen. This combination results in an estimated 10 % occurrence of unexpected failures, which is believed to be a reasonable performance for a predictive maintenance policy. For comparison, in a white paper by Strukton Rail (2016) about the merits of predictive maintenance for the maintenance on railway switches, a reduction of failures of 50% is claimed to be achieved. Here however, also random failures are considered.

8. Priority factors

The number of priority factors assumed in the model was deducted from considering that:

- The crew works a maximum of 10h a day
- Every corrective maintenance tasks is expected to cause a 2 hour workload
- Every corrective maintenance task occurs without notice, and should therefore be modelled not to allow for efficient routing.

In the current state, each day can account for 5 tasks (10h/(2h per action)). For each task, it should be possible for the model to generate a different random number. Therefore, the number of priority factors should be 5. In AIMMS, this can be modelled as: Round (Uniform (0,4),0). For preventive maintenance actions, the factor is always 2. This both enables the 'occurrence' of CM actions before, during and after PM actions, and the ability to efficiently plan the PM action set.

9. Distance Matrix

See figure x for a screenshot of the distance matrix used.

	Alphen	Arkel	Boskoop	Botlek	Delft	Den Haag	Dordrecht	Gorinchei	Gouda	Leiden	Leiderdor
Alphen	0	125,792	14,4	123,358	74,826	70,134	113,004	136,298	33,106	42,254	36,922
Arkel	125,792	0	129,5	118,83	135,674	149,142	60,702	8,71	124,202	156,104	150,772
Boskoop	14,4	129,5	0	102,496	65,594	61,3	97,682	127,162	21,764	43,1	37,768
Botlek	123,358	118,83	102,496	0	54,672	68,14	78,494	107,974	94,548	95,24	96,542
Delft	74,826	135,674	65,594	54,672	0	23,378	93,896	123,376	72,284	48,512	49,814
Den Haag	70,134	149,142	61,3	68,14	23,378	0	109,324	138,804	67,134	43,108	44,41
Dordrecht	113,004	60,702	97,682	78,494	93,896	109,324	0	49,522	90,314	135,02	136,322
Gorinchei	136,298	8,71	127,162	107,974	123,376	138,804	49,522	0	128,332	166,674	161,342
Gouda	33,106	124,202	21,764	94,548	72,284	67,134	90,314	128,332	0	86,806	71,738
Leiden	42,254	156,104	43,1	95,24	48,512	43,108	135,02	166,674	86,806	0	7,494
Leiderdor	36,922	150,772	37,768	96,542	49,814	44,41	136,322	161,342	71,738	7,494	0

Figure C4. Distance matrix snapshot

Appendix D. Verification and Validation

Contents

1. List of figures

2. List Of Tables

3. Data validity

Sargent (2010) reasons that data is required for the following three purposes:

- Building the conceptual model
- Validating the model
- Performing experiments with the validated model

Here, only the validation for the first two purposes are considered. The validity of the data used during experimenting, along with its effect on the results, is described in chapter 9.

a. Building the conceptual model

To build a conceptual model that adequately represents the problem entity for its intended purpose, there must be sufficient data. Much of this 'data' has been acquired through the semi-structured interviews with stakeholders. Because of business sensitivity, the claims could not be supported by hard data. The data that was supplied however, did not meet the specifications required for accurate modelling.

b. Validating the model

To compare the model behaviour to that of the problem entity, real life behavioural data is required. Because such data is not available here, and the operational validity can therefore not be quantified, Sargent (2010) states that high model confidence cannot be attained. Section 4 of this appendix is used to described the approach used to mitigate this fact.

4. Conceptual model validation

During conceptual model validation, the correctness of the theories and assumptions underlying the mathematical model should be determined. Such an assessment is required to validate that the model's representation of the problem entity is reasonable. To this end, each sub-model and the overall model must be evaluated. This includes an evaluation of the detail considered with respect to the models intended purpose.

Both scheduling and routing models have been based on models from literature. Since the authors of the original papers have validated these models extensively, it is assumed that the basis of the applied principles suffice. Sargent (2010) describes face validation by domain experts as an additional means to conceptual model validation. Both the model formulation as well as solving approach presented in chapter 7 have been reviewed by M. Duinkerken from the section Transportation Engineering and Logistics (TEL) of the faculty of Mechanical, Maritime and Materials (3ME) at the TU Delft.

5. Computerized model verification

The next step in the framework by Sargent (2010) is ensuring that model programming and implementation are correct. The author recommends using structured walkthroughs through the different parts of the model. In the following, the verification of the core sub models (Simulation, scheduling, routing) will be described.

c. Simulation

The diagnostics and prognostics model subsequently performs the following steps:

- Sampling of the failure probability increase
- Determination of the failure probability prognosis
- ➔ Scheduling
- Sampling of failure/survival
- Registering of tasks in schedule
- ➔ Routing
- Updating parameters

Scheduling and Routing will be verified under b. and c. respectively.

i. Sampling failure probability increase and prognosis

At the start of each 'roll' of the horizon, the increase of the failure probability of an asset is increased by either the useful life increment, or wear out increment. Figure 1 depicts the situation in which asset 1 (see red frame) is in the useful life phase, with a failure probability of 0.01, and an increment of 0. Hence, the failure probability forecast (see green frame) is 0 as well. Figure 2 depicts the situation in which the planning interval advanced five time steps (see blue frame), and thereby entered the wear out phase. It can clearly be seen that the failure probability (yellow frame) and corresponding forecast have changed accordingly.

(see b for scheduling)

ii. Sampling random failure and registering tasks in overall schedule

Following the scheduling step (see subsection b.), the occurrence of unexpected failures is simulated. Hereafter, both scheduled tasks as unexpected tasks are registered in the overall schedule. Figure 3 depicts the situation in which a maintenance task is scheduled by using the prognostic curve. The 'maintenance indicator' ($x_{a,t}$) of asset 6 has the value 1 at time t=5 (see green frame), and the overall schedule is updated with a 1 (designating planned tasks). In figure 4 (bottom), the occurrence of a random failure is depicted. Note that the random number drawn for asset 5 is zero (see green frame), which is less than the failure probability of that asset. Hence, a '2' is registered in the overall schedule (see red fame), designating an unexpected failure. See figure 5 for a graphic representation of the model output. Here, the top part depicts the failure probability progression of asset 1 over the horizon. The bottom part resembles the schedule for asset 1 to 10 over the horizon.

(see c for routing)

iii. Updating Parameters

After the execution of scheduling, routing, and all previously mentioned steps in the program, the results should be registered in the output identifiers. In the following, this procedure will be verified by considering the exemplary problem used in the verification of both routing and scheduling (see figure x).

Total Execution Costs

The total execution costs, which amount to 662.5 euros for route (0-3-9-1-0) (see purple frame), are calculated by using the minimum latency route. When considering that $C_{pers}^{u} = 100,\ v^{vehicle} = 80,$ $t_{CM}^{service} = 2\ and\ t_{PM}^{service} = 0.5$, this can be verified accordingly:

- Total execution costs = (Total travel time + Total service time) * C_{pers}^{u}
  - Total Travel time = $\sum_{va=1}^{r} Dist_{va,va2}$ / $v^{vehicle}$

    = (60+30+130+70) / 80 = 3.625
  - Total Service time = $\sum_{va=1}^{r} t_{va}^{service}$

    = 1*2 + 2*0.5 = 3

The total executional costs are therefore (3.625+3) *100 = 662.5 euro.

Total Downtime

Similarly, the total downtime is calculated based on the minimum latency solution. For route (0-3-9-1-0) the total downtime amounts to 2.8 hours. When considering the parameters as above, this can be verified by:

- Total downtime (TDT) = $TDT_{travel} + TDT_{service}$
  - TDT_{travel} = $\sum_{fa=1}^{q} Dist_{l,fa} / v^{vehicle}$

    = (60)/80 = 0.75
  - $TDT_{service}$ = $\sum_{fa=1}^{q} t_{fa}^{service}$

    = 1*2 = 2

The total downtime therefore is 2+2.75 = 2.75 hours (rounded to 2.8).

Total Emissions

Finally, the total emissions for this specific problem instance amount to 159 kg's of CO_2. When considering that E_{prod}^{u}= 100 kg, E_{reman}^{u}= 15 kg, and $E_{travel}^{u=km}$= 0.1kg, this can be verified by:

- Total Emissions (TEm) = $TEm_{production} + TEm_{reman} + TEm_{travel}$
  - $TEm_{production}$ = # failed assets * E_{prod}^{u} = 1*100 = 100 kg
  - TEm_{reman} = # planned assets * E_{reman}^{u} = 2*15 = 30 kg
  - TEm_{travel} = $\sum_{va=1}^{r} Dist_{l,va} * E_{travel}^{u}$ = 290 km * 0.1 = 29 kg

The total emissions therefore are 100 + 30 + 29 = 159 kg of CO_2.

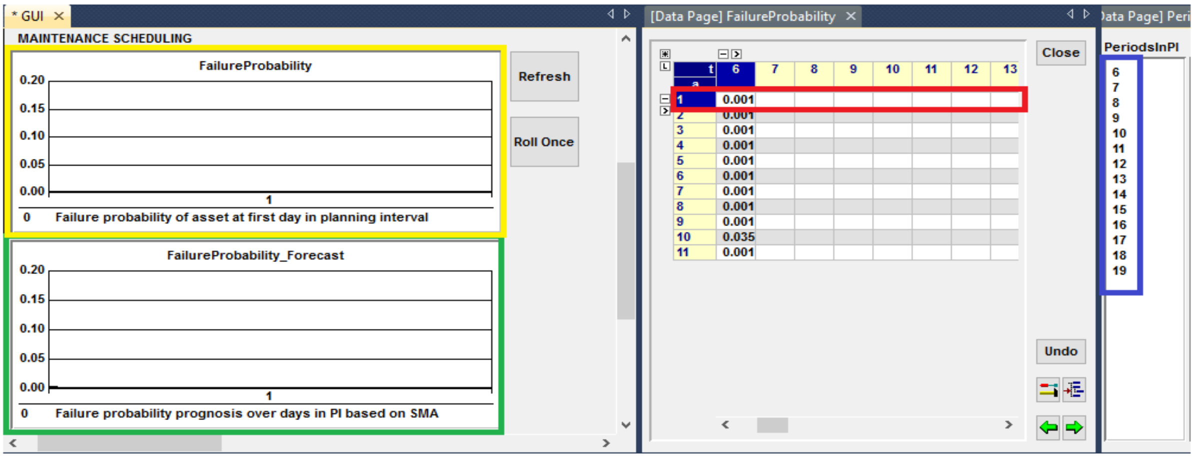


Figure D5. useful life phase

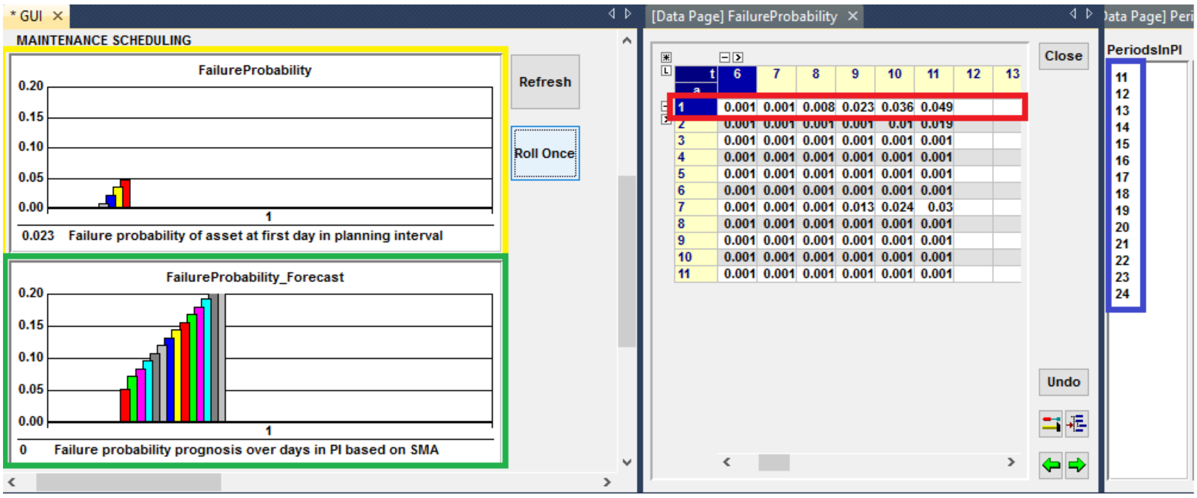


Figure D8. wear out phase

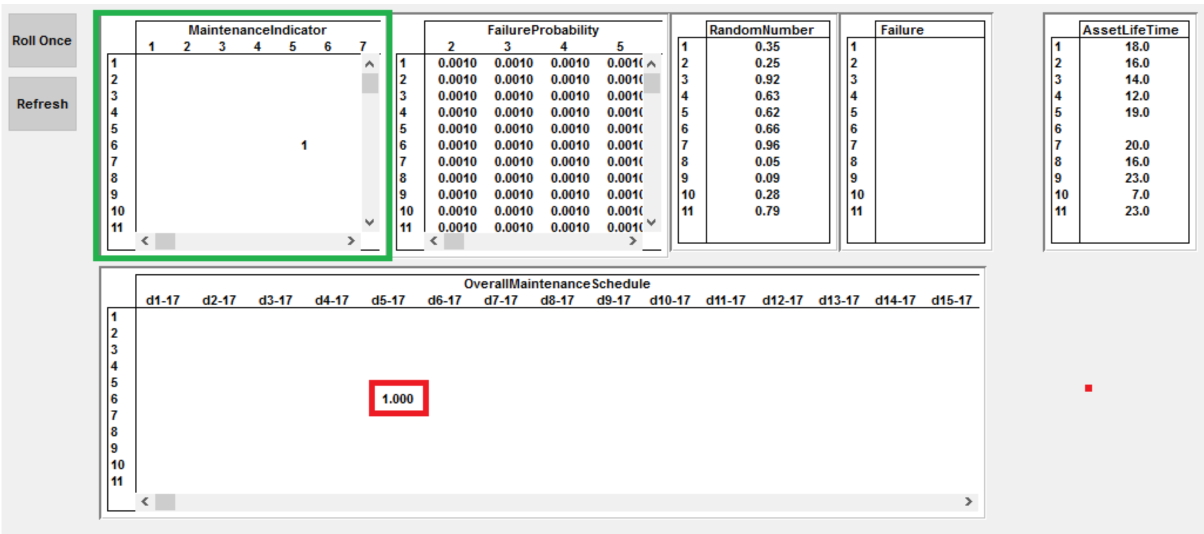


Figure D11. maintenance scheduled

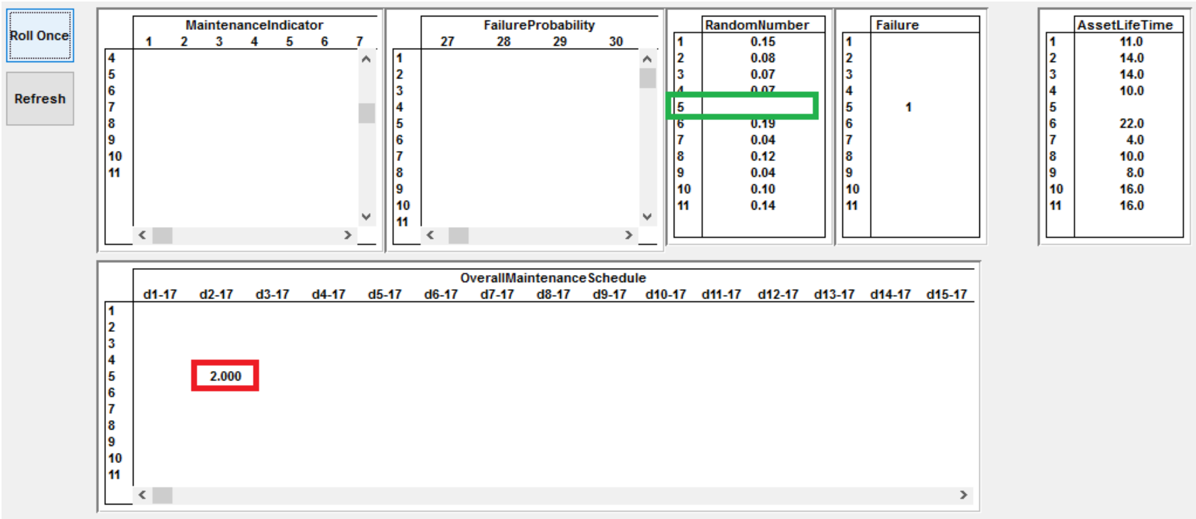


Figure D14. Unexpected failure occurence

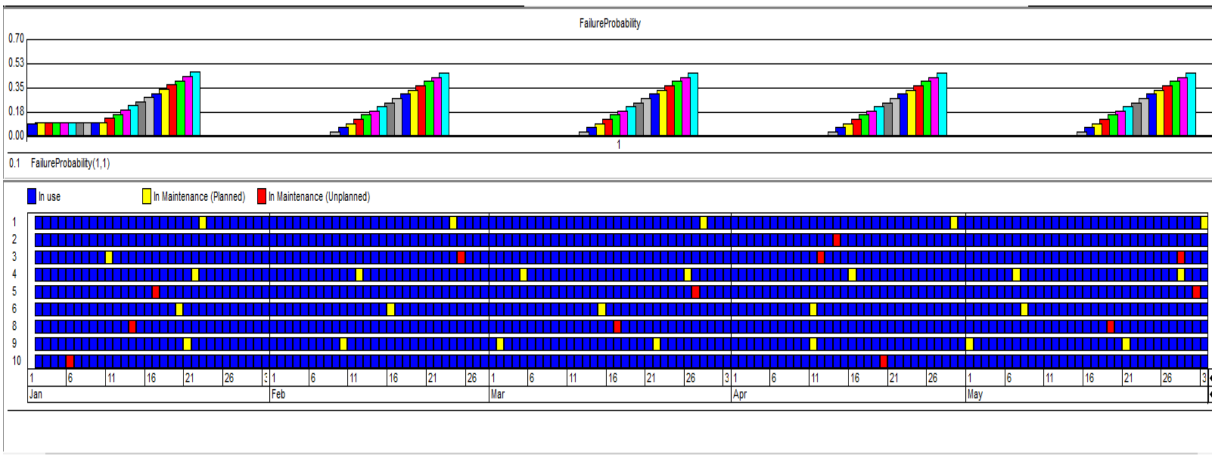


Figure D5. Model output over horizon

d. Scheduling

During schedule optimization, the day within the PI on which maintenance is hypothetically planned is varied to find the minimum of the aggregated failure costs and maintenance costs. The parameters that affect this procedure are:

- C^{u}_{CM} $\quad$ $Execution\ costs\ per\ CM\ action$ $\quad$ $(direct\ failure\ costs)$
- C^{u}_{DT} $\quad$ $Downtime\ costs\ per\ failure$ $\quad$ $(indirect\ failure\ costs$
- C^{u}_{PM} $\quad$ $Execution\ costs\ per\ PM\ action$ $\quad$ $(maintenance\ costs)$
- $P^{P}_{a\ ,t}$ $\quad$ $Expected\ F(t)\ from\ prognostics$
- P^{R}_{t-LM} $\quad$ $AGAN\ F(t)\ from\ specs$

In the following subsections, these parameters will be varied to mimic certain situations. By using these situations as small scale 'test' scenario's, the adequate working of the software implementation is verified.

Situation 1: Incipient failure, early maintenance

In the situation where the prognostics curve shows an incipient failure, maintenance should be scheduled. When during scheduling, the aggregated failure and maintenance costs curve is non-decreasing, and the failure costs are larger than the maintenance costs, maintenance should be scheduled early in the PI. Figure 8 depicts such a cost curve, with corresponding input in figure 7. The output for this example situation was enumerated in excel (see table 1).

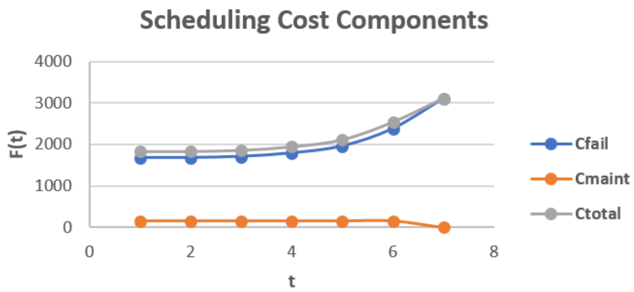


Figure D16. situation 1: scheduling cost

Parameter	Value [€]
C^{u}_{CM}	400
C^{u}_{DT}	1000
C^{u}_{PM}	100

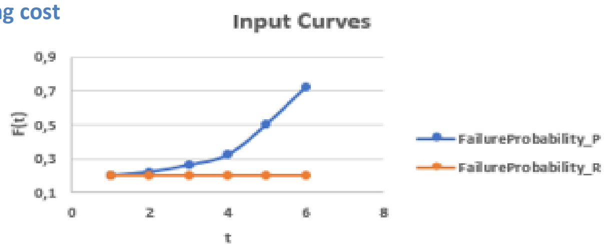


Figure D19. situation 1: input curves

Table D3.: situation 1: enumerated scheduling example

	Cfail							Cmain							
	1	2	3	4	5	6	Total	1	2	3	4	5	6	Total	Totot
Maint. @ t =															
1	280	280	280	280	280	280	1680	80	0	0	0	0	0	160	1760
2	280	280	280	280	280	280	1680	0	80	0	0	0	0	160	1760
3	280	308	280	280	280	280	1708	0	0	80	0	0	0	160	1868
4	280	308	364	280	280	280	1792	0	0	0	80	0	0	160	1952
5	280	308	364	448	280	280	1960	0	0	0	0	80	0	160	2120
6	280	308	364	448	700	280	2380	0	0	0	0	0	80	160	2540
x	280	308	364	448	700	1008	3108	0	0	0	0	0	0	0	3108

Figure 9 depicts the output of the AIMMS model for a single asset in a single planning interval. The colour green depicts the failure probability data from prognostics (P_P), blue depicts the failure probability of an AGAN system (P_R), and red depicts the cumulative failure probability (P^{cum}). Note that the parameters have been given written names in AIMMS. It can clearly be seen that the aims model comes up with the same solution as the enumerated example.

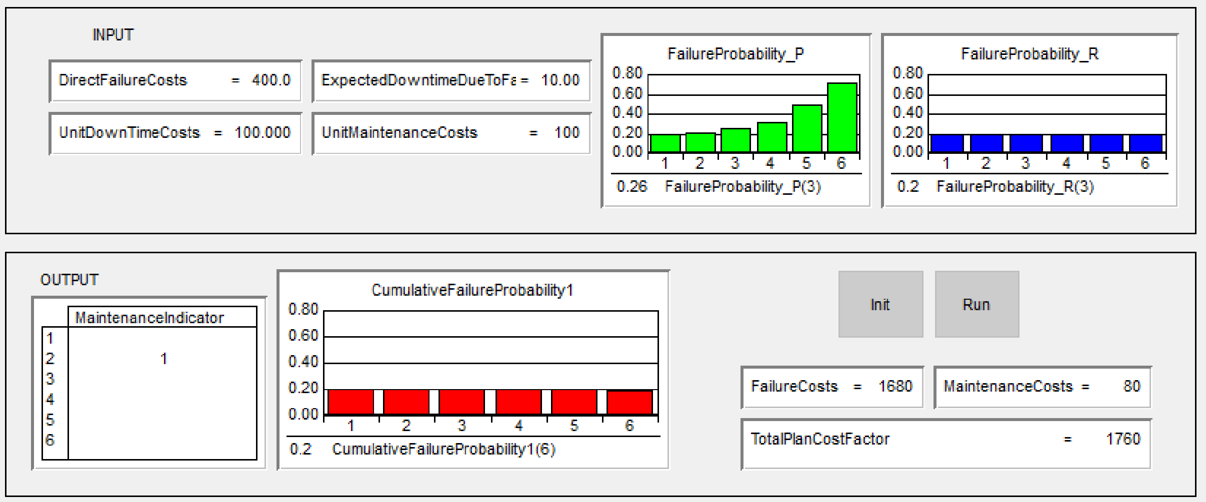


Figure D22 situation 1: aimms output

Situation 2: Incipient failure, postponed maintenance

When during scheduling, the aggregated failure and maintenance costs curve is convex, and the failure costs are larger than the maintenance costs, maintenance should be scheduled later in the PI. Figure 10 depicts such a cost curve, with corresponding input in figure 11. The output for this example situation was enumerated in excel (see table 2).

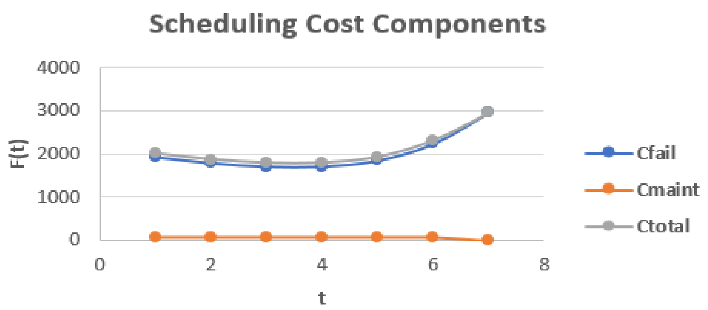


Figure D24. situation 2: scheduling cost components

Parameter	Value [€]
C_{CM}^{u}	400
C_{DT}^{u}	1400
C_{PM}^{u}	100

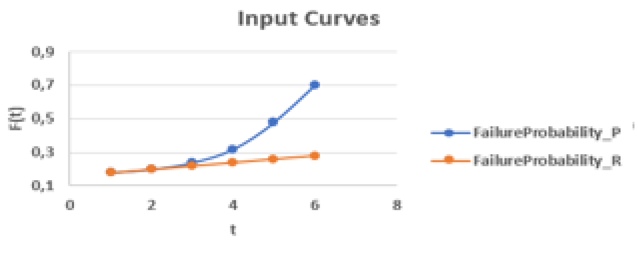


Figure D23. situation 2: input curves

Table D4. situation 2: enumerated scheduling example

	Cfail							Cmain							
	1	2	3	4	5	6	**Total**	1	2	3	4	5	6	**Total**	**Totot**
Maint. @ t =															
1	252	280	308	336	364	392	1932	82	0	0	0	0	0	82	2014
2	252	252	280	308	336	364	1792	0	82	0	0	0	0	82	1874
3	252	280	252	280	308	336	1708	0	0	82	0	0	0	82	1790
4	252	280	336	252	280	308	1708	0	0	0	82	0	0	82	1790
5	252	280	336	448	252	280	1848	0	0	0	0	82	0	82	1930
6	252	280	336	448	672	252	2240	0	0	0	0	0	82	82	2322
x	252	280	336	448	672	980	2968	0	0	0	0	0	0	0	2968

Figure 12 depicts the output of the AIMMS model for a single asset in a single planning interval. It can clearly be seen that the aims model comes up with the same solution as the enumerated example.

Figure D28. situation 1: aimms output

Situation 3: No Incipient failure, no maintenance

When during scheduling, the costs for not performing maintenance are smaller than the costs for maintenance, maintenance should not be scheduled at all. Figure 13 depicts such a cost curve, with corresponding input in figure 14. The output for this example situation was enumerated in excel (see table 3).

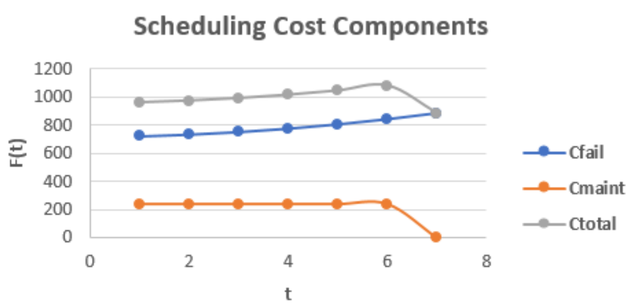


Figure D29 situation 3: scheduling cost components

Parameter	Value [€]
C^{u}_{CM}	400
C^{u}_{DT}	200
C^{u}_{PM}	300

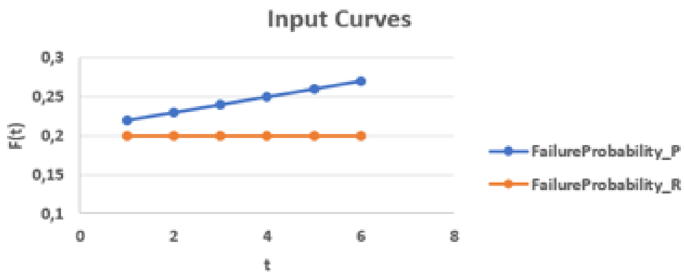


Figure D30: situation 3: input curves

Table D5. situation 3: enumerated scheduling example

	Cfail							Cmain							
	1	2	3	4	5	6	**Total**	1	2	3	4	5	6	**Total**	**Totot**
Maint. @ t =															
1	120	120	120	120	120	120	720	240	0	0	0	0	0	240	960
2	132	120	120	120	120	120	732	0	240	0	0	0	0	240	972
3	132	138	120	120	120	120	750	0	0	240	0	0	0	240	990
4	132	138	144	120	120	120	774	0	0	0	240	0	0	240	1014
5	132	138	144	150	120	120	804	0	0	0	0	240	0	240	1044
6	132	138	144	150	156	120	840	0	0	0	0	0	240	240	1080
x	132	138	144	150	156	162	882	0	0	0	0	0	0	0	882

Figure 15 depicts the output of the AIMMS model for a single asset in a single planning interval. It can clearly be seen that the aims model comes up with the same solution as the enumerated example.

Figure D31. situation 3: aimms output

e. Routing

During routing optimization, the minimum latency route is sought while complying with the priority factor constraint (constraint 5). Figure 16 depicts the situation where the overall schedule for the current day (see green frame and graphical plot) contains one unplanned task (asset 3) and two planned tasks (asset 1 and 9). Note that each of these assets have been assigned priority factors as described in section 3 (red frame). In the yellow and orange frame, the distance matrix and arc cost matrix (travel time + service time) have been depicted respectively. Finally, the blue frame represents the emissions for producing, remanufacturing, and transporting per unit respectively.

Figure 16 depicts the solution for the afore mentioned situation. As expected, the calculated route visits the assets in descending order of priority (3-9-1).

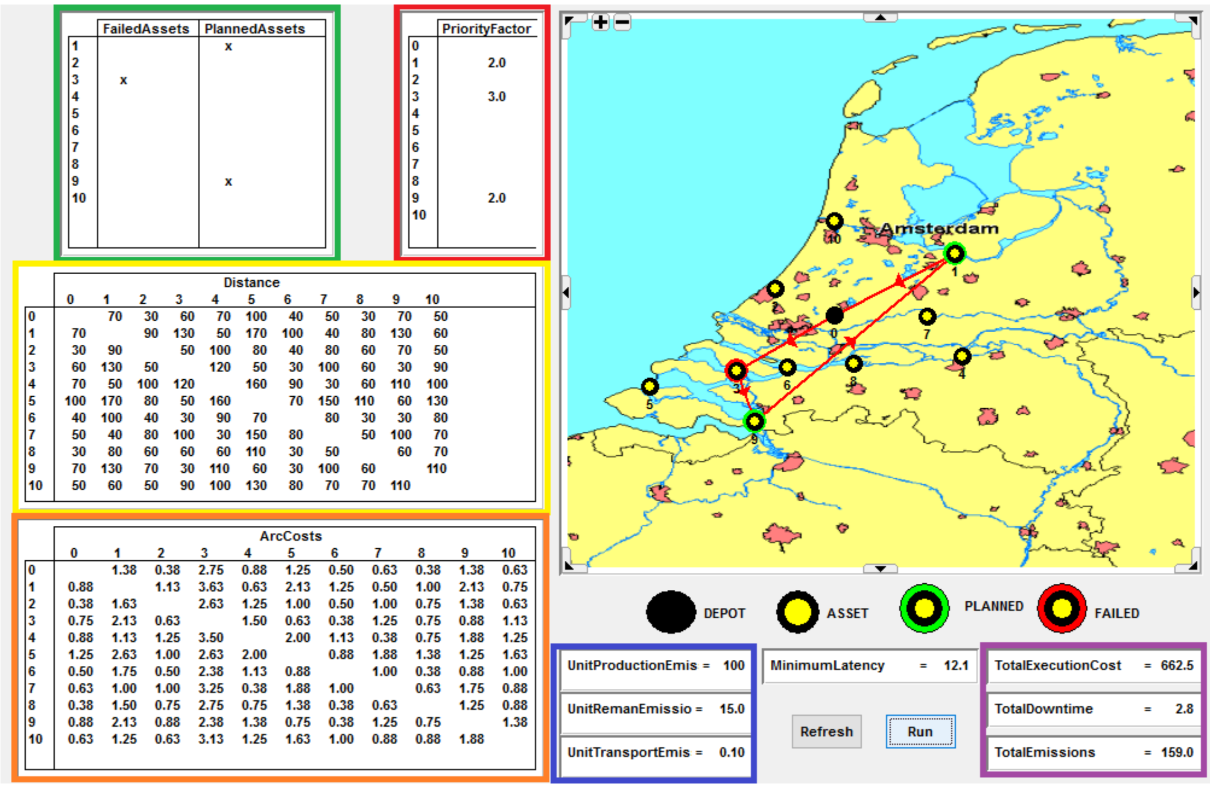


Figure D32. Routing example

Objective

For this problem instance, the objective function (minimum latency) has the value of 12.1. To check this value for correctness, the problem is enumerated below:

- For 4 locations, of which the depot is fixed as starting point, 6 different routes (permutations) exist (see table 4).

Table D6. routing permutations

		Visit order			
		1	**2**	**3**	**4**
Routes	**1**	0	1	3	9
	2	0	1	9	3
	3	0	3	9	1
	4	0	3	1	9
	5	0	9	1	3
	6	0	9	3	1

- Only route 3 and 4 (indicated in yellow) satisfy the priority constraint, and can therefore be in the final solution. The corresponding arc latencies are depicted in table 5.

Table D7. routing arc latencies

I\I2	**0**	**1**	**3**	**9**
0	0	1,38	2,75	1,38
1	0,88	0	3,63	2,13
3	0,75	2,13	0	0,88
9	0,88	2,13	2,38	0

- The total route latencies are depicted in table x. Note that the latencies in table x have been multiplied by the factor (r) for an arc between the depot and an asset, and by (r-k) for the other arcs. It is verified that in this specific situation, the minimum latency route has a total latency of 12.1.

Table D8. total route latencies

		Arc latency				
		0-1	**1-2**	**2-3**		**Total**
Routes	**1**	4,14	7,26	0,88		12,3
	2	4,14	4,26	2,38		10,8
	3	8,25	1,76	2,13		12,1
	4	8,25	4,26	2,13		14,6
	5	4,14	4,26	3,63		12,0
	6	4,14	4,76	2,13		11,0

6. Operational validation

The final step is to determine if the output behaviour has the required accuracy for the model's intended purpose. As was mentioned in section 1 of this appendix, the absence of real life data makes that the operational validity cannot be quantified. In such cases, Sargent (2010) recommends exploring model behaviour as much as possible. This includes the use of various sets of experimental conditions and examining model output by performing sensitivity analyses.

f. Parametric analysis

To verify that the model is doing what it is supposed to do, a continuity test is performed by means of a parametric sensitivity analysis. This analysis also serves the goal of investigating the effect of assumptions and input data uncertainty on model output. In chapter 9, the results from this analysis are used during the discussion of the results. Furthermore, an additional sensitivity analysis is performed there, mainly being aimed at aiding the formulation of conclusions and recommendations.

In the following, the following key model parameters are varied:

- h — $number\ of\ time\ units\ in\ H$
- T — $number\ of\ time\ units\ in\ PI$
- z — $number\ of\ samples\ in\ MA$
- n — $number\ of\ assets\ in\ A$
- $Incr_F^{wearout}$ — $wear\ out\ increment$
- $\#f_{va}^{prio}$ — $number\ of\ priority\ classes$

These parameters, as well as the ranges at which they are investigated, were at first selected by using subjective judgement. Later, literature research, experiences from experimenting with the model as well as input from graduation committee members have caused some further refinements. See table 7 for a summary of the results (green indicates that there is a significant effect on model KPI's between the bounds observed, whereas red indicates that there is not).

Table D9. model parameter sensitivity table

	KPI's	**OPEX**	**TEm**	**TDT**
Parameters	Range			
n	3-30			
h	1-9 [yrs.]			
T	5-25 [days]			
z	2-6			
$Incr_F^{wearout}$	0.01 – 0.05			
$\#f_{va}^{prio}$	2-6			

See the remainder of this section for the analysis results per parameter.

Number of Assets

During the assessment of the profitability of the future state, the number of assets will be varied to gain insight into the effect of an increased service area. Below, the model behavior is depicted when the number of assets in the service area is varied between 3 and 30. It can clearly be seen that there is a significant effect of varying the number of assets within the service area, and that an almost linear effect can be observed. (note that during these experiments, the average distance between depot and the assets has been kept constant.

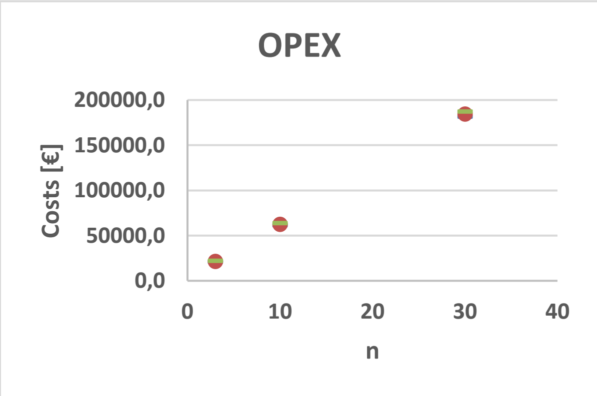


Figure D17. number of assets vs. OPEX

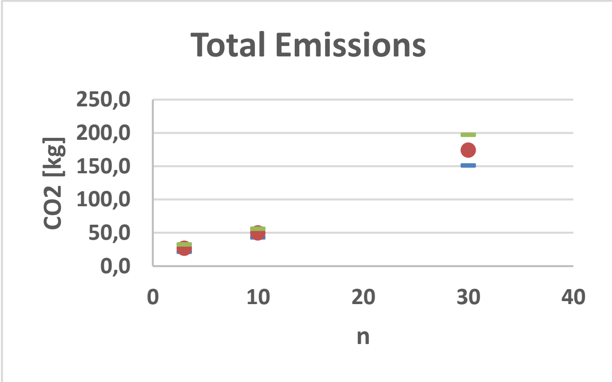


Figure D18. Number of assets vs. TEm

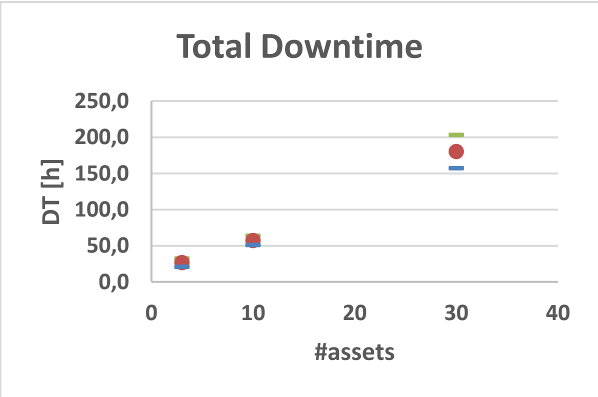


Figure D33. Number of assets vs. TDT

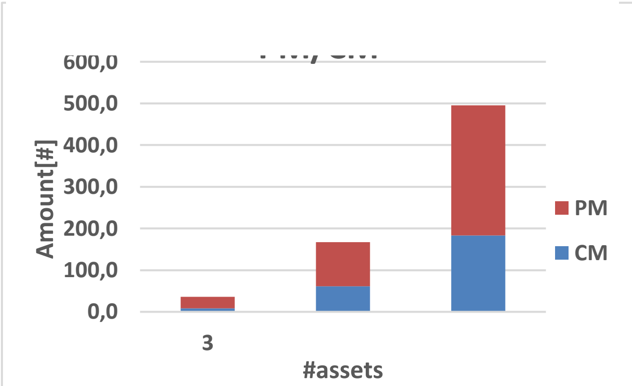


Figure D20. Number of assets vs. PM/CM

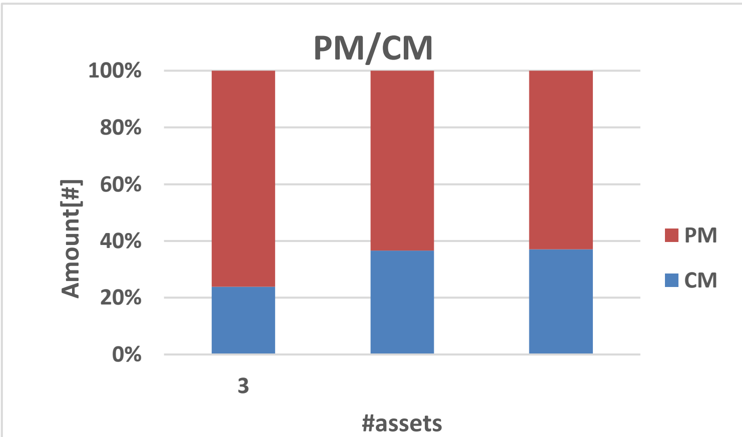


Figure D21. Number of assets vs. PM/CM (ratio)

Length of Horizon

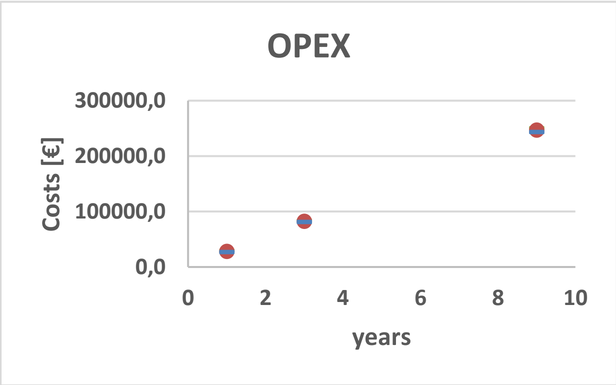


Figure D22. Length of horizon vs. OPEX

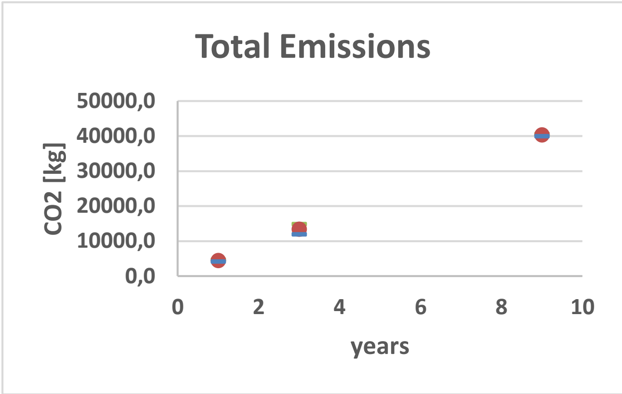


Figure D23. Length of horizon vs. TEm

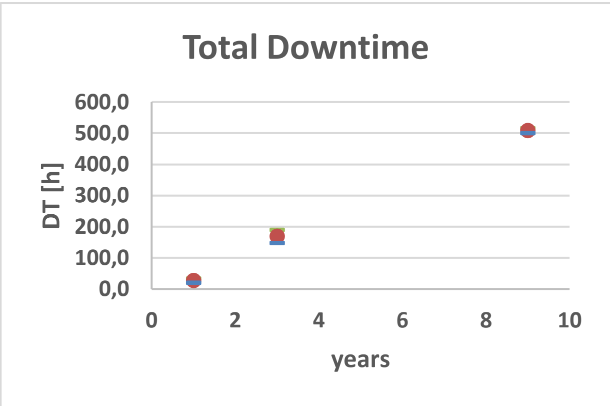


Figure D34. Length of horizon vs. TDT

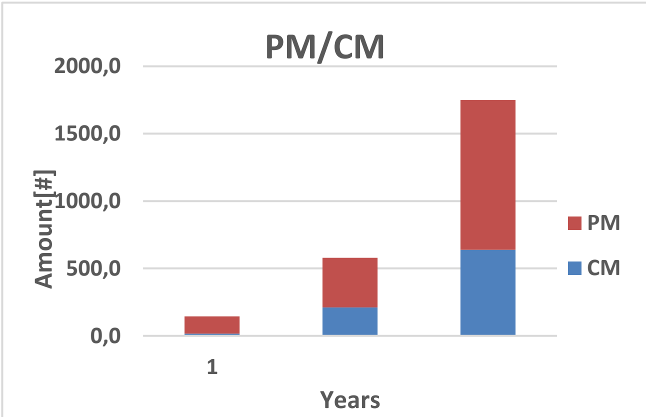


Figure D25. Length of horizon vs. PM/CM

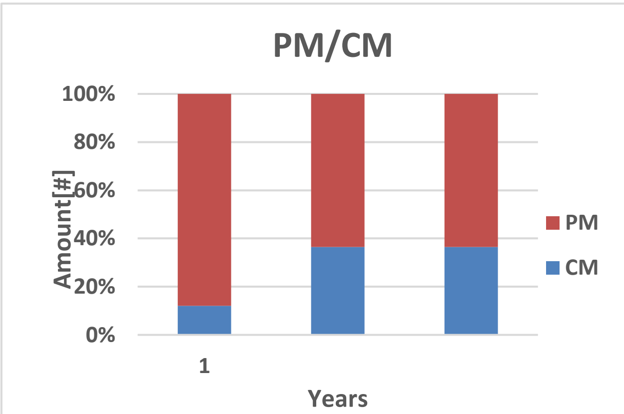


Figure D26. Length of horizon vs. PM/CM (ratio)

Number of time units in Planning Interval

In practice, the number of periods in the planning interval resemble the 'look ahead' period of the prognostics module. Within such an interval, based on previous data and a forecasting approach (e.g. by using a PoF model), it is assessed how large the probability on a failure is during this interval. This planning interval may be limited by the nature of the failure mechanism involved, and is highly dependent on type of system under consideration. For aviation electronics, examples between roughly 5 and 25 days were found. See figure x, y and z for the model output within this ranges of T. Although for every KPI a small increase can be observed for increasing T, the increase was not found to be significant. See table 8.

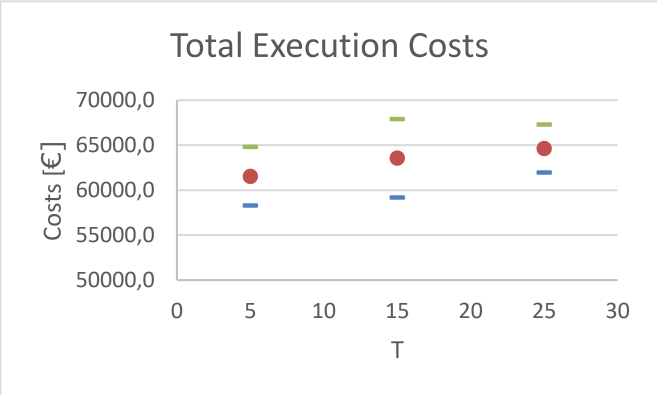


Figure D27. Length of horizon vs. OPEX

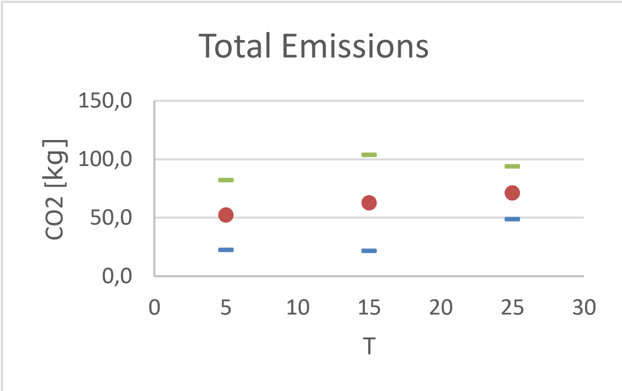


Figure D28. Length of horizon vs TEm

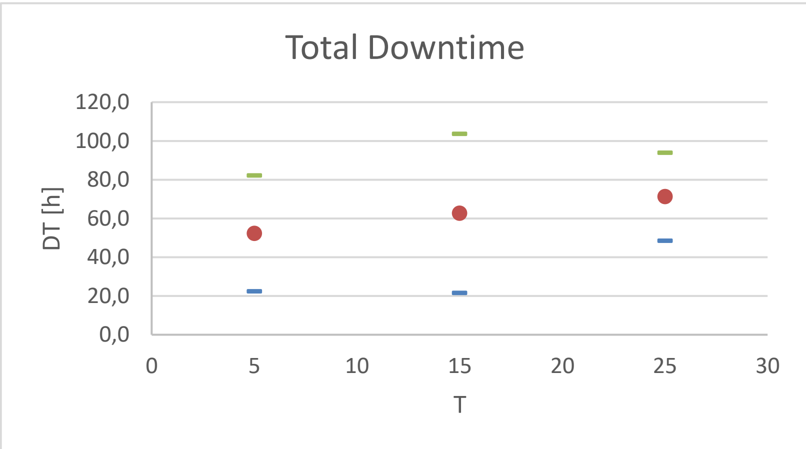


Figure D29. Length of horizon vs. TDT

Table D10. T_2 sided 95% t-stat

	t-critical (95%,2sided), unequal var	T-stat
OPEX	2.77644	2.07
TEm	2.77644	1.65
TDT	2.77644	1.43

Moving average sample size

Figure D30. MA sample size vs. OPEX

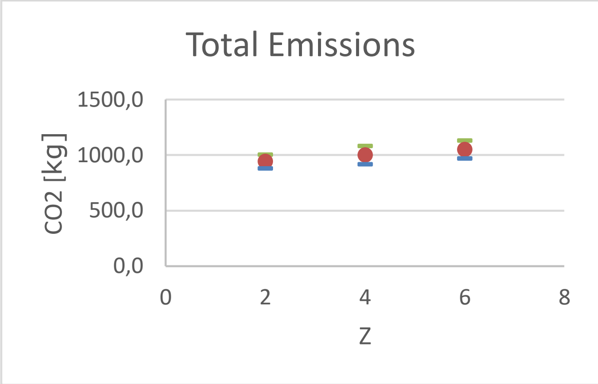


Figure D35. MA sample size vs. TEm

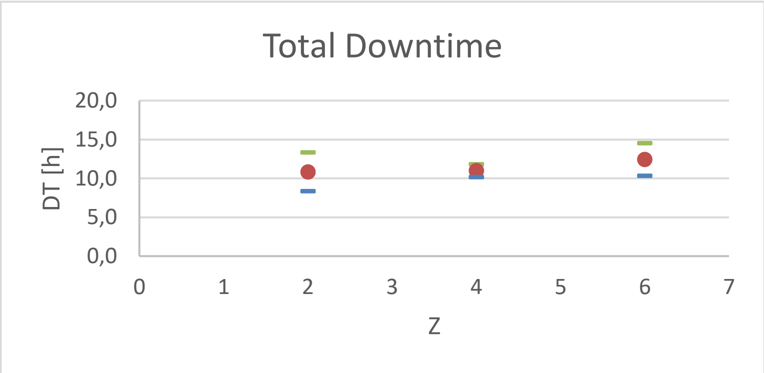


Figure D32. MA sample size vs. TDT

Wear out increment

Because of the reliability parameter estimation method employed in this research (see 3.6.2), it is expected that there is a significant estimation error involved. Here, the effect of the wear out increment on the KPI scores is therefore assessed. When assuming that the expected lifetime and useful life period (3/4L) of an asset remains constant, and varying the wear-out scale parameter, it was deducted that the wear-out increment could vary between roughly 0.005 and 0.015. From the graphs below it can be deducted that varying the increment within this range yields a small but significant difference in the model KPI's (see table x).

Figure D33. WOI vs. OPEX

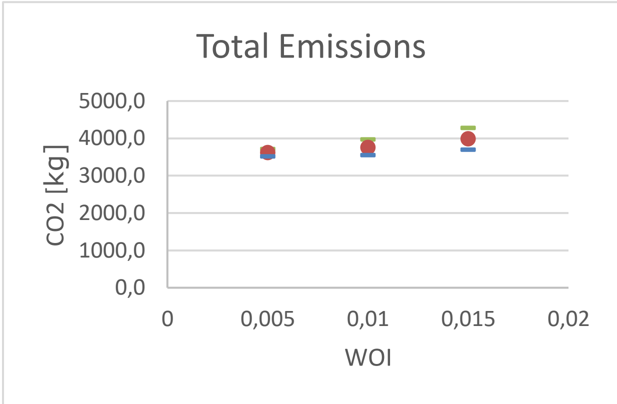


Figure D36. WOI vs. TEm

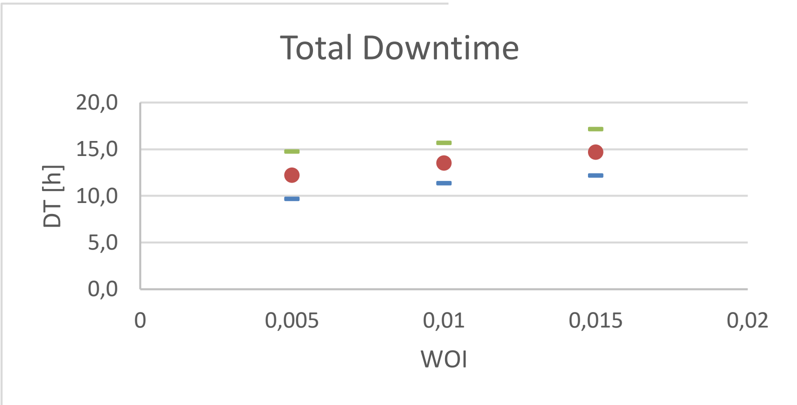


Figure D35. WOI vs. TDT

Table D11. WOI_2 sided 95% t-stat

	t-critical (95%,2sided), unequal var	T-stat
OPEX	3.18244	3.34
TEm	3.18244	3.54
TDT	3.18244	3.69

Routing Priority factors

During routing simulation, the priority factors make sure that the effect of randomly occurring failures during the day is considered. It should be verified that these priority factors indeed have the intended impact on the results. From reviewing the plots and table below, it can be concluded that increasing the number of priority factors in the model, indeed affects the KPI scores as expected. This can be explained by considering that every priority class imposes a constraint on the minimum latency route. This makes that certain 'better' solutions are not permitted. When considering practice, this could be translated to a situation where the chance of being forced to take an objective-wise unattractive route, because of random occurrence of failure somewhere else in the service area.

Figure D36. #f_prio vs. OPEX

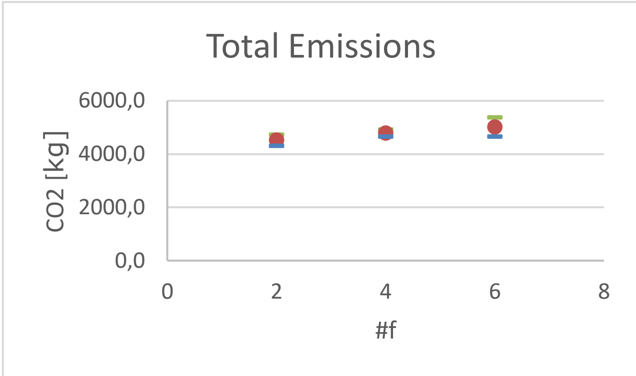


Figure D37. #f_prio vs. TEm

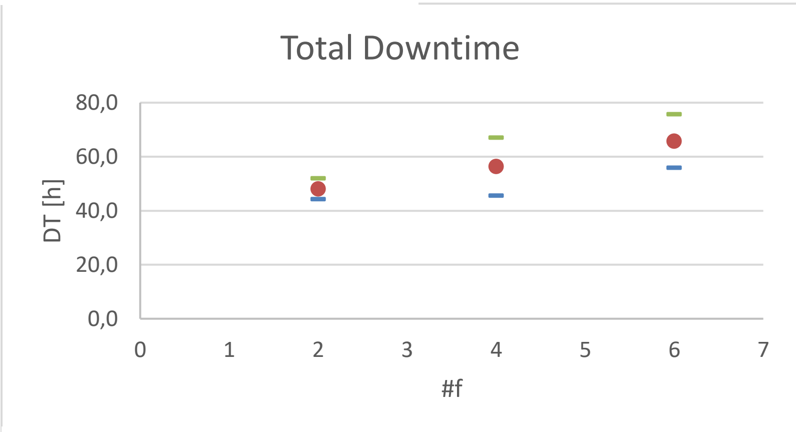


Figure D37. #f_prio vs. TDT

Table 12. #f_prio_2 sided 95% t-stat

	t-critical (95%,2sided), unequal var	T-stat
OPEX	3.18244	3.91
TEm	3.18244	3.38
TDT	3.18244	4.72

a. *Effect of assumptions*

Besides an estimation of the effect of varying input on the model output, the effect of certain assumptions on the KPI's should be investigated. Three of the main assumptions/simplifications underpinning the results are:

- That the failure probability (F(t)) progression curves are linear
- The fact that the prognostics curve (P_P) is made using SMA
- That the failure probability of a newly installed asset is AGAN

In the following, the effect of these assumptions on the results is described.

It is assumed that during simulation, the failure probability increases linearly. At every time step, the SMA prognostic model uses the previous realizations to forecast the expected failure probabilities over the PI. This fact causes that once a failure is incipient, P_P lags F(t) by several time steps. This causes that the scheduling model does not schedule an action (scheduling situation 3 in the 'computerized model verification' section), while the failure probability is increasing. This behavior is depicted in figure 39.

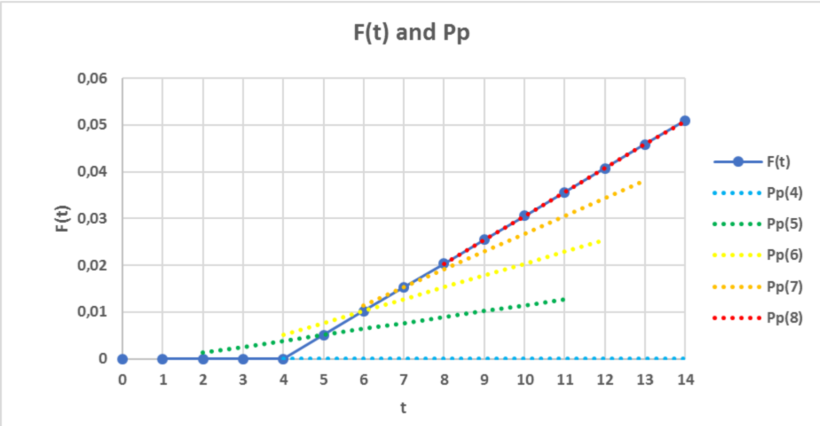


Figure D38. forecast lag

Once the P_P curve has 'caught up' with F(t) (in figure x, 4 time steps after entering wear out phase), maintenance is scheduled immediately the next time step (scheduling situation 3 in the 'computerized model verification' section). This can be accounted to the fact that the P_R curve is assumed to begin at AGAN conditions, and the P_R curve increases linearly. It can therefore be concluded that due to assumptions as listed above, the scheduling model does not exactly work as expected. In practice, it is expected that F(t) does not progress linearly, nor is a prognostic module expected to produce a linear prognostic curve based on a moving average of previous realizations. Furthermore, a remanufactured product will in practice never be AGAN. Together, this would change the schedules produced as well as the KPI scores. The parameters that determine this difference are:

- $Incr_F^{wearout}$
- The SMA sample size

In the following, the effect of these parameters is further analyzed.

Wear out increment

In the example as depicted above, a $Incr_F^{wearout}$ of 0.005 was used along with a 4 point SMA. This has resulted in a 4-period time lag between the prognostic curve and the real failure probability curve. The failure probability increases to 2% within this lag period, which accumulated causes an expected bias in the occurrence of random failures of 0.005+0.01+0.015+0.02 = 0.05 (5%). Doubling $Incr_F^{wearout}$ result in a doubling of the effect. Within the range as considered in during validation therefore (0.005 – 0.015), a difference in the steady state results of 15% can be expected.

SMA sample size

When instead the sample size for the moving average is varied in the example as above ($Incr_F^{wearout}$ = 0.005), the lag time changes. For a sample size of 6 time units, the lag time increases to 6 time units, resulting in an increase of 0.005+0.01+0.015+0.02+0.025+0.03 = 0.105. Similarly, lag time and the corresponding accumulative failure probability decreases when the SMA sample size. For a sample size of 1, the model would exactly follow the realized failure probability curve. This case is not considered to be realistic.

The combined effect of varying $Incr_F^{wearout}$ and SMA sample size, in percentages of the total number of replacements in the simulation, is depicted in table 11. Regarding the large dependency of each of the KPI's on the amount of random failures, this effect is expected to propagate directly into the results. In the comparative case study presented in chapter 8, and the discussion of the result thereafter, this table will be used to choose a 'reasonable' configuration and to assess the quality of the results respectively.

Table D13. WOI vs. SMA size sensitivity

	$Incr_F^{wearout}$	*0,005*	*0,01*	*0,015*
SMA ss				
2		1,5	3	4,5
4		5	10	15
6		10,5	22	32,5

7. Conclusion

Although the external validity of the model cannot be quantified, and that due to the failure probability assumptions the scheduling model does not exactly work as intended, it is believed that the overall model does still possess the accuracy intended for the objective. The magnitudes of the improvements may well not be accurate, but for the comparative nature of the hypothesis, it is expected that the direction of improvements is sufficiently reliable.

Appendix E. Semi-structured Interviews

Contents

1) Introduction

As part of the practice research of this thesis, several meetings were held with experts within the professional scope under consideration. During these meetings, several topics were discussed in a semi-structured interview setting as discussed by Dul and Hak (2008). In the following sections, the structure will be as follows:

- Introduction of the conversation partners.
- Presentation of the discussed topics, questions, and corresponding answers
- Brief conclusion or comment when appropriate

It should be noted that due to the focus on the Dutch infrastructure sector, all conversations were held in Dutch. To avoid rephrasing errors as much as possible, it is therefore chosen here to present the remainder of this section in Dutch.

2) Asset Owners

AO1: Matthias Buyze, Adviseur Asset Management Rijkswaterstaat, Clusterorganisatie WNZ-A Vaarwegen. Telefoongesprek van +/- 1.5 uur.

AO2: Bert vd Pas, Adviseur-specialistisch medewerker, Clusterorganisatie WNZ-A Vaarwegen. Aanwezig geweest tijdens een vergadering omtrent te vervanging van een CCTV installatie van een beweegbare brug in Dordrecht. Daarna is er +/- een half uur nagesproken.

Q1: Hoe kijkt jullie organisatie aan tegen het proces omtrent onderhoudscontracten en welke verbeteringen zien jullie voor de toekomst?

(AO1): RWS is opgedeeld in districten met elk hun eigen budget en activiteiten. Wanneer voor een object binnen een district een nieuw prestatie-onderhoudscontract moet worden afgesloten, dan verloopt de communicatie hiervoor verplicht via de Programmas, Projecten en Onderhouds (PPO) afdeling van die regio. Binnen dat contract worden de functionele eisen door RWS (of adviesbureau) voorgeschreven en hebben de aannemers alle vrijheid om te engineeren. Voorheen betroffen zulke contracten dikwijls meerder objecten door grote aannemers, maar dit wordt niet meer gedaan door oneerlijke concurrentie irt MKB. Het innovatieve character van deze contracten is echter tegengevallen. De prestatie-contracten voor installaties van beweegbare objecten zijn te kort. Aannemers doen voorstellen voor verbeteringen via PPO aan RWS, maar deze worden vaak hogerop afgekeurd door budgetrestricties. Het komt ook voor dat aannemers een tender toegewezen krijgen maar eigenlijk nog geen idee hebben over hoe het goed te doen. In het recente verleden is de overstap gemaakt van alles voorschrijven (a la prorail) naar meer vrijheid. De daadwerkelijke speelvrijheid voor aannemers valt echter tegen en de contractduur is bovendien vaak te kort.

Conclusie:

Door de procedure omtrent het afsluiten van prestatiecontracten met onderhoudsaannemers, en de uitvoering van het uiteindelijke contract valt het beoogde innovatieve karakter van de functionele specificities tegen. Door gebrek aan technische kennis en de focus op laagste kosten ontstaat er een race naar de bodem met nadelige gevolgen voor de betrouwbaarheid. Meer budget voor innovatie, meer vrijheid voor de juiste aannemers en een langere contractuur worden ook hier gezien als verbetering voor de toekomst. Op districtsniveau lijkt RWS het hier redelijk eens te zijn met de aannemers. Echter, de wet en regelgeving moet van boven komen en deze moet nog ontwikkeld worden.

<u>Q2: In hoeverre wordt logging van omgevingsparameters toegepast, en in welke mate worden deze gebruikt in het plannen van onderhoud?</u>

(AO2): De technische installaties worden 6 of 12 maandelijks visueel respectievelijk volgens metingen geinspecteerd. De betrouwbaarheid van kritieke infrastructuur wordt getracht middels een conservatief preventief onderhoudsbeleid te worden gegarandeerd. Predictief onderhoud middels real time monitoring wordt niet toegepast en is ook niet meegenomen in de geplande renovaties. Er is wel operationele logging (eventlog), maar daar houdt het op. Waarom dit zo is is niet bekend.

<u>Q3: In hoeverre worden waardebehoud praktijken toegepast?</u>

(AO2): Bij vervangingen is de insteek dat de aannemer met de vervangen systemen mag doen wat hij wil (in de plomp gooien), we doen er namelijk toch niets mee. Het gebeurd wel dat vervangen systemen op voorraad worden gehouden als spare parts als een generatie 'technische installaties' elders in het areaal nog geinstalleerd is

<u>Comment:</u>

Er waren alleen RWS mensen aanwezig bij de vergadering, er lagen aanbiedingen van enkele aannemers.

3) Service Providers

SP1: Michiel Berkheij (Asset Manager Vialis). Vialis is een aannemer die gespecialiseerd is in moderne veiligheidssystemen en verkeersregelsystemen voor de infrasector. Naast het uitvoeren van onderhoud houden ze zich ook bezig met het ontwikkelen van innovatieve systemen.

SP2: Jeroen Vermeulen, Onderhoudsmanager VolkerInfra. Jelte Snel (JS), Installatiedeskundige VolkerInfra. VolkerInfra is een onderdeel van VolkerWessels, dat zich onder andere bezighoud met het uitvoeren van onderhoudscontracten in de infrasector.

SP3: Peter Oud, Hoofd projected Mobility Dynniq. Dynniq Control Systems is een aannemer die onder andere is gespecialiseerd in het ontwikkelen en implementeren van control centers en de daartoe behorende randsystemen.

SP4: Erik Bakker, Business Unit Manager Hacousto. Hacousto is een bedrijf dat gespecialiseerd is in onder andere videotechniek, en is actief in de infrasector (bijvoorbeeld beweegbare spoorbruggen van prorail, stations van NS). Hacousto levert hardware en softwarediensten voor het generereren van beeld, besturing, datastorage en management (surveillance, onderhoud).

Q1: Welke electronische ' systemen', (subsysteem/assembly/module/component), worden door jullie in het algemeen het vaakst uit een beweegbare brug gehaald tijdens correctief/preventief onderhoud?

SP1: CCTV systemen, verkeersregelsystemen en slagbomen

SP2: 95% van de storingen zijn door electronica. Meestal geld hier dat als een component overlijd deze vervangen wordt, bij relatief goedkope massaproductie componenten geld dat deze vervangen worden als ze storen. Dit gebeurt het meest bij relais en eindschakelaars, afhankelijk van hoe intensief ze gebruikt zijn.

Conclusie:
Vooral electronica stoort en wordt vaak vervangen. Control and operations, Verkeersregelsystemen en Communicatiesystemen zijn hierin het meest vertegenwoordigd.

Q2: Wat gebeurt er dan met deze technische systemen? Gaat het terug naar de opdrachtgever? Gaat het naar één of meerdere fabrikanten terug? Wordt het aan een recycler overgedragen? Waarom?

SP1: Dit hangt af van de situatie. Soms worden systemen afgevoerd met inachtneming van de geldende milieuwetten, soms worden delen van de installatie als wisseldelen gehouden. Het komt een enkele keer voor dat systemen worden geretourneerd naar de opdrachtgever zodat ze elders kunnen worden ingezet. Er zit echter geen strategie vanuit de beleidsbepaler achter en doorgaans wil een opdrachtgever geen AGAN systemen, enkel nieuwe. Er zijn geen afspraken met de fabrikant. Fabrikanten ondersteunen vaak maar een heel beperkt aantal jaren een generatie systemen, juist om zo snel mogelijk weer een nieuwe generatie op de markt te brengen

SP2: De systemen worden na vervanging afgevoerd als afvalstroom

SP3: Nagenoeg niets wordt meer teruggegeven aan de opdrachtgever. Afhankelijk van het systeem en de situatie wordt er remanufacturing toegepast. Bijvoorbeeld het motortje van een PTZ camera wordt vervangen. Voor sommige componenten is dit kostenvoordeliger. Via de fabrikant is Dynniq dan gecertificeerd om de producten te repareren. Over timing van deze processes valt weinig te zeggen, maandelijks zou een erg grove aanname zijn.

SP4: De technische levensduur wordt nooit gehaald. Vervangen systemen eindigen altijd in de prullenbak. Als ze een jaar oud zijn, zijn ze al teveel verouderd om nog bruikbaar te zijn voor remanufacturing/hergebruik, de volumes zijn te laag en de manuren om te ontmantelen en inspecteren zijn te duur. Het gebruiken van sensorinformatie om de restwaarde te bepalen is een idee maar biedt te weinig zekerheid. Uiteindelijk wil je toch het apparaat inspecteren.

Conclusies:
Het grootste deel van de systemen wordt volgens het contract afgevoerd volgens de geldende mileunormen (lees: laagwaardig recyclen). De systemen worden niet teruggenomen door de OEM omdat hier geen afspraken over zijn (wat weer kan worden verklaard door een gebrek aan prikkel voor de OEM). In de praktijk gebruiken aannemers die daartoe de mogelijkheden hebben onderdelen van vervangen systemen om kostenvoordelen te genereren. Er zijn geen punten in het contract opgenomen die op een situatie met minimaal waardeverlies aansturen.

Q3: Krijgen jullie hier een vergoeding/compensatie voor? Waar is deze van afhankelijk?

SP1: Nee, geen vergoeding

SP2: geen compensatie

SP3: Deze compensatie is afhankelijk van de kwaliteit/waarde van de camera m.a.w. camera's uit het dure segment worden doorgaans wel gereviseerd. Een enkele keer wordt er gewerkt met verrekenbare hoeveelheden.

Conclusies:
Er zijn in principe geen afspraken tussen de partijen over vergoedingen/compensaties voor het retourneren/terugnemen van vervangen systemen.

Q4: Hoeveel wordt er niet terug gestuurd? Waarom?

SP2: Er zijn geen afspraken met de andere betrokken partijen

Conclusies:
Er zijn niet of nauwelijk afspraken tussen de partijen (lees: geen samenwerking op het gebied van CE praktijken)

Q5: Hoe verloopt verder de procedure rond deze systemen bij jullie (onderhoudsstrategie, policy etc)? Worden er voorraden aangehouden? Worden er gedurende de levenscyclus van het systeem ook deelsystemen vervangen of gerepareerd?

SP1: Dit hangt af van de situatie. Voor electronische systemen wordt storingsafhankelijk onderhoud toegepast. Wat betreft periodiek groot onderhoud wordt clusteren wordt zoveel mogelijk toegepast om de beschikbaarheid van de objecten niet te verstoren

SP2: Vanuit een werkomschrijving van RWS wordt er 1 op 1 een taakplan gemaakt door VI. Met CMMS (software) wordt dan een periodiek onderhoudsschema opgesteld. Dus vanuit een onderhoudscontract met de AO worden de onderhoudsschema's voor meerdere objecten opgezet. Dit schema wordt vervolgens gecommuniceerd met en uitgevoerd door de uitvoerder van VI.

SP4: een real time-scheduling approach wordt gebruikt zoals bijvoorbeeld bij prorail. Bepaalde variabelen worden gemonitord met sensoren en vergeleken met een treshold. Hierin zijn voor de operator de kleuren groen (goed), oranje (waarschuwing) en rood (actie vereist) te onderscheiden. Hiervan wordt een email naar de juiste monteur in de juiste regio gestuurd, welke na een vakkundige beoordeling actie onderneemt of niet.

Q6: Is er(geanonimiseerde) data beschikbaar die de de bovengenoemde procedures onderbouwen?

SP1: Deze data is aanwezig, maar kan helaas niet worden gedeeld vanwege het feit dat dit afstudeerwerk vanuit W+B wordt gedaan.

SP2: De data die wordt bijgehouden is van beperkte waarde. Het enige dat door de storingsmonteur ter plekke wordt geregistreerd is het moment van aankomen. Verder is er de onderhoudsregistratie in het CMMS, waarin de storingsmeldingen en daarop volgende acties worden begehouden. Dit gebeurd tot op een relatief beperkt detailniveau. Bij tunnels en Prorail zijn ze hierin verder, hier is het onderhoudsproces dynamischer (lees: real time gestuurd)

SP3: Er is heel veel data maar ik denk dat je daar niets aan zult hebben. Over het algemeen is een monteur wel een uur zoet met het vervangen van een camera, vooral als deze aan paalconstructies hangt.

Conclusies:
Doorgaans is er beperkte data aanwezig, meestal is deze vanwege de concurrentiepositie niet beschikbaar. VolkerInfra is bereid geweest een onderhoudsregistratiebestand te delen.

Q7: Zijn er gebruiks en/of omgevingsmetingen beschikbaar van deze systemen? (statistiek brugopeningen, temperatuur/vochtigheid statistieken)

SP2: Nee, bij de tunnels van RWS worden zulke dingen wel bijgehouden in besturingscentra. Hiervoor worden SCADA of SATTLINE systemen gebruikt. Vooralsnog kunnen aannemers niets met deze data, omdat dit is afgeschermd om cybersecurity risico's te beperken. De aannemer is alleen verantwoordelijk voor het dataverkeer binnen de grenzen van het object.

SP4: Omdat de systemen steeds complexer worden is er meer informatie en kennis nodig om de juiste middelen op de juiste manier in te zetten (soort monteur bijv.) verschillende variabelen worden gemeten door metertjes te plaatsen. Bijvoorbeeld temperatuursensors, stroommeters, etc. Dit is afhankelijk van de toepassing. Meestal is er dan een beveiligde draadloze verbinding rechtstreeks met Hacousto. RWS is echter nog terughoudend met ditsoort technieken omdat ze er weinig van begrijpen. Er is vaak bediening op afstand, dus de verbinding ligt er wel.

Conclusies:
Voor beweegbare bruggen worden dergelijke parameters niet gelogd. Bij kritieke infrastructuur zoals tunnels doen ze dit wel.

Q8: Zien jullie mogelijkheden voor deze (of andere) technische systemen waardoor de procedure wellicht efficiënter kan door een veranderd ontwerp en/of het toepassen van monitoring technieken?

Conclusies:
Door zowel Vialis als Dynniq werden hier CCTV camera's als mogelijkheid bevestigd, maar in de huidige setting is hier geen ruimte voor.

Q9: Op welke manier zouden deze componenten/faalvormen volgens jullie gemonitord kunnen worden om een inschatting te maken van de toestandsdegradatie? (dus in plaats van het monitoren van leeftijd en storingen, het monitoren van leeftijd, gebruik en/of belasting)

n.v.t.

Q10: Zien jullie mogelijkheden voor systemen die bij een aangepast ontwerp of procedure in aanmerking zouden kunnen komen voor een beter behoud van waarde? Bijvoorbeeld in plaats van weggooien à recyclen, in plaats van recyclen à remanufacturing.

SP1: Het CE verhaal is alleen realistisch voor systemen in bulk. Je moeten voldoende hoeveelheden van dezelfde systemen hebben. De control & operations systemen voor de hoofdfunctie van de brug zijn te verschillend en te verspreid om dit kosteneffectief te kunnen doen. Bovendien wordt alles gefaseerd vervangen door statistische dissimilariteit van de systemen, en door beperkte budgetten.

Bovendien is er steeds meer beslissingscapaciteit virtueel. Een gevolg hiervan is dat het totale gewicht aan control hardware minder wordt en dat er steeds minder personeel aanwezig is bij beweegbare objecten. Daarom is er een grote toename van het aantal CCTV toepassingen, een trend waarvan verwacht wordt dat deze zich doorzet. CCTV systemen storen relatief veel, worden vaak vervangen en bevatten waardevolle componenten. Daarnaast worden dezelfde systemen naastin beweegbare objecten ook toegepast in tal van andere situaties (langs wegen, rondom panden, etc.). Dit maakt CCTV systemen een eventuele kanditaat voor CE praktijken. Om te ontwerpen voor remanufacturing is jaren de tijd nodig en de fabrikant heeft vooralsnog geen prikkel om dit te doen. De opdrachtgever en beleidsmakers bepalen uiteindelijk wat er gebeurd middels het bestek en het contract

SP2: Het toepassen van real time monitoring gestuurd onderhoud zoals bij prorail zou voor bruggen zonder twijfel ook rendabel zijn. Door kortlopende onderhoudscontracten is hier echter nog geen ruimte voor. Een aannemer moet elke cent omdraaien om een bieding te winnen. Voorstellen voor technische verbeteringen stranden vaak hogerop bij RWS door geldgebrek.

SP3: Verbeterde informatie wat betreft kwantiteit, timing en restlevensduur zou zonder meer grote voordelen opleveren in de reverse supply chain planning. In principe is veel van de infrastructuur die nodig zou zijn om predictief onderhoud toe te passen al aanwezig (communicatiehardware). De betrouwbaarheid van deze systemen zal echter moeten worden gere-evalueerd m.b.t. het toegenomen dataverkeer in combinatie met de bestaande bandbreedte. Predictief onderhoud blijkt in de praktijk echter lastig door verantwoordelijkheid en contracten. De discussies gaan namelijk vooral over wie waar verantwoordelijk voor is. Echte innovatie kan plaatsvinden in nieuw te bouwen objecten. 80 % is echter renovatie waarbij je te maken hebt met wat je aantreft. Voor zulke contracten zijn de looptijden vaak te kort om innovaties door te voeren. Bij tunnels worden wel langlopende contracten mbt de installaties afgesloten met als gevolg dat tijdens revisies hier wel de nieuwste technieken worden toegepast. De wetgeving ivm innovatieve contracten achter. De opdrachtgever zou meer moeten investeren in onderzoek naar hoe innovatie in deze sector tot stand komt. Het innovatieve karakter van 'functionele beschrijvingen' is namelijk niet niet goed uit de verf gekomen, doordat ze uit kostenoverwegingen klakkeloos worden gebaseerd op specs die door de fabrikant worden opgegeven, maar deze niet kloppen of niet van toepassing zijn. Bij problemen wordt dan de verantwoordelijkheid doorgeschoven. Bij prorail bijvoorbeeld is dit anders geregeld, hier wordt tot op de kleinste details voorgeschreven hoe de aannemer dingen moet uitvoeren.

SP4: Pas als er een echte incentive is om de kosten daarvoor te maken. CO2 oid zou dan dus belast moeten worden. Verder moet er organisatorisch bij de opdrachtgever iets veranderen. Er zit wel vooruitgang in het predictive monitoring verhaal doordat er steeds meer jonge ingenieurs doorstromen. Deze weten meer van nieuwe technieken en zijn bovendien meer gericht op samenwerking.

Conclusies:

De situatie zoals die nu is leent zich niet optimaal voor CE praktijken. Noch de aannemer noch de fabrikant worden geprikkeld om CE praktijken toe te passen. De CE praktijken die wel worden toegepast worden alleen door daarvoor gespecialiseerde aannemers gedaan omdat dit hun kostenbesparingen kan opleveren. De aannemers onderkennen dat verbeterde conditie informatie in combinatie met betere afspraken hier grote verbeteringen in kunnen brengen. Echter onderkennen ze ook allemaal dat dit vanuit de opdrachtgever moet worden gestuurd door een verbeterde procedure omtrent de contractprocedure.

Q11: Hoe kijkt jullie organisatie aan tegen het proces omtrent onderhoudscontracten en welke verbeteringen zien jullie voor de toekomst?

SP3: We merken dat er veel aan de contracten verbeterd kan worden, maar dat dit in de praktijk geen prioreit heeft. Het zou interessant zijn om de verschillende perioden qua strategie naast elkaar te leggen: hoe het 20 jaar geleden ging, hoe het nu gaat, en hoe het over 20 jaar zou moeten gaan. Als wij ergens instappen dan moeten we zeker zijn van dat het ons binnen enkele jaren iets gaat opleveren.

4) Original Equipment Manufacturers

OEM1: Erik Brecht, ABB. ABB is een groot technisch concern dat technische toepassing ontwerpt, maakt en vermarkt. Telefoongesprek van ca. 10 minuten.

OEM2: Marco Vermeulen, Siemens. Siemens is een groot technisch concern dat technische toepassing ontwerpt, maakt en vermarkt. Telefoongesprek van ca. 5 minuten.

OEM3: John Brouwer, Bosch Rexroth. Bosch Rexroth is een groot technisch concern dat technische toepassing ontwerpt, maakt en vermarkt. Telefoongesprek van ca. 5 minuten.

Q1: Hoe kijkt uw concern aan tegen een toekomstscenario waarbij CE praktijken zoals remanufacturing worden toegepast om de afhankelijkheid van virgin raw materials te beperken?

OEM1: De personeelskosten voor het vervangen van electronische systemen zijn hoger dan die voor de systemen zelf, daarom laten ze alles zo lang mogelijk zitten. Op het moment dat de systemen echt niet meer functioneren gaan alles zo snel mogelijk naar de schredder en wordt het vervangen.

Conclusies:
Personen bij de fabrikanten waren erg moeilijk te bereiken voor een gesprek. Als er uiteindelijk contact werd gevonden dan was men erg terughoudend of stelde men voor later contact op te nemen. In elk geval is er via deze weg geen tot weinig informatie verkregen. Door de reactie van Erik Brecht van ABB is de indruk gewekt dat er niet positief wordt gedacht over zo'n scenario.

5) Consultants

CON1: Renee Eijsbouts, technisch bedrijfskundige gespecialiseerd in WEEE, Circulaire Economie groep Witteveen+Bos. Rob Dijcker, Milieukundige, Circulaire Economie groep Witteveen+Bos. De CE groep van W+B is een net opgerichte groep die zich bezighoud met CE gerelateerde vraagstukken.

Q1: Wat gebeurt er op het moment met vervangen electr(on)ische systemen uit beweegbare bruggen?

In principe gaat alles terug de economie in volgens de volgende stromen: schroot en edelmetalen. Voor schroot is er al een redelijk effectieve reverse supply chain. Het terugwinnen van waarde uit edelmetalen in de vorm van electronica loop echter niet. Veel printplaten eindigen in de afvalbak doordat het niet kostenvoordelig is te demonteren.

Conclusies

Alle materialen vinden hun weg terug naar de economie, echter voor electronic gebeurt dit verre van optimaal met betrekking tot waardebehoud

Q2: *Wat zijn de beweegredenen voor deze keuzes?*

Het totaalgewicht aan hoogwaardig materiaal bepaald, geld is dus leidend. De opdrachtgever huurt iemand in om het afval af te handelen binnen de kaders van de wet en is zich verder meestal niet bewust van de restwaarde. Bovendien is hier geen controle op. Het zou niet verbazen als de aannemer wel bewust is van deze waarde en er illegale handeltjes zijn.

Conclusies

De opdrachtgever heeft in de praktijk andere prioriteiten en is zich niet bewust van de restwaarde van electronica. Aannemers voeren alleen uit wat er in het contract staat.

Q3: Hoe wordt er bij CE gedacht over een toekomstscenario met een lange termijn PSS waarbij de SP eigenaar blijft van de technische installaties en OEM en SP nauw samenwerken

Ontwerpen voor remanufacturing zou een uitkomst zijn. OC Venlo en Fairphone ontwerpen modulaire producten met een bijbehorend contract zodat de producten makkelijk kunnen worden vervangen en de waarde zo efficient mogelijk kan wordn teruggewonnen. Waar dit niet mogelijk is moet onderscheid worden gemaakt tussen hoogwaardig en laagwaardig recyclen. Een verbeterde grondstoffenhuishouding moet worden afgedwongen middels het bestek, de aannemer moet dit dan uitvoeren.

Conclusies

Verwacht wordt dat CE praktijken zoals design for remanufacturing en modulair ontwerpen de grondstoffenhuishouding kunnen verbeteren, zoals dit ook bij OC venlo en Fairphone het geval is. Dit moet echter worden afgedwongen middels het bestek (door de opdrachtgever) en vervolgens worden bekrachtigd door controles.

Appendix F. Other

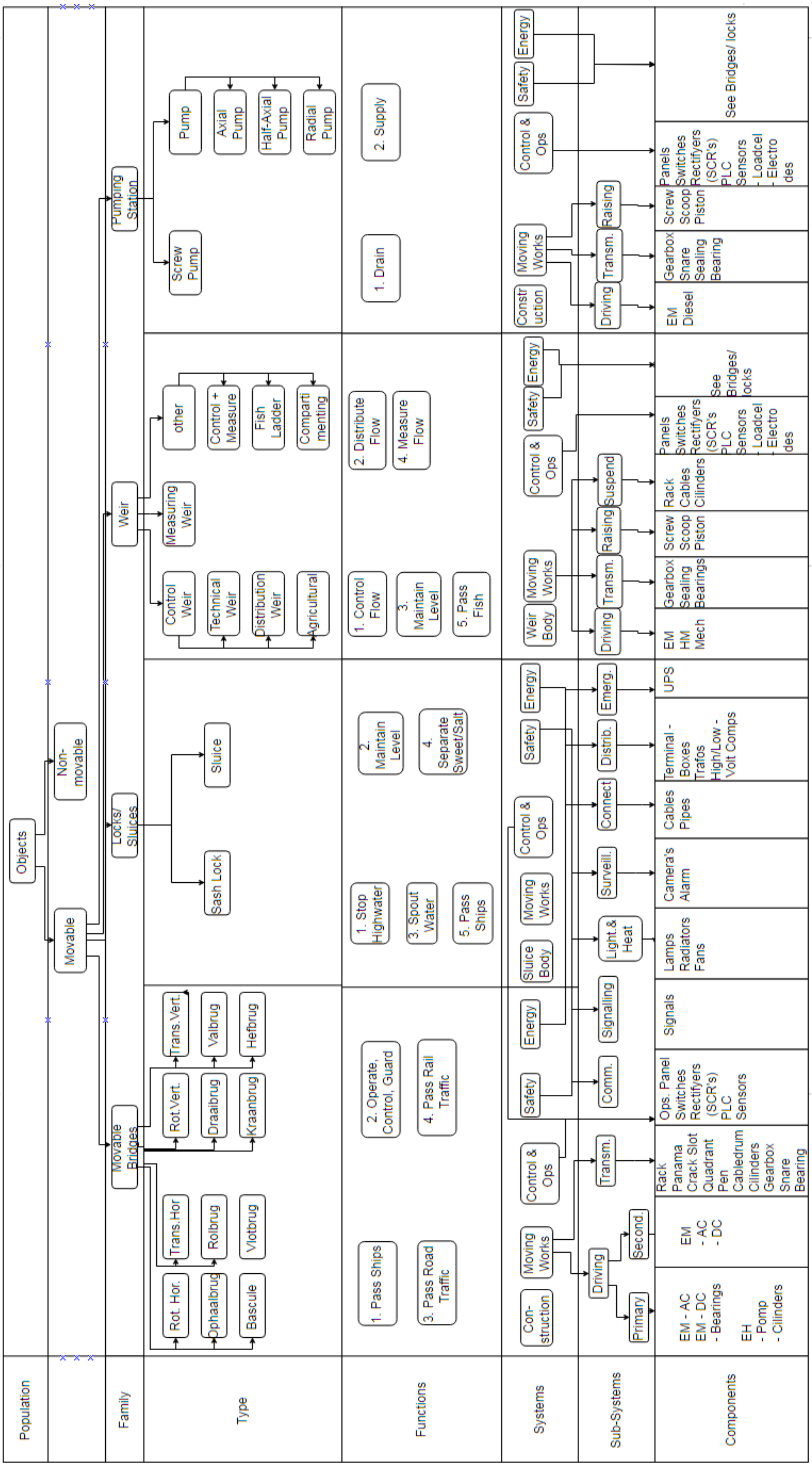


Figure F1. Object Decomposition

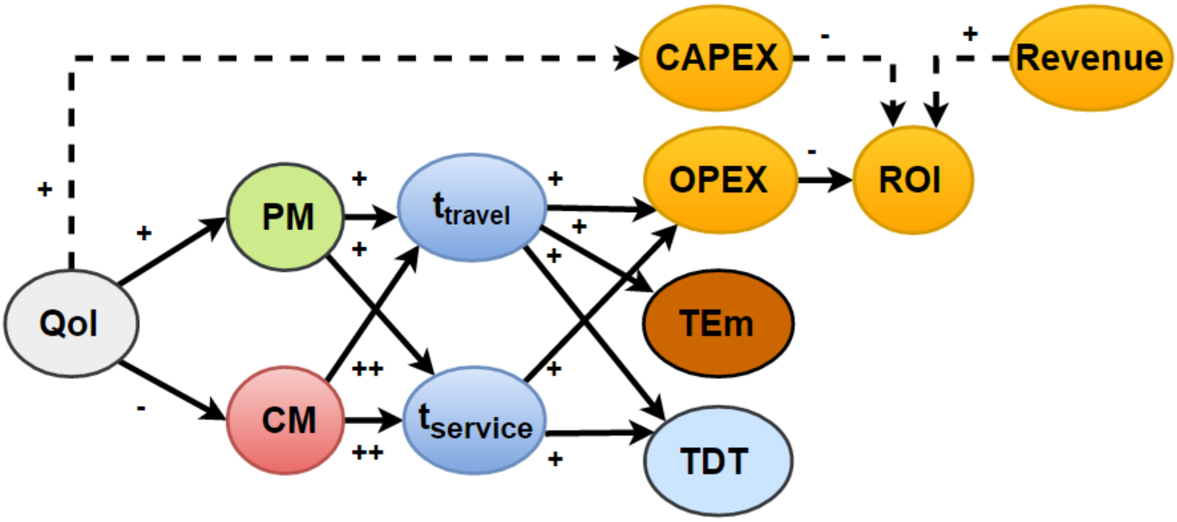


Figure F2. construct relations