MSc Thesis in Hydraulic Engineering

Assessment on the effect of flood defences asset management maturity to cost and performance

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TU Delft

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Executive Summary

Asset management is the activities which intent are to assure the full potential performance of the asset. Asset management enables an organization to realize value from asset and fulfill the organizational objectives. Asset management includes the full range of asset planning, creation strategies, operation and maintenance, and performance monitoring. The benefit can be directly assessed and quantified, for example reduced capital and maintenance cost and reduced risk exposure. Other benefits can be much more difficult to quantify but may be equally important in terms of asset performance.

In flood defence asset, asset management is essential for an organization to implement. An organization's top management, employees and stakeholders faces challenges which requires to foresee and respond threats to its operating asset. A failure flood defences asset may cause significant consequences which involves loss of life, economic damage and pollution. Hence, the organization should be capable of managing an asset to meet the current and future needs. The extent of asset management capability can be measured using maturity model.

The concept of a maturity model is a structured guideline that identifies how different dimension or processes may influence a set of pre-determined organizational outcomes. This concept has been used in wide range of fields, including area of infrastructure management. Maturity model offers a structured measurement of asset management maturity to identify current capability, strength, and weaknesses in relation to the intended goals. Asset management maturity can be divided into five different levels which are optimized, well-managed, standard, repeatable, and ad-hoc. These levels are used to rank the various dimension or process of an organization. However, maturity levels only describe a general description of capability. The effect of different maturity levels towards the organizational outcomes is speculated based on the description of each maturity levels. Hence, the use of the maturity model output (maturity levels) is limited in the pre-determined description of each level.

The objective of this research is to assess the effect of asset management maturity towards cost and performance. The assessment is conducted to a semi-hypothetical case of flood defences asset (grass revetment) using Dynamic Bayesian Network. The maintenance model (or network) is developed by modelling the process of grass revetment maintenance. The network models the asset degradation and the conditional outcome of different asset management maturity. There are three component of asset management that is developed in the model, which are the information, maintenance decision, and maintenance execution. Each component is represented as a network. The simulation is done by adjusting the network to a specific scenario that combines both degradation process and the effect of different management maturity.

In the maintenance network, grass revetment is modelled as Markov property using the grass quality definition in Dutch safety assessment (closed, open and fragmented). The degradation probability of a grass state is not yet studied. Therefore, the degradation probability is assessed using structured expert judgment which involves both operational and researcher as experts. The assessment was done using Cooke's classical model for expert judgment where the experts are scored and weighted based on their performance. Cooke's model also establishes different combined experts performance which is called the decision-maker. Based on the assessment, most experts produces a low calibration. The combined experts scores relatively different for each weighting scheme. The highest calibration was obtained from DM Optimized with 0.707. By using DM Optimized distributions on uncertainty, the degradation rate is obtained and used in the maintenance network.

Different scenarios is developed by considering the existing management dimension and the application towards the developed model. There are four scenarios which is associated to a maturity dimension. These maturity dimension are the asset management dimension, asset information, internal coordination and culture and leadership. Each maturity dimension are connected to a specific network elements where it is translated

as a model input for each maturity levels. The goal is to obtain asset cost and performance from different management maturity. The result shows a success on obtaining the cost and performance for each scenario. The reliability of the result depends highly on the model parameters.

In a nutshell, this research has shown a possibility to predict the effect of different management maturity towards the asset cost and performance on a semi-hypothetical case using Dynamic Bayesian Network. The limitation of the research was found on the model parameters which limits the utilization of the scenario and can be improved in future research.

Abstract

Maturity model has proven to be helpful for an organization to identify its current capability, strength, and weaknesses through maturity levels. These levels are used to rank the various dimension or process of an organization. However, maturity levels only describe a general description of organization capability. The effect of different maturity levels towards the organizational outcomes is speculated in the basis of the description at each maturity levels. The use of the maturity levels is limited in the pre-determined description. This research is an attempt to foresee the effect of different management maturity towards asset cost and performance by using Dynamic Bayesian Network. The network is developed by using a semi-hypothetical case on grass revetment management. The network models the maintenance process which covers the asset degradation and the influence of different extent of management towards grass condition in time. The degradation probability was determined by using Cooke's classical model expert judgment. We designed different network involving four management dimension that was translated as model scenarios. The result provides an insight into the potential gain or loss of different management maturity which is beneficial for organizations in evaluating different alternatives of management improvement.

Keywords: Asset Management, Maturity Model, Grass Revetments, Expert Judgment, Dynamic Bayesian Network, Flood Risk, Maturity Levels

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1 Introduction

1.1. Background

Adaptation to Flooding

The biggest natural disaster of the twentieth century in the Netherlands occurred in 1953 from a North Sea flood. The floods struck the Netherlands the hardest, but it also has affected Belgium, England, and Scotland along the process. This phenomenon has taken lives and caused massive damage to infrastructure, residential, and livestock. Since then, the North Sea Region (NSR) countries have focused on investing in flood defences (Vlad, 2017). Collectively, European Union (EU) Member States invest a yearly average of around € 3 billion on flood protection infrastructure (The North Sea Region Programme, 2019). However, the flood defences structure are ageing and required further attention to maintain its performance. Even more, we are now living in paradigm of uncertainty as a result of increasing threats of sea level rise and socio-economic changes. Hence, we have shifted our paradigm from reacting after flood occurrence, to an adaptation in a proactive manner (Gersonius, 2012) through flood risk management. This adaption requires complex and challenging decisions from the asset owners and managers. Especially for coastal regions, operating authorities need to adapt their maintenance regime to ensure the best value from their flood protection assets.

FAIR Project

The Interreg NSR program recognized these challenges and launched a project in 2015, called the FAIR project (Flood defence infrastructure asset management & investment in renovation, adaptation, optimization, and maintenance) which involved all NSR countries in improving the practice of flood defence asset management. The objective of the FAIR project is to reduce flood risk in the NSR by improving the flood infrastructure performance. This is achieved by improving asset management and investment planning decision making, and by demonstrating climate change adaptation strategies (The North Sea Region Programme, 2015). FAIR projects include asset owners and science partners to share, improve, and promote flood risk management practice across. Within this context, this research aims to contribute within the objective of the FAIR project focusing on flood defences asset management.

Asset management

One important field of study in flood risk management paradigm is asset management (Vlad, 2017). Based on the Organization (2004), asset management is defined as "a coordinated activity of an organization to realize value from assets “. Asset management (AM) is the initiatives in an organization to maintain the value of its assets, such as identifying the current needs, providing logistic and maintenance support, acquiring, disposing, and renewing asset. The goal of asset management is to develop an organization that possesses functional assets that fulfil its business needs. It can be achieved by providing support services to assure the functionality and efficiency of asset operational throughout its service life (Hastings, 2010). There are several types of assets identified within an organization. In this study, we focus solely the physical asset which is a grass revetments on a dike.

The benefit of asset management can be recognized from the improved financial performance and lower risk generated by the flood defence performance. Asset management translates the organization objective into asset-related decisions, plans, and activities through a risk-based approach (Organization, 2004). To fulfil the organizational objective, an organization is required to develop an asset management system. An asset management system is a set of interrelated and interacting elements of an organization in the form of asset management policy, objective, and processes. This system gives assurance that asset management activities will be delivered.

Asset management are implemented in different societal level, from national, regional and local level (van der Velde et al., 2013). The way flood structure is managed depends on the institutions, on the interaction between different stakeholders, and the extent of asset management is applied within the organization. However, the dynamic changes of load parameters have challenged asset managers on adapting to their operation and management. A good practice of asset management can respond with a cost-effective strategy of maintenance and operation, i.e, one which results in the lowest possible long-run cost and which satisfies flood protection standards imposed by the regulator throughout the entire planning horizon (Postek et al., 2019).

Maturity Model

Maturity models are one of the widespread areas in the field of improving organizational performance (Khoshgoftar and Osman, 2009). A maturity model is a tool to assess the efficiency or capability of a particular individual or group. This method can identify organizational strengths and weaknesses and potential for improvements (Volker et al., 2013). In general, maturity models use five different maturity indicators (e.g., ad-hoc, repeatable, standard, well-managed, and optimized). Based on Paulk et al. (1993), maturity is defined as an extent where a process is explicitly defined, managed, measured, controlled, and effective. It implies the potential for growth in capability and indicates both the richness of an organization its processes and the consistency with which it is applied in projects throughout the organization.

In the beginning, most of the maturity models have focused on improving the software process by developing a process maturity framework (Paulk et al., 1993). This development was initiated by the Software Engineering Institute (SEI) in the request by the federal government to develop a method for assessing the capability of software contractors. After several years of study, SEI has developed a maturity framework called the Capability Maturity Model for Software (CMM). The CMM is based on knowledge acquired from software process assessments and extensive feedback from both industry and government. This model provides valuable input for establishing process improvement programs (Dooley et al., 2001).

During the 1990s, several maturity models have been proposed focusing on project management which most of it was based on the PMI's Guide of the Project Management Body of Knowledge (PMBoK) and built by using the Capability Maturity Model's (CMM) five maturity levels as the benchmark (Paulk et al., 1993). At a later stage, a new maturity model was developed under various standard reference which few of them deviates from the initial standard of PMBOK and different focus of the domain. After several years, the maturity model has evolved from handling software processes to another area such as water utilities, railroads, offshore industries, asset management, etc. (Volker et al., 2011). For an asset management maturity model, it consists of assessing the strategy, planning, operation, and maintenance of an organization which is later developed by considering parameters that influence asset management. One of this research focuses is to use the most applicable maturity model to the case of asset management on grass inspection and maintenance on a dike.

In general, an initial stage of an organization asset management maturity mostly focuses on developing standards, process, and concepts. At a later stage, the organization tends to improve by initiating a critical means of evaluation, feedback, integration, and collaboration on important issues concerning their asset functional performance. Therefore, the maturity model would likely give a structural framework of assessing and understanding the current organization management maturity and their potential improvement.

1.2. Problem Formulation

There are many types of maturity model available in different industries which each have a different focus. Infrastructure Management Maturity Model is one of the recent models that is developed and implemented in an infrastructure organization. Infrastructure Management Maturity Matrix (IM3) distinguishes management maturity into five levels, from ad-hoc to optimize with seven management dimensions (Volker et al., 2011). The result of the model gives a general maturity overview within the seven-management dimension of the organizational capability. IM3 implementation enables the organization to discuss the possibility of management improvement based on the maturity model result. The result shows the organization management capability in the form of maturity. However, maturity levels hold a limited substance of information, especially to acknowledge the opportunity loss towards an asset performance. Rijkswaterstaat has implemented IM3 to measure the maturity level of the organization within the seven dimensions in two separate years (Volker et al., 2013). The initial measurement is to obtain the initial maturity, and the second measurement is to assess its change within the period. The result shows a considerable learning curve amongst the divisions and the employee. However, the result does not show the potential organization gain of improving or loss of not developing their maturity. Almost all maturity models have a similar limitation.

An initial attempt has been made to expand the use of maturity model by projecting an information management maturity level into a project indicator by using Dynamic Bayesian Network (Adhi, 2019). The aforementioned research objective was to link the maturity levels to a degradation model using Dynamic Bayesian Network. The result is the relative cost of the maintenance activity in an organization at different information management maturity levels. This gives a new understanding of asset cost and performance in different maturity level, which can be useful information in the decision-making process. However, this approach was developed under various assumptions. One of the significant challenges was that the maturity dimensions are defined on a very general level, such that it is challenging to associate maturity levels to specific activities. Other than that, the network was formulated using Genie program, which gives a limited application on adapting the network towards a particular AM scenario.

1.3. Knowledge Gap

A deteriorating asset can be efficiently maintained if the lifetime serviceability can be predicted. If a deterioration process has a very random nature, it can be a challenge to efficiently maintain an asset. Therefore, asset management is essential for organization to implement due to the unpredictability of asset deterioration that may cause an unexpected risk. A particular management maturity can be implied to the organization capability on the asset life-cycle monitoring and maintenance. For example, an ad-hoc management maturity would likely to have lack of motivation to monitor or maintain their asset. Whereas, mature management would acquire a better asset performance from their inspection and maintenance activities. In a nutshell, efficient asset management can be measured not only quantitatively (asset performance and cost) but also qualitatively (management maturity). The different level of management competency can be acquired by using the maturity model. The maturity model can indicate the organization management capability from different management perspective. But, the implication of a certain management maturity towards asset performance has not been studied so far. It would be useful for organization to understand their potential gain/loss of their asset cost and performance for different management maturity.

1.4. Research Objective and Question

This section starts with the main research objective and is followed by sub-questions that would help answer the main research objective. Each research question is individually elaborated.

1.4.1. Main Objective

"Assess the effect of different management maturity levels to cost and performance of a flood defences asset"

As mentioned in the knowledge gap, the use of the maturity model output (maturity levels) is limited in the pre-determined description of each level. Maturity levels describes the current management performance without an implication the asset performance. In a logical sense, organizations, with different management maturity, would have a different strategy on managing their asset, thereby leading to a different outcome of asset performance. Hence, it is informative if an organization can estimate the gain/loss of asset cost and performance by improving their management maturity. In other words, this information should help decision-makers understand the opportunity of different maturity levels relative to their current asset management maturity. This research is focusing solely on maintenance and inspection of grass revetments.

1.4.2. Research Question 1

"What is the deterioration rate of grass revetments?"

Grass revetment is known for its low-cost and environmental friendly compared to other dike revetments. Like any other structures, grass revetment can degrade over time due to its natural behaviour or external forces. Unfortunately, there is limited knowledge about the deterioration behaviour of grass revetments.

1.4.3. Research Question 2

"What is the most effective inspection and maintenance interval of grass revetment management?"

In this research, different scenarios of management maturity will be developed and translated to the network. It is important to specify the most effective inspection and maintenance interval under a perfect management maturity. In order to predict different asset performance under different maintenance interval, a maintenance model is required. We have not found any studies concerning the inspection and maintenance interval on grass revetment. Therefore, a maintenance model will be developed using Dynamic Bayesian Network.

1.4.4. Research Question 3

"Which maturity maturity model is suitable for infrastructure asset management and can be translated to the developed maintenance model?"

Several maturity models have been developed in recent years. Some of the models have a specific purpose for indicating the current management performance towards infrastructure asset. An initial attempt at translation was made in a previous study, and it found some difficulties due to the inter-relations of maturity dimensions (Adhi, 2019). Therefore, it is essential to thoroughly assess other potential models and translation approach that might be more suitable for this research purpose.

1.4.5. Research Question 4

"What is the expected total cost reduction from different asset management maturity levels?"

Maturity level is a subjective measurement of asset management competency. It illustrates a particular organization/individual management work process which classifies within the maturity levels. Mature management should showcase an optimal asset operational cost and performance. Vice versa, immature management may showcase an inefficient asset performance due to its inefficient work process. Hence, each maturity levels presents a distinctive asset cost and performance. Through the maintenance model, the different maturity levels are modelled through different scenarios. The outcome should demonstrate the different asset cost and performance for different maturity levels.

1.5. Research Scope and Limitation

This study will focus on assessing the effect of maturity levels towards the asset cost and performance of a grass revetment asset using Dynamic Bayesian Network. The semi-hypothetical case study focuses on the inspection and maintenance activities on grass revetment in the Netherlands, and different scenarios of management maturity are developed in which will be translated into a maintenance network. The maintenance network will provide the developer to model and modify different scenarios. The simulation of the maintenance network is simulated using MATLAB and validated partially using Genie Program.

This study also cover expert elicitation of grass degradation that will be applied in the maintenance network. The grass cover degradation rate is determined using Cooke's Classical Model of Expert Judgment. The targeted participants are professionals or scientists who have adequate experience with (inspecting) grass revetment. Although grass revetment can restrengthen in time, during expert elicitation, we only consider the degradation of grass revetments.

2
Methodology

2.1. General Approach

A predictive approach was used for this thesis. Predictive research is a quantitative approach to predict the effect on one variable by manipulating another variable. The rational motive for using predictive approach is to explore the asset cost and performance from different management maturity. There is evident relationship within the asset management and asset performance. In this thesis, different scenarios of management maturity were used as the controlled variable to obtain the asset cost and performance as the output which is developed using a maintenance model.

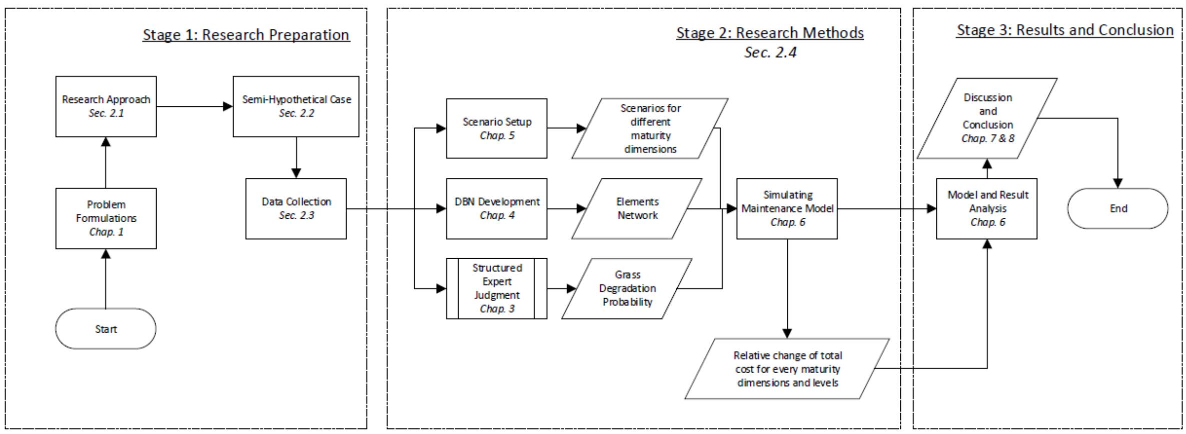


Figure 2.1: Research Process

As shown in figure 2.1, the research begins by formulating the problem and the research approach. This research uses a semi-hypothetical case on grass revetment management on a typical dike in the Netherlands as a case study(see Section 2.2). Then, three essential steps are conducted, which are the structured expert judgment (SEJ), maintenance model development, and scenario setup. SEJ is conducted to unveil the degradation rate of grass revetments. It will be used to illustrate the degradation through the maintenance model. The maintenance model is developed using Dynamic Bayesian Network which contains several network elements, that depicts the degradation and improvement of grass revetments from different management maturity. Furthermore, scenario setups will discuss the process of obtaining different scenarios that represent a particular asset management maturity. These scenarios are translated to the maintenance model through different set of network or inputs (see Chapter 5). Then, the maintenance model (developed in Chapter 4), is simulated using the degradation probability obtained in Chapter 3, and through different scenarios. The maintenance model will illustrate the asset performance throughout a time-horizon from different management maturity. The results of each scenario are analyzed in Chapter 6 and the overall research is discussed further in Chapter 7.

2.2. Semi-Hypothetical Case

Grass revetment role on dike

The grass revetment is generally applied for reinforcement of river dike surface (Technische Adviescommissie voor de Waterkeringen, 1999). Grass cover plays a significant role in the dike reliability in two main ways: provide protection against erosion and stability. Physical experiment and investigation on grass cover resistance towards erosion have been proven to be beneficial (Hoffmans et al., 2015; Jan Steendam et al., 2015; Piontkowitz, 2010). Erosion by wave overtopping at dike is a major cause of dike damage or failure during severe overtopping events (Hoffmans et al., 2015). On the other hand, the soil can be unstable, especially if the slope is steeper than the angle of repose of the grain. A small scour or hole can initiate larger holes and can lead to instability on the dike surface. The grass cover naturally gives an extra resistance towards erosion, which provides higher stability against sliding mechanism (Van Hoven et al., 2010).

Figure 2.2: Examples of references picture for different grass condition. The grass condition of the left picture is in the closed state; the middle is an open condition, and the right is the fragmented condition. Images are taken from Het Waterschapshuis (2016)

Grass degradation behaviour

The grass sod quality can grow naturally or degrade through several mechanisms. Most degradation is shock-based, and cumulative without the presence of maintenance. Most common degradation factor are human/animal/vegetation sudden intervention, wave/current impact, and changes of precipitation. According to the WBI 2017 (Standard practice for dike management), three different qualities are distinguished in the Dutch safety assessment: closed, open and fragmented (Dutch: gesloten, open en fragmentarisch; see Figure 2.2). This term is mostly used when executing an inspection routine based on visual. Based on this three distinction of grass quality, the critical velocities and critical overtopping discharges can be approximated based on several physical experiments (Le et al., 2017; Peeters et al., 2012). In a closed condition, the root of the grass is strong and keeps the soil against loads. As holes appear on the grass surface, some weak spot may initiate a complete failure of the dike. The probability of failure would be higher when the grass condition is weaker/fragmented.

Semi-Hypothetical Case

The case focuses on a typical dike with slope ratio 1:3 and uses as grass revetment. The dike is located in a rural area where there are few human activities and wave attacks. Like any other asset, asset management can be implemented to grass revetment to maintain its performance. Inspection and maintenance are commonly applied. The demonstration of asset management influences the performance and cost of the asset. This study explores the asset cost and performance for different management maturity using a maintenance model.

2.3. Data Collection

This study focuses on a semi-hypothetical case on a typical dike with grass revetments in the Netherlands. The semi-hypothetical case is developed through a literature review. Grass degradation probability is important for the maintenance model. Unfortunately, there is a lack of study of grass degradation rate since it depends on different stochastic factors. Hence, this study uses Structured Expert Judgment, which is a deliberate effort to acquire experts opinion in a structured manner (see Chapter 3). The goal of this application is to obtain the uncertainty of grass quality degradation in time. The experts involved in this study are the dike inspectors and scientist on the related field of grass revetment. A similar study was done to reveal the degradation probability of a bridge element (Kosgodagan et al., 2016). Other than that, this study did not conduct an appropriate sampling on an actual data since it is difficult to obtain information on a particular cost and performance of a similar grass revetment and exposed to a similar environment. Inputs are developed based on literature reviews.

2.4. Methods

2.4.1. Expert Judgment

Eliciting data from experts opinion using Cooke's method is growing popular and applied in many fields (Cooke et al., 2008). This method involves several experts on the related area to give their expert opinions and score them based on their ability to project uncertainty. This method is better than a traditional expert judgment because Cooke's model measures an actual judgment of a person through a statistical assessment to eliminate inadequate experts. Some questions are designed to calibrate, and others are given to project the target variables. Based on the answers, experts will be scored and weighted based on the performance. Cooke's model also establishes a combined experts performance called the decision-maker.

2.4.2. Dynamic Bayesian Network

Degradation modeling is a key point for maintenance model. The accuracy of all maintenance model depends on the quality of degradation modeling. Commonly used stochastic degradation process is Poisson process (Kuijper and Kallen, 2012) and Gamma process (Pandey and Noortwijk, 2004). These methods take into account the temporal aspect modeling the evolution of degradation of the system in time. Although these methods can depict the expected number of failure in a warranty period, Dynamic Bayesian Network depicts the degradation as a discrete and finite states space which is suitable for developing a maintenance model on a degrading system that can be represented as states such as bridge elements and grass.

Dynamic Bayesian Network (DBN) is one of few approaches on designing a maintenance model. It allows us to model the propagation of information from assets inconsistent manner. The modeling of maintenance model on a degrading structure involves uncertainty variables. A number of researchers have applied BN in the context of deterioration modeling. Kosgodagan-Dalla Torre et al. (2017) studied the application of DBN on large-scale degradation on bridge elements. Another study by Friss-Hansen (2000) focuses on decision support of inspection and maintenance of a degrading asset through DBN. DBN and Markov Decision Process (MDP) are quite a similar approach where it depicts the degradation as a discrete and finite space. The advantage of using DBN is the ability to adjusting the different combination of network in different temporal time-steps which is useful to illustrate different maintenance strategy.

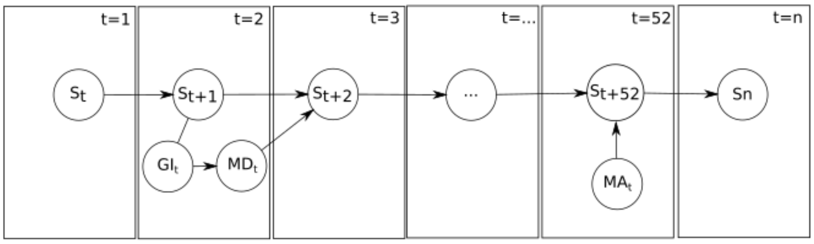


Figure 2.3: Schematic dynamic bayesian network where inspection and maintenance occur every two time-slices and annual maintenance occur every 52 time-slices. (Own picture, 2019)

This study utilized the Dynamic Bayesian Network to look into different asset cost and performance for different maturity levels. The model is designed to represent inspection and maintenance scheme of grass revetments on the inner dike. Figure 2.3 shows an example of Dynamic Bayesian Network for inspection and maintenance. Within the network, there are several asset management processes that are depicted. **These processes or elements** are the Asset/Grass and degradation (S_t), Asset/Grass Information (GI), Maintenance Decision and Execution based on the obtained asset information (MD), and Annual Maintenance (MA). This network will be adjusted to different scenarios that represent maturity dimensions.

2.4.3. Maturity Dimensions for Scenario

Maturity dimensions is a term used in this research to refer the different asset management dimensions commonly used by Volker et al. (2011). As discussed earlier, there is evident relation of different level of maturity dimensions and the organization strategy on asset management. Through the developed maintenance model, there are several elements that can be controlled and shape to explore different scenarios. Those elements are:

- Inspection and Maintenance Interval
- Perfect and Imperfect Information
- Perfect and Imperfect Decision
- Perfect and Imperfect Maintenance Execution

These scenarios can be related to a certain maturity dimension. In this research, we produce a particular maturity dimension that can be implicated to the relevant scenarios. The considerations are discussed in Chapter 5. Within the scenarios, sub-scenarios are assigned to explore the different asset cost and performance in different maturity levels. Each dimension is associated only to a single element of the network and translated as model input.

2.5. Simulation of the Maintenance Model

The simulation of the maintenance model is combining information obtained from structured expert judgment on grass degradation probability and developing different maintenance network based on the developed scenarios. The simulation is developed using MATLAB. The main output is the relative change of total cost of asset between different maturity levels at every scenario. Relative change is a way to express changes in a variable using percentage. It represents the changes between the old and new value. The main output allows us to understand the gain and loss of asset cost and performance from different management maturity. The whole process of model development and results are then analysed and discussed for its achievement and limitation.

3
Expert Judgment

3.1. Introduction

The goal of this chapter is to answer the first research question:

"What is the deterioration rate of grass revetments?"

Due to the limitation of data availability, performance-based expert judgment is applied to unveil the degradation rate of grass revetments. This chapter will follow the framework shown in Figure 3.1. This chapter introduces the method of performance-based expert judgment. Then, we will discuss the elicitation procedure performed in this study. At last, the expert opinions are scored, which will be analysed and discussed in the last section. The output of this assessment will be applied in the latter maintenance model.

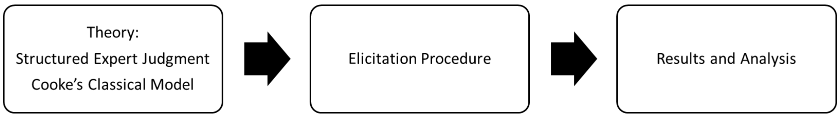


Figure 3.1: An illustration on the framework of expert judgment chapter

3.2. Structured Expert Judgment

This section will introduce the literature and general application of performance-based expert judgment, also called Cooke's classical model, named after professor Roger Cooke.

3.2.1. Expert Judgment

Expert judgment exemplifies subjective probabilities and has been derived from the theory of rational decision making in Savage (1972). Subjective probability of a person is an actual judgment, typically representing the way of a person think, in view of their knowledge and information (Jeffrey, 2004). Subjective probability differs between each person and contains a high degree of personal bias. Goosens and Cooke (2008) develops a statistical assessment for expert judgment within the assumption that the expert's opinion for the future can be measured.

The fundamental assumption of the classical model of expert judgment from Roger Cooke is that the reliability or statistical accuracy of expert's opinions for the future can be measured by the reliability or statistical accuracy of their opinions for situations in the past (Goosens and Cooke, 2008). Due to this assumption, experts are scored using seed variables to calibrate their competency on expressing uncertainties. Furthermore, seed variables should resemble as much as the target variables. Multiple contributions of experts can increase the reliability of the assessment.

Seed variables are used to evaluate the expert's ability to expressing uncertainty in which the value is known. Target variables focus on the variables in which the research is aiming. For the seed variables, data should exist to have a point of reference for the actual value. On the other hand, target variables are the uncertainty that is hard to obtain. Based on the answers, experts will be scored and weighted based on the performance. Cooke's model also establishes a combined experts performance called the decision-maker.

3.2.2. Elicitation

Experts are asked to express their opinion of uncertainty with a representation of 5th, 50th, and 95th percentile. This expression is used for both seed and target variables. Using the three percentiles results in the intervals: [0;0.05], [0.05;0.50], [0.50;0.95], [0.95;1.00] with probability vector. These intervals can be expressed as this following:

$$p = \begin{Bmatrix} 0.05 \\ 0.45 \\ 0.45 \\ 0.05 \end{Bmatrix} \tag{3.1}$$

3.2.3. Scoring Method: Calibration

The calibration measures the statistical likelihood that the actual values in the seed variables correspond to the expert assessment. In other words, it indicates the reliability of experts estimation. Based on the expert's opinions, each response of the seed variables will be evaluated relative to the realization. If N quantities of seed variables, each expert are assessed its statistical hypothesis, by fitting the realization value within the interval based on expert responses. Equation 3.2 describes that each realization (x_i where $i = \{1, ..., N\}$) are fitted to the right expert's interval. The sample distribution (s) is then the sum of number of realization falls at each inter-quantile intervals divided by the total number of seed variables.

$$\begin{aligned}
s_1(e) &= \#(i|x_i < 5\%\ quantile)/N \\
s_2(e) &= \#(i|5\% < x_i < 50\%\ quantile)/N \\
s_3(e) &= \#(i|50\% < x_i < 95\%\ quantile)/N \\
s_4(e) &= \#(i|x_i > 95\%\ quantile)/N \\
s(e) &= (s_1, ..., s_4)
\end{aligned} \tag{3.2}$$

The realizations are then computed to the likelihood ratio and will be calculated further with the calibration score. The calibration is defined as the index (CE) for getting an information score worse than a score that would be obtained if an experts assessment is equal to the theoretical mass function. It is calculated using the chi-square distribution with three degrees of freedom. To be a good uncertainty assessor, one's assessment should be similar to the theoretical assessment. If an expert provides no relative information (I(s,p)=0), the calibration scores will be 1. In other words, his assessment represents reality. On the other hand, a low calibration can be depicted as experts that deviate from the theoretical mass function and receives a score approaching 0.

$$\begin{aligned}
2NI(s(e)|p) &= 2N \textstyle\sum_{i=1,...,4} s_i \ln\left(s_i/p_i\right) \\
CE(e) &= P\left\{2NI(s(e)|p) \geq r|H_e\right\} \text{ or} \\
CE(e) &= 1 - \chi^2(2NI(s(e)|p), DF)
\end{aligned} \tag{3.3}$$

N	Number of seed variables
s(e)	Sample distribution of expert

p	Probability vector of 1x4 matrix
I(s(e)|P)	The relative information of distribution s conditional to p
r	Realization of the variable (actual value)
χ^2	Chi-Square
DF	Degree of freedom

3.2.4. Scoring Method: Information

Information measures the degree to which the uncertainty distribution of an expert is concentrated compared to other experts. Informativeness can be defined as experts confidence in their assessment, which is measured by developing an intrinsic range that captures the range of possible outcomes which was necessary to be accurate. The range of uncertainty based on expert response can be written as; $I = [q_L, q_H]$. The classical model implements a so-called k% overshoot rule where the smallest interval at each item contains all the assessed quantiles of all experts and realization. Therefore, the extended interval according to the rule of overshoot:

$$\begin{aligned} I &= [q_L, q_H] \\ q_L &= q_5 - k\left(\tfrac{q_{95}-q_5}{100}\right) \\ q_H &= q_{95} + k\left(\tfrac{q_{95}-q_5}{100}\right) \end{aligned} \tag{3.4}$$

A higher k-value tends to make all experts looks informative and minimize the gap of information scores between experts. For this study, a typical k value of 10% is used. The information score can be calculated with this following equation:

$$\begin{aligned} I(e) &= (1/N)\cdot\textstyle\sum_{i=1,\ldots,4}\left\{I(f_{e,i}|g_i)\right\} \\ I(f_{e,i}|g_i) &= \textstyle\sum_{i=1,\ldots,4}\left\{f_{e,i}\cdot ln(\tfrac{f_{e,i}}{g_i})\right\} \end{aligned} \tag{3.5}$$

I	Information score
$f_{e,i}$	Experts e's density for item i
g_i	background density for variable i

The actual informativeness per expert is defined by calculating the average of all information scores per variable. Information score is represented by a positive value that increases when experts express a narrow bound. In other words, higher information score refers a confident assessment.

3.2.5. Decision Maker

The goal of this method is to obtain a distribution from expert opinions where each individual can contribute based on their performance. A combination of expert assessment is called Decision Maker (Aspinall, 2008). The experts are weighted based on their calibration and information scores. Expert with high calibration and information score will influence profoundly on the decision-maker. Given the set of weights, target variables for each query variable can be computed for the DM.

The DM is a normalized weighted linear combination of the expert's distributions per item:

$$DM = \frac{\sum_{e=1,\ldots,N_e}(w_e\cdot f_{e,n})}{\sum_{e=1,\ldots,N_e}(w_e)} \tag{3.6}$$

DM	Distribution function of the DM for item n
w_e	Weight of experts per item depending on the weight method
N	Number of experts

The DM can be seen as a virtual expert based on the combination of influential experts. Experts can be given weight in different ways:

- Global weights: uses un-normalized weights (w_e). The weights are all the same for all items
- Item weights: A weighting scheme where the different items are weighted differently. For this weighting scheme, the information scores per item separately instead of the average score overall item.
- Equal weights: the weight for all experts are all the same ($w_e = 1/N$)
- Optimized DM: choosing for which the gobal unnormalized weight of the DM is maximal. This can be done for global and item weights. It is not meaningful for equal weight.

3.2.6. Robustness

Robustness is a concept to evaluate the consistency of the expert judgment result by eliminating a few experts or seed questions. There are two types of robustness, which is the itemwise robustness and expertwise robustness. It evaluates the model to its immunity from the error, which may increase or decrease the calibration or information scores. For each exclusion of seed items or experts, the overall performance is recalculated and analysed whether the outcome is more reliable or worsened.

3.3. Procedure

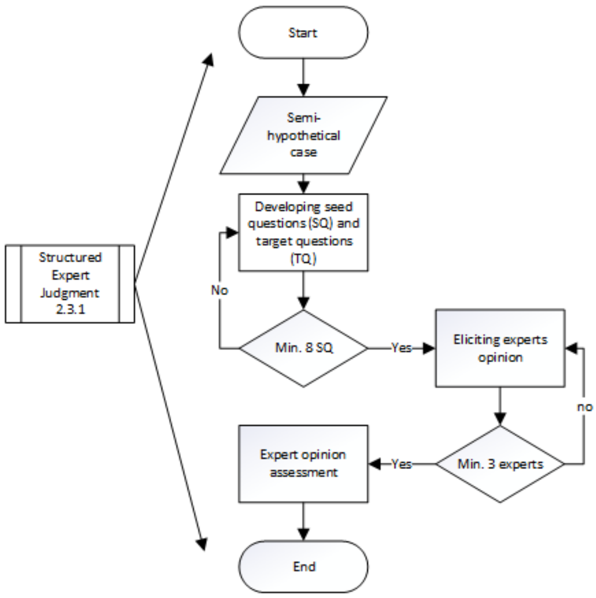


Figure 3.2: An illustration on the procedure of expert judgment conducted in this research.

This section aims to present the process of SEJ that has been conducted in this research (see Figure 3.2). It starts by developing the seed and target questions based on the target variables. After acquiring enough seed questions, experts opinion are elicited using the required expression. Later, after all opinions are elicited, experts are scored based on their elicitation on the seed and target questions. Each experts will be evaluated by using two scoring methods that has been discussed in the previous chapter. The output of the assessment is the distribution of from the combined experts opinion which are weighted based on their performance.

3.3.1. Developing Variable of Interest

The target variables focus on the degradation probability of a particular grass condition in a period of time. The spatial time refers to a six-month period. In other words, we would like to know:

"The degradation probability of a closed sod transition to an open or fragmented sod after a 6-month period"

This information will support the latter maintenance model. The grass condition is categorized into three conditions (see section 2.2) which are closed, open, and fragmented. There are different groups of questions and scenarios which is presented in Table 3.1. Within the fifteen target variables, this study divides into three groups of questions. The different group of question is to provide different ways to project uncertainty. Those unit of references are **grass degradation in time**, **degradation probability**, and **spatial degradation**. Within the group questions, there are different scenarios which provide different input on different types of degradation. These scenarios are the **type of degradation** (**spot holes and overall degradation**), **different degradation intensity** (**high loading & low loading**), and application of maintenance. These variables are used as additional information by cross-validating between similar target questions (see Table 3.1)

Table 3.1: There are fifteen target questions which consist three different group of question and scenarios. This table is a summary of the target questions regarding the scenario, time units, and grass state transition.

Target questions	With maintenance		Without maintenance	
	a	b	a	b
Degradation time	-	1-2; 1-3	1-2; 1-3; 2-3	1-2; 1-3
Degradation probability	-	1-2; 2-3	-	1-2,2-3
Spatial degradation (few human activities)	-	1-2; 1-3	-	-
Spatial degradation (many human activities)	-	1-2; 1-3	-	-
Information	overall degradation (a), grass spots (b), closed sod (1), open sod (2), and fragmented sod (3)			

3.3.2. Developing Calibrating Variables

In the seed variables, experts are requested to express their uncertainty on the questions where the realizations are known. The seed questions are constructed within the subject of grass degradation. There are two groups of seed questions used in this research, which are:

Sod Cover Measurements

Six seed questions are acquired from a sod cover measurements report (Summary and Aerospace, 2003). Sod cover measurements is an inspection activity to acquire information on the grass cover condition. The result of the inspection determines the grass condition (closed, open, or fragmented). In the seed question, experts are required to reassess the grass condition based on a picture taken from the inspection report. Since the report explicitly determines the grass condition qualitatively, in this seed questions, experts are required to give a range between 1-9, where "1" indicates a fragmented sod and "9" indicates a closed sod.

Figure 3.3: This figure is seed question 4 and it is an example one of sixth seed questions on the grass condition that was given to the experts. In this picture, the grass condition represents a closed sod .

Wave Overtopping Experiment

Four seed questions were obtained from a wave overtopping experiment that was conducted on a grass slope (Steendam et al., 2012). Within the experiment, pictures were taken to distinguish the different slope condition after certain cumulative loads. In this seed question, two pictures of grass condition were given to expert with additional information on the experiment parameter. The first picture is the initial condition of grass before given the wave load. A second picture is also given, which shows the aftermath of the experiment after an undisclosed time of the experiment. The experts are asked to express their approximation at the time of the experiment in which the second photo was taken.

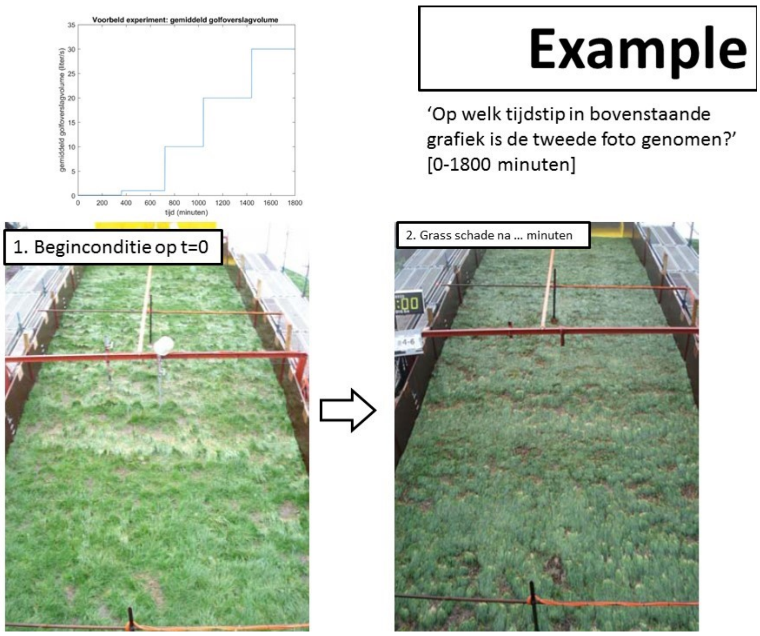


Figure 3.4: A figure showing an example of the second group seed questions on wave overtopping experiment. It consist of two different grass condition at different time in an experiment and the setup

3.3.3. Expert Elicitation

The questionnaire will be handed out to experts that have experience on grass revetment management in the Netherlands. Furthermore, experts should fulfil several criteria. First, experts should understand the WBI 2017 method on grass quality categorization. WBI 2017 is a tool and guidelines which consist of Ministerial Order, which gives the safety assessment for the primary flood defences. Second, experts should have more than one year of experience as a dike inspector, dike owner, or researcher. This exclusion is to prevent experts with inexperience on dike revetments. An initial interview was performed to collect background information for the experts. It is done to identify potential experts that fulfil the criteria. In this research, we acquired seven experts from different role and experience on grass revetments. (see Table 3.2)

Table 3.2: Participating experts with its role on grass revetment

Role Orientation	Total (Participant)
Research	1
Consultancy	1
Operational	5

Both seed and target questions are compiled and published through Google Form. In total, there are 25 questions that experts are required to answer using compulsory expression. The questionnaire is presented in Appendix A. The expert elicitation is then compiled and assessed in the next section.

3.3.4. After Elicitation

After conducting the elicitation, experts assessment will be combined, scored, and analysed whether experts are able to evaluate the grass revetment conditions. Analysis will be illustrated with tables covering the combined scores and experts performance. Furthermore, analysis will be also given as a graph to see the different distribution of the target questions.

Strategy Analysis

Figure 3.5 illustrates the strategy of the expert judgment analysis. The combined experts' opinion is analyzed using the scoring method and combined using different weighting schemes given in section 3.2. A first conclusion is drawn based on experts performance. Then, a robustness and discrepancy analysis will be conducted. Robustness is performed to acknowledge the contribution of each item and expert towards the overall performance. The discrepancy analysis is drawn to examine the consistency between different type of target questions. In the end, a final conclusion of the structured expert judgment is drawn.
The questionnaire can be divided into six types of questions, as shown in Table 3.3. The seed variables and the target variables are labeled as SQ and TQ respectfully. These variables are separated to make a clear division during the analysis.

Table 3.3: Expert judgment type of questions

No	Type	Label Questions
1	Sod cover measurement	SQ1, SQ2, SQ3, SQ4, SQ5, SQ6
2	Wave overtopping experiment	SQ7, SQ8, SQ9, SQ10
3	Grass spots without maintenance	TQ3, TQ4, TQ10, TQ11, T12, T13
4	Grass spots with maintenance	TQ1, TQ2, TQ8, TQ9
5	Grass spots without maintenance + many human activities	TQ14, TQ15
6	Overall degradation scenario	T5, T6, T7

3.4. Expert performance analysis

3.4.1. Expert Performances

The expert's uncertainty is processed by using a toolbox for structured expert judgment in MATLAB called ANDULIR (Leontaris and Morales-Nápoles, 2018). The expert performance is measured by combining cali-

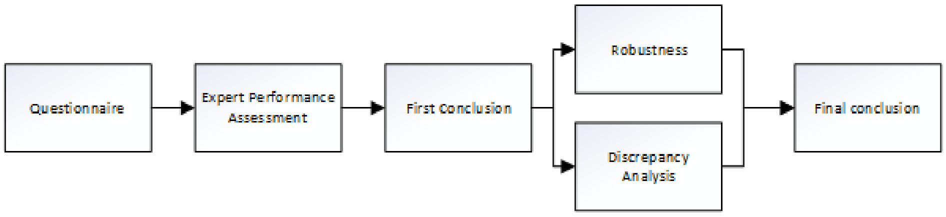


Figure 3.5: Schematic framework showing the analysis strategy which starts by assessing the expert performances and proceed with the robustness and discrepancy analysis.

bration scores and relative information scores. Table 3.4 shows that most of the experts have a low calibration. In other words, most realizations did not fit into the experts' range of estimation. The best expert was scored by Exp. 3 with the calibration of 0.707. This score is relatively high compared to other experts. If we look closely, the relative information of all experts seems to be lower in the seed questions rather than the overall questions. In other words, experts seem to be more confident in target questions.

Table 3.4: Experts Performance

Expert ID	Calibration	Relative information	
		Total	Realization
Exp. 1	8,92E-06	1,314	1,140
Exp. 2	3,22E-05	2,699	1,688
Exp. 3	0,707	2,190	1,097
Exp. 4	1,17E-07	1,785	0,860
Exp. 5	0,014	1,114	0,481
Exp. 6	0,006	0,752	0,372
Exp. 7	0,006	0,890	0,742

Overall, we expected that estimating uncertainty on sod condition through pictures would be difficult and would create a broad range of uncertainty. The resulIt hows that most experts that have low information score on the seed questions performs relatively scorer on the calibration score. There were no problems with the seed questions since no feedback was given by the experts. From the results, it shows that the seed questions does eliminate under-performed experts.

3.4.2. Combined Expert Performance

Different weighting schemes might result in a virtual expert with better performance. In this sub-section, we analyse all four weighting scheme.

Equal Weight

Table 3.5 presents the output using equal-weight. The scheme results in a relatively high calibration score (0.493). However, the calibration score is not as high as the best experts (0.707). A lower calibration might be the cause of overconfidence. In this case, the equal DM has a low information score (0.243) which is ten times smaller than the best experts. This can be seen by the wide range of experts elicitation (see Figure B.1 and B.2). In general, the combination of experts with equal weight does give a good estimation with wide range of uncertainty.

Table 3.5: ANDURIL output using equal weight

Expert ID	Calibration	Relative information		Unnormalized without DM	Normalized with DM
		Total	Realization	Equal	Equal
Exp. 1	8,92E-06	1,314	1,140	0,143	1,25E-05
Exp. 2	3,22E-05	2,699	1,688	0,143	6,15E-05
Exp. 3	0,707	2,190	1,097	0,143	0,847
Exp. 4	1,17E-07	1,785	0,860	0,143	9.857E-08
Exp. 5	0,014	1,114	0,481	0,143	0,009
Exp.6	0,006	0,752	0,372	0,143	0,002
Exp.7	0,006	0,890	0,742	0,143	0,006
Equal Weight	0,493	0,243	0,154		0.136

Global Weight and Item Weight

For this weighting scheme, a cut-off value is applied to eliminate under-performed experts. The cut-off value generally cuts experts that perform lower than 0.05 from the evaluation. Unfortunately, only one expert scores higher than the cut-off value. Therefore, a cut-off value of of 0.001 is applied to involve four experts.

Table 3.6 shows the output scores by using Item and Global Weight. Both weighting schemes has a calibration score 0.007 which is far lower than the best expert calibration. The low calibration is the result of an uneven distribution. Most realization in the DM Global and DM Item falls in the 50-95% percentile which lower the scores drastically. A good uncertainty assessor capture the right value in different bins of his interval. The information scores are also lower than the best expert in both seed variables (0.9 vs 1.097) and variables of interest (1.3 vs 2.19). Compared to the DM Equal, although it has a wide range of uncertainty, the calibration is much higher than the DM Global or Equal.

Table 3.6: ANDURIL output using item and global weight

Expert ID	Calibration	Relative information		Normalized without DM	Normalized with DM	
		Total	Realization		Global	Item
Exp. 3	0,707	2,190	1,097	0,7755	0,974	0,974
Exp. 5	0,014	1,114	0,481	0,0067	0,008	0,008
Exp.6	0,006	0,752	0,372	0,0023	0,003	0,003
Exp.7	0,006	0,890	0,742	0,0047	0,006	0,006
Global Weight	0,007	1,269	0,904	0,00674	0,008	
Item Weight	0,007	1,391	0,958			0,008

DM Optimized

For the DM optimized, all of the weight are given to the best experts. In other words, the virtual experts (DM optimized) is equal to the best experts (Exp.3). Exp.3 shows both high calibration and high information in both seed questions and target questions. However, there is an interesting finding on Exp.3 assessment particularly in the target questions which will be discussed in section. In a nutshell, the finding implies that if DM Optimized is chosen, only degradation time unit should be used in the model.

First Conclusion

After scoring and combining experts opinion, several conclusion can be drawn. In general, most experts have low calibration and high information on the seed questions. Only one expert scores higher (0.707) than the typical cut-off value (0.05). From this information, we can identify that most experts have difficulties estimating the grass condition.

In DM Equal, the calibration score is higher than most experts. Although the majority of expert panels have low calibration, the combined and equally weighted experts perform much better despite to the broader range of uncertainty. In other words, DM Equal produces a high calibration with less confidence. Due to the high calibration, DM Equal should be considered as one of the option to represent the target variables distribution. A possible options also is the DM optimized which has a higher calibration and information than DM Equal.

On the other hand, DM Global and Item has a low calibration score than the best experts. It has 100 times (0.007)smaller than the best experts (0.707). One of the reason is that most experts, that scores than the cut-off value, tend to estimate lower than the realization. Most of the realization falls at the higher bin, which causes low calibration. Meanwhile, the information scores are relatively high than most experts.

Overall, the optimized decision maker in this assessment is dominated by DM Optimized and DM Equal based on the calibration score. It is important to note that the low information score discredit the use of DM Equal. The preferred option based on the scoring performance is the DM Optimized. Further considerations will be analysed in the next section.

3.5. Robustness Analysis

Robustness is a typical approach to assess the contribution of each experts or seed questions to the overall scoring. The purpose of a robustness test is to see the result change if different experts or different seed variables had been used. In other words, the goal is to see whether the expert judgment series is robust by excluding some seed variables or experts.

Itemwise Robustness

We examine the fluctuations of DM scores by removing a single seed question out of the assessment. Table 3.7 shows the different DM scores if a particular item is taken out of the assessment. In general, the first group of seed questions shows no significant improvement. On the other hand, the second group of seed questions indicate a higher calibration until 10x by excluding SQ8. The sudden increases of calibration are the result of a heavier weight on Exp.3 (the best expert). In the assessment, Exp. 3 scores the highest calibration (0.7) and the high information score, which indicates his confidence. Precisely, in SQ8 (see Appendix B), Exp.3 did not correctly predict while other contributing experts did. Therefore, by neglecting SQ8, Exp.3 assessment is in somewhat more similar to the theoretical mass function, hence a higher calibration. Therefore, Exp. 3 is given a heavier weight which increases the overall calibration.

Table 3.7: Itemwise robustness

Excluded Item	Information Score (All Items)	Information Score (Seed items)	Calibration Scores
SQ1	0,9307	0,6909	0,0125
SQ2	1,2343	0,8990	0,0125
SQ3	1,0738	0,6803	0,0059
SQ4	0,7894	0,5762	0,0125
SQ5	1,1353	0,7408	0,0125
SQ6	1,0259	0,6639	0,0125
SQ7	1,7733	1,1242	0,0125
SQ8	2,2529	1,1496	0,7306
SQ9	1,2086	0,8441	0,0125
SQ10	1,2086	0,8441	0,0125

Expertwise Robustness

Excluding experts may result in changes on the overall assessment score. The robustness was done with a cut-off of 0.001 (see Table 3.8). A significant change on the calibration is shown when Exp.5 is excluded. Based on the prior overall performance, Exp.5 has the second-highest weight. Excluding Exp.5 tends to heavily influenced by Exp.3. As the calibration score, excluding Exp.5 results to a higher information score which appears to be influenced heavily by Exp.3. Other than that, excluding other expert does not give any significant difference from the initial assessment.

Table 3.8: Expert robustness

Excluded Expert	Information Score (All Items)	Information Score (Seed items)	Calibration Scores
Exp. 1	0,9668	0,9038	0,0075
Exp.2	0,9667	0,9037	0,0075
Exp. 3	0,7879	0,4566	0,0140
Exp. 4	1,5439	0,9612	0,0075
Exp. 5	2,1338	1,0880	0,7071
Exp. 6	1,5208	0,9294	0,0075
Exp. 7	1,5414	0,9760	0,0075

Second Conclusion

The itemwise robustness analysis showed many agreements on the calibration. Removing one seed variables slightly improves the calibration by 0.05. Surprisingly, by removing SQ8, the calibration increases drastically. The sudden increases of calibration are the result of a heavier weight on Exp.3 (the best expert). Meanwhile, in the expertwise robustness, the domination of Exp.3 and Exp.5 dominates the assessment. It shows that both experts significantly contributes to the overall scores. In a nutshell, the elicitation is robust against the choice of seed items but has significant dependency on Exp.3 and Exp.5.

3.6. Discrepancy Analysis on the Degradation rate

Discrepancy analysis is an effort to assess the consistency of expert assessment. Several target questions are designed with different unit of references or scenario. Some target questions are coupled to cross-validate each other. This analysis will reveal the consistency of the expert judgment series. Different degradation unit is applied in the target questions. It is applied to provide expert on expressing their uncertainty with different degradation unit. The goal is to analyse the discrepancy between degradation unit if there is similarity. There are several combination for analysis which is shown in Figure 3.6. To simplify, the analysis is only compared between DM Equal, best experts (Exp.3), second-best experts (Exp.5) and third-best expert (Exp.6).

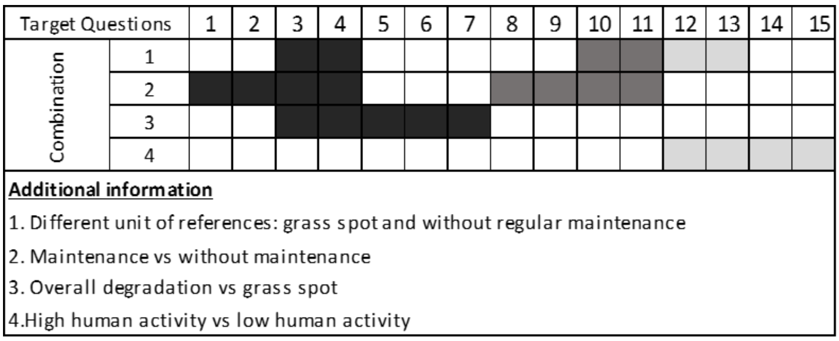


Figure 3.6: A table illustrating the different combination of target questions for the discrepancy analysis. There are four different combination which refers to different cross-validation subject.

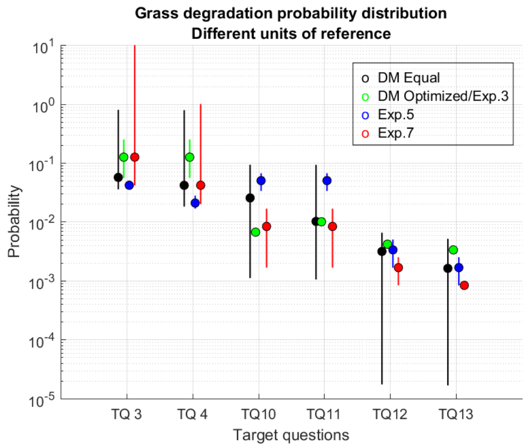
The target question DM and Expert distribution is transformed to a monthly degradation probability to support the cross-validation analysis. The degradation time target question is transformed using Equation 3.7 which is obtain by dividing one over degradation time given on the assessment. The degradation probability target questions is transformed using Equation 3.8 which is obtained by dividing the degradation probability of the assessment with the time horizon of the scenario (6 months) and divide the percentage by 100. The spatial degradation is transformed using Equation 3.9 which is obtained by dividing the spatial degradation given in the assessment by the time horizon of the scenario (6 months) and the total of dike section (200 sections).

$$P(DT) = \frac{1}{DT} \tag{3.7}$$

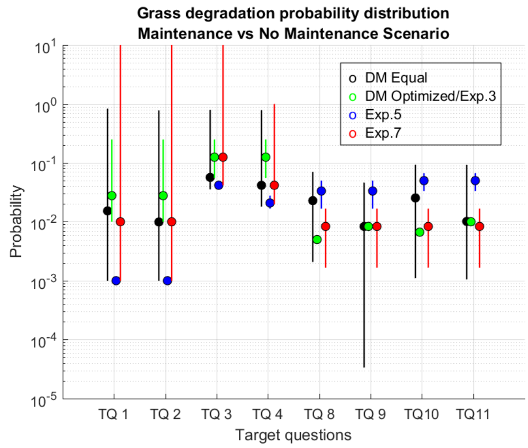
$$P(DP) = \frac{DP}{6 \cdot 100} \tag{3.8}$$

$$P(DS) = \frac{DS}{6 \cdot 200} \tag{3.9}$$

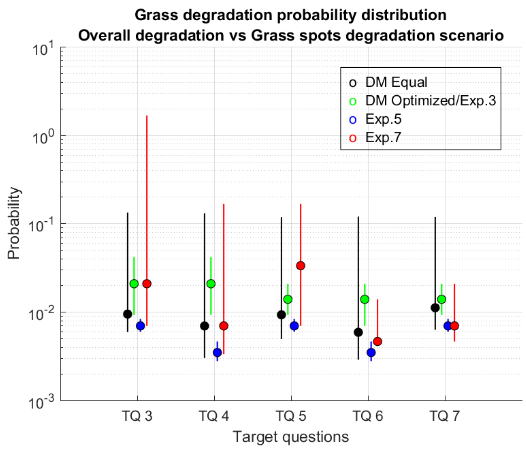
P	Monthly grass degradation probability
DT	Degradation time distribution for target question 1-7
DP	Degradation probability distribution for target question 8-11
DP	Spatial degradation distribution for target question 12-15



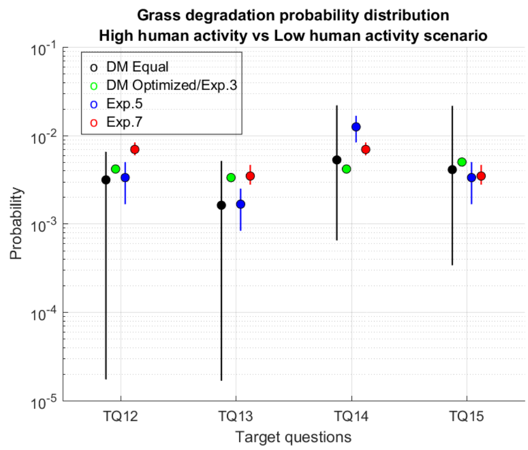
(a) Combination 1: Different units of reference for grass degradation



(b) Combination 2: Maintenance and no maintenance scenario



(c) Combination 3: Different types of degradation scenario (Overall degradation vs. grass spot degradation)



(d) Combination 4: Different human activity intensity scenario

Figure 3.7: The uncertainty intervals from DM Equal, DM optimized, Exp.5 and Exp.7. Each target question has been transformed into a monthly degradation probability by using equation.

Combination 1: Different unit references, grass spot, and without maintenance

The first coupling is to identify the consistency between degradation unit using the scenario grass spot degradation and no regular maintenance (see Figure 3.7a). As expected, the results show inconsistency for each different degradation units. Interestingly, TQ3 and TQ4 have a broader range of uncertainty from all experts. Meanwhile, TQ12 and TQ13 show high information (narrow distribution). This information could suggest that experts are more comfortable expressing their uncertainty by using time reference or more confident using spatial references or probability.

Combination 2: Maintenance vs Without Maintenance

The second coupling is to compare the consistency between grass degradation probability with and without maintenance scenario (see Figure 3.7b). As an initial hypothesis, the degradation probability with maintenance should have a lower probability. The result shows a striking difference between degradation unit. Comparing TQ1-TQ4, the result shows as expected where the degradation probability is lower in the maintenance scenario with a large difference. Meanwhile, for TQ8-TQ11, the results have the same trend as expected, but the difference between the scenario is much smaller. This result could fortify the previous notion that expert expresses much comfortably using time references or are more confident using probability.

Combination 3: Overall degradation vs grass spot

The third combination aims to compare the different type of degradation (see Figure 3.7c). As an initial hypothesis, overall degradation of grass revetment should occur less frequently than grass spots. The result shows differently as an initial hypothesis. One out of three experts (Exp.3) has the same trend as our hypothesis. Exp. 5 has an opinion that both degradation type will have the same degradation rate. Meanwhile, Exp.7 shows no trend (TQ5 is higher than TQ3 and TQ6 is lower than TQ4). The different estimation from Exp.7 might be the result of indirect feedback by using the online questionnaire. DM Equal shows the same trend as our initial hypothesis and Exp.3. This information is an additional reason for using DM Equal as the performance-based virtual expert.

Combination 4: Many human activities vs Few human activities

The fourth combination (see Figure 3.7a) aims to identify consistency and the degradation probability for a different level of loadings (human activities). As an initial hypothesis, a higher human activity scenario should have a higher probability of degradation. Most of the experts agree with the initial hypothesis. Interestingly, Exp.3 confidently believes that closed sod is more likely to degrade to fragmented than open sod. Meanwhile, Exp.5 and Exp. 7 expects differently than Exp.3. A conclusion can be drawn that Exp.3 has trouble expressing uncertainty using a spatial unit reference (narrow distribution). It might be the result of the indirect feedback by using an online questionnaire.

3.7. Conclusion

The goal of this chapter is to answer:

"What is the deterioration rate of grass revetments?"

Based on the assessment, there are two DM that can be applied for this research which are the DM Equal (Calibration score: 0.493)and the DM Optimized (Calibration score: 0.707). Furthermore, based on the discrepancy analysis on the different degradation unit, experts tend to express uncertainty much better using time reference. It can be identified by the broader range of uncertainty. there is no significant implication within the three different units. For the maintenance model, we focus only on grass degradation without maintenance scenario. From the discrepancy analysis, most experts express more comfortably using degradation time. Therefore, this research applies the DM Optimized as the uncertainty distribution.(See table 3.9). Two reason on using DM Optimized than DM Equal; (1) DM Optimized has a higher calibration (2) Based on the discrepancy analysis, every experts give a broader uncertainty interval on the degradation time. If the discrepancy analysis resulted to a different unit of references, DM Optimized can not be used because of the extremely narrow uncertainty interval.

Table 3.9: Grass degradation probability in a month for different degradation unit for DM Optimized

Group question	Target Questions	5th	50th	95th	Units
Degradation time	Closed → Open	0,03576	0,06957	0,87446	-
	Closed → Fragmented	0,01818	0,04161	0,79068	-
Probability	Closed → Open	0,00614	0,05972	0,55015	-
	Closed → Fragmented	0,00579	0,06071	0,54902	-
Dike sections	Closed → Open	0,00002	0,00246	0,00628	-
	Closed → Fragmented	0,00002	0,00148	0,00498	-

4

Maintenance Model

This chapter explores the development of the maintenance model using Dynamic Bayesian Network. The goal of this chapter is to answer the second research question:

"What is the most effective inspection and maintenance interval of grass revetment management?"

This chapter follows the framework, as shown in Figure 4.1. This chapter starts by discussing the fundamental theory on Dynamic Bayesian Network and the application on maintenance model. Then, the network elements are developed by considering the degradation phenomenon of grass revetment and several aspects of asset management. This transform associates both management aspect and asset natural degradation and translates it into a Dynamic Bayesian Network. After the fundamental network elements have been developed, the boundary conditions are discussed in the next section. The boundary condition contains information on the case of the model, model inputs and different scenarios on maintenance interval. Then, the maintenance network is simulated under the developed boundary conditions and scenarios. The output of the model shows the expected asset cost and performance from different maintenance interval.

Figure 4.1: A general guideline of chapter 4

4.1. Dynamic Bayesian Network

Bayesian Network (BN) has been used in several applications in engineering risk and reliability analysis (Faber, 2002; Salem et al., 2006). BN can model the causal relationship of related variables in a system. In addition, BN can be embedded with the Markov Chain, which is suitable to model the degradation shock-process of grass revetments. This section begins by introducing Bayes' rules, followed by Bayesian Network, and Dynamic Bayesian Network.

4.1.1. Bayes' Rules

Bayesian analysis is a popular method in the statistic world. It offers the possibility to include past experiences as prior information in the form of distribution. The Bayesian computes posterior distribution conditional to the prior distribution. The Bayes rules can be expressed as follows:

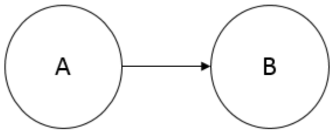


Figure 4.2: Example of a simple Bayesian network where node B is conditional to node A

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} \tag{4.1}$$

where:

P(B|A)	Probability given b when a occurred
P(A|B)	Probability given A given B occurred
P(A)	Probability A occurence
P(B)	Probability B occurence

4.1.2. Bayesian Network

Bayesian Belief Network or Bayesian Network is a graphical probabilistic model that describes a system by representing as a chain of causal relations. This relation is visualized as a Directed Acyclic Graph or DAG (Landuyt et al., 2017). The Bayesian network represents joint probability models among given variables. Each variable is represented by a node in a graph. It describes their dependencies using a DAG and conditional probabilities (CP) between connected variables (Koski and Noble, 2011). BN appears to be a solution to model complex systems because it performs the factorization of variables joint distribution based on the conditional dependencies (Weber et al., 2012).

In many situations, the directed edges between variables in BN can be interpreted as a causal relationship. This representation of the causal relationship is represented as probability; the relation between variables is computed based on parent's states and the conditional probability table (CPT). When a Bayesian network represents a causal structure between variables, it may be used to assess the effects of an intervention, where the manipulation of a cause will influence posterior variable. PT and CPT, together with the independence assumption defined by the graph, present a unique joint distribution over all the variables (Salem et al., 2006).

In the mathematical expression, Bayesian Network (B) is defined by $B = (DG, C_p)$ with the following elements:

1. The directed acyclic graph DG=(V,A), where:
   - V is representing random variables which is a non-empty and finite set of nodes $V = \{X_1, ..., X_n\}$
   - $A(\subset)VxV$is the set of directed arcs between nodes
   - The nodes, that are directed towards another node, are called parent, while the directed nodes are called a descendant or child. Any nodes that are not a parent or a child are called non-descendant
   - The graph has no directed cycles
2. The set of conditional probability distributions $C_p = \{P(X_i|Parents(X_1))\}_{v\epsilon V}$ which indicates the significance of parents nodes as prior information towards child nodes expressed in probability.

For instance, two variables which A and B where the arrow shows the relation between both variable (see Figure 4.2). The node A is the parent where it has two states (A1 & A2), and B is the child which also has two states (B1 & B2). Prior probability information for node A is defined in table 4.1. From Figure 4.2, it is illustrated that node B is given based on node A. In other words, node B has a conditional dependency over node A. Therefore, the CPT represents the conditional probabilities of B given prior information of node A (see table 4.2).

Table 4.1: Probability table (PT) of node A

Variable A	
A1	P(A=A1)
A2	P(A=A2)

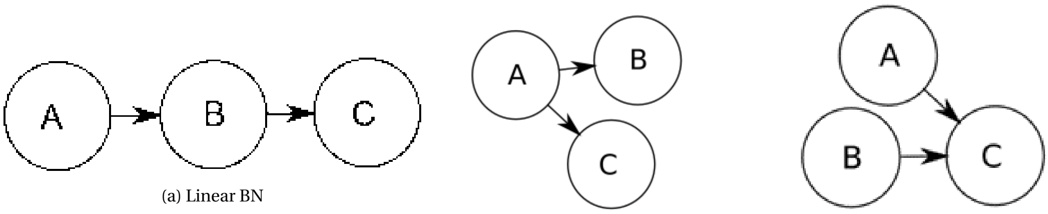
Table 4.2: CPT of node B given prior information of node A

Prior Information Nodes A		Condition A1	Condition A2
Posterior Nodes B	Condition B1	P(B=B1|A=A1)	P(B=B1|A=A2)
	Condition B2	P(B=B2|A=A1)	P(B=B2|A=A2)

Therefore, we may compute the probability of nodes B result to condition B1 or P(B=B1):

$$P(B = B1) = P(B1|A1) \times P(A1) + P(B1|A2) \times P(A2) \tag{4.2}$$

The result shows the probability of condition B1 occurs based on prior information. It shows the functionality of graph theory and probabilistic theory in a graphical model. There are several possibilities of variable connection which is shown in Fig.



(a) Linear BN

(b) Convergent BN

(c) Divergent BN

Figure 4.3: Different variable connection in Bayesian Network

4.1.3. Dynamic Bayesian Network

In practice, events occur through multiple states in time until it develops to a final condition that we observed. This field is known as time series analysis. Time-series is a sample realization of the stochastic process consisting of a set of observations made sequentially over time (Mihajlovic and Petkovic, 2001).

Dynamic Bayesian Network (DBN) is a model that describes a system that is dynamically changing over time. DBN is a particular class of BNs which represents stochastic processes. This model suits for degradation modeling (Straub, 2014). These slices are connected by directed links from nodes that have dependencies between time-series. In other words, time is represented as discrete-time slices or steps that are connected by directed arcs from nodes in time slices t to nodes in time-slices t+1 (Kosgodagan-Dalla Torre et al., 2017). The deterioration should be in compliance with the Markovian properties. Only at time slice t, the system is independent. Similar to the static version, the DBN is defined by the graph structure or DAG at time t, between t and t+1, and t+2.

For many stochastic processes, the first order MC is not sufficient to describe the deterioration model. Commonly, it is required to acknowledge more than one state in the past to predict the future. DBN able to provide a solution that may be implemented for a different order, which is called N-Time slices Bayesian Network (T-TBN) (Salem et al., 2004).

The network can be represented differently at each time slice. If the model structure and conditional probability are identical at every time-slices except the first time slice, then DBN can be characterized as a homogenous DBN. In contrary, the network can be different at every time slice depending on the model. Thus, this

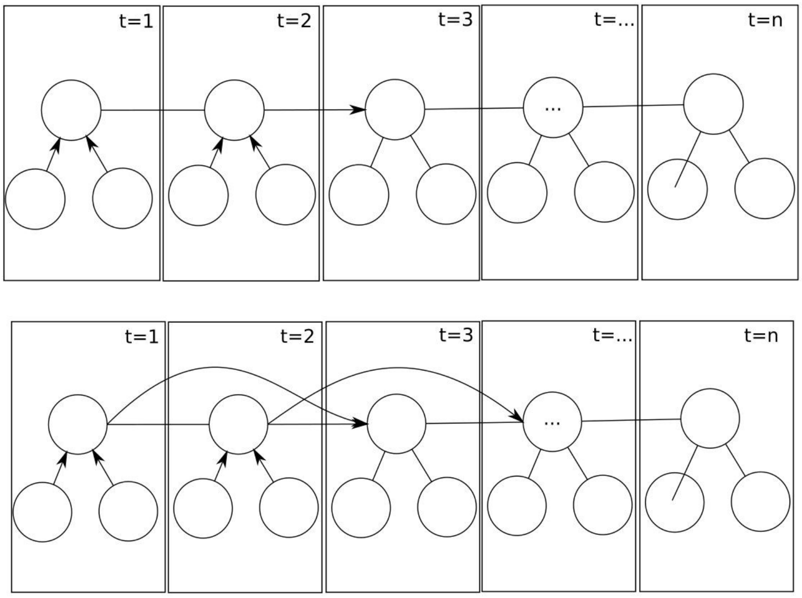


Figure 4.4: First order (upper) and second-order (down) of dynamic bayesian network

DBN can be characterized as a non-homogenous network. Dynamic Bayesian Network represents a random variable X_t where t indicates the time slices. For this example, the variable at each time slice is conditional to the prior time slices or a first-order time-slices Bayesian Network. Hence, it can be express as follows:

1. The directed acyclic graph DG=(V,A), where:

   - V is a non-empty and finite set of nodes $V = \{X_1, ..., X_t\}$ with $V = \left\{X^1, ..., X^n\right\}$. X_t represents the variable at a certain time slice, and X^n represents a single variable. X^n can be represented by multiple singular variables.
   - $A(\subset) V x V$is the set of directed arcs between nodes. In addition to DBN, the intra-slice arcs connect nodes within time slices, and inter-slice arcs connect nodes between time slices.
   - The nodes that are directed towards another node is called parent, while the directed nodes are called a descendant or child. Any nodes that are not a parent or a child are called non-descendant
   - The graph has no directed cycles

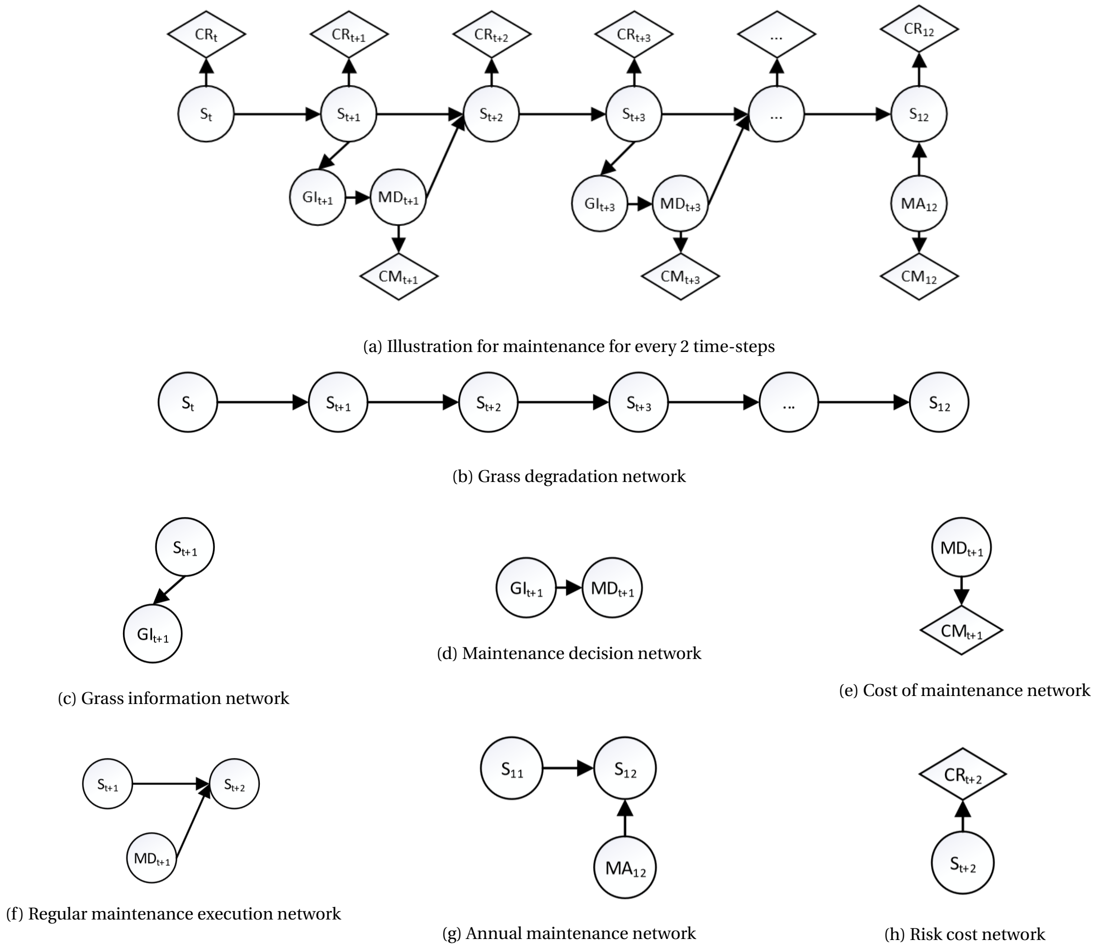
2. The set of conditional probability distributions $C_p = \{P(X_i|Parents(X_1))\}_{v\epsilon V}$ which indicates the significance of parents nodes as prior information towards child nodes expressed in probability.

There are three common distributions used to construct DBN, which are:

- $P(X_0)$: Prior distribution over the state variable
- $P(X_t|X_{t-1})$: It illustrates the conditional probability of inter slices relationship between two equivalent node. In other words, it can be referred to as the transition probability.
- $P(X_t|Y_t)$the conditional model where it specifies the conditional probability within the time slices (intra-slices relationship)

4.2. Elements of the model

This section discusses each element presented in Figure 4.5. Elements of the model are the network that illustrates a particular event of asset management. It is constructed based on the relevance in management practice and asset degradation. These elements are illustrated through Bayesian network and assigned in different combination depending on the scenarios. An example of DBN on grass maintenance is presented in Figure 4.5a. This figure shows an illustration a maintenance network on a particular maintenance scenario. Each network will be introduced in this section.



(a) Illustration for maintenance for every 2 time-steps

(b) Grass degradation network

(c) Grass information network

(d) Maintenance decision network

(e) Cost of maintenance network

(f) Regular maintenance execution network

(g) Annual maintenance network

(h) Risk cost network

Figure 4.5: Illustration for grass revetment maintenance network

1. **Grass Revetment Condition (S_t) and Grass Degradation**
   As explained in Section 2.4.2, grass deterioration is modelled as discrete-time Markov process. Grass revetment (S) is represented as a node that describes the grass state at certain time slices. Grass revetment condition is depicted into three different states that has been discussed in Section 2.2, which are "Closed," "Open," and "Fragmented". For this research, the posterior condition of grass revetment is illustrated to have a conditional relation to the prior condition as shown in Figure 4.5b. The grass degradation is illustrated using transition probability, $P(S_{t+1}|S_t)$, which is determined based on the SEJ carried out in Chapter 3.

$$P(S_{t+1}, S_t) = P(S_t) \times P(S_{t+1}|S_t) \tag{4.3}$$

S_{t+1}	Grass state node at t+1

S_t	Grass state node at time-steps t
$P(S_{t+1}\|S_t)$	Transition probability of grass degradation
t	time-steps

2. **Grass Information (GI)**
In a maintenance decision process, the quality of information affects the effectivity of a decision. In this research, it is depicted as a node GI which stands for grass information (GI). It is a node that describes the organization beliefs on the grass condition. As shown in Figure 4.5c, the information accuracy on grass revetment condition is conditional to the organization capability on acquiring information which is depicted as a conditional probability $P(GI_t|S_t)$. This node is assigned to illustrate the significance of accurate information on maintenance decision process. The grass condition should be known for a maintenance decision to occur. The joint probability of this network is presented in Equation 4.4.

$$P(GI_t, S_t) = P(S_t) \times P(GI_t|S_t) \tag{4.4}$$

GI_t	Grass information at time-steps t
S_t	Grass condition at time-steps t
$P(GI_t\|S_t)$	CP of grass information with respect to the S_t
t	time-steps

3. **Maintenance decision (MD)**
Maintenance decision is a node that illustrates the different state of maintenance decision that may be executed based on the information obtained from the organization GI (see Figure 4.5d). There are several type of maintenance that is applied in practice, which are corrective maintenance, preventive maintenance, or do nothing. Based on node GI, the organization would acquire information that may be used for maintenance decision. Since DBN acknowledge grass condition in a discrete manner, it is important to set the most ideal rule of maintenance. In this model, we assume the ideal rule of maintenance should align the following arguments:

    - **Corrective maintenance (MC)**: if grass cover is a bad (fragmented sod) condition, corrective maintenance occurs
    - **Preventive maintenance (MP)**: if grass is expected to threaten the dike in near future (open sod), preventive maintenance will occur within the near time.
    - **Do nothing maintenance (MN)**: when the grass condition is relatively in good condition (closed sod), maintenance is not required.

    The maintenance decision affects the posterior condition of grass revetment which is depicted in Figure 4.5f. The organization capability on executing maintenance is depicted through the conditional probability, $P(S_{t+1}|S_t, MD_t)$. The joint probability can be calculated using Equation 4.5 and 4.6.

$$P(MD_t, GI_t) = P(GI_t) \times P(MD_t|GI_t) \tag{4.5}$$

$$P(S_{t+1}, S_t, MD_t, GI_t) = P(S_t) \times P(S_{t+1}|S_t, MD_t) \times P(MD_t|GI_t) \times P(GI_t|S_t) \tag{4.6}$$

S_{t+1}	Grass condition probability at t+1
$P(S_{t+1}\|S_t, MD_t)$	Conditional probability for S at *t+1* conditional to S at *t*, MD and GI
$P(MD_t\|GI_t)$	Conditional probability for MD conditional to GI
$P(MD_t\|GI_t)$	Conditional probability for GI conditional to S
t	time-steps

4. **Annual Maintenance (MA)**
Annual maintenance is a node that illustrates influence the posterior grass condition without any decision process. In practice, in early spring, an obliged maintenance is conducted. It is done to restore grass cover that are damaged due to the winter season. In Figure 4.5g, the annual maintenance occurs at every 12th time-steps with an assumption that 1-month is equal to 1 time-steps. Similar to the previous element, the posterior condition of grass revetment is conditional with nodes MA and S_t. The joint probability of this network can be calculated using Equation 4.7.

$$P(S_{t+1}) = P(S_t) \times P(S_{t+1}|S_t, MA_t) \tag{4.7}$$

$P(S_{t+1})$	Grass condition probability at *t+1*
$P(S_t)$	Grass condition probability at t
$P(S_{t+1}\|S_t, MA_t)$	Conditional probability for annual maintenance
t	time-steps

5. **Risk Cost** (CR_t)
CR Utility refers to the expected risk of the system at a particular time-step. This network is illustrated through Figure 4.5h where it has a direct relation towards the grass state (S_t). Each grass state appoints to a different risk based on the case scenario. The utility risk is calculated using Equation 4.8 where $U(CR_t|S_t)$ has a discrete relation towards the parent nodes. The value of the utility is developed further in the next section.

$$CR_t = P(S_t) \times U(CR_t|S_t) \tag{4.8}$$

CR_t	The expected risk at time-steps t
$P(S_t)$	Grass condition probability at t
$U(CR_t\|S_t)$	Utility for risk conditional to grass condition
t	time-steps

6. **Maintenance Cost (CM)**
Maintenance cost is the utility node that illustrates the cost of maintenance based on the maintenance decision (MD). CM measures the expected maintenance cost based on the assigned network. The expected maintenance cost is calculated using Equation 4.9. $U(CR_t|S_t)$ is the maintenance cost utility which is determined based on the scenario.

$$CM_t = S_t \times U(CM_t|S_t) \tag{4.9}$$

CM_t	The expected maintenance cost at time-steps t
$P(S_t)$	Grass condition probability at t
$U(CR_t\|S_t)$	Utility for maintenance cost conditional to grass condition
t	time-steps

4.3. Model Setup

In this section, we will introduce the boundary conditions of the maintenance model. As mentioned in the previous chapter, this research utilizes a semi-hypothetical case of grass revetments management. Therefore, each boundary conditions are created with respect to the semi-hypothetical case and developed using different works of literature that can support the assumptions.

- **Model Input**

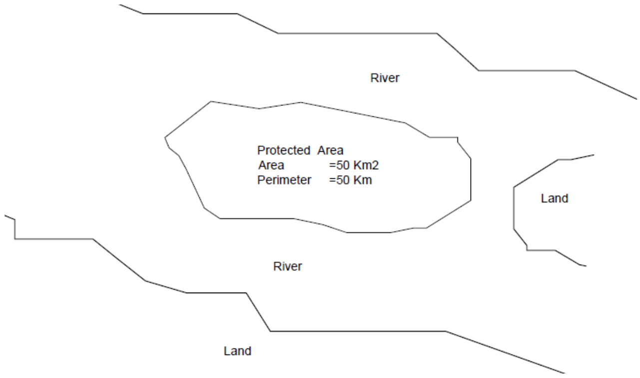


Figure 4.6: Sketch of the semi-hypothetical case on dike ring which protects 50 km2 km^2 of a rural area

1. **General Case Description**

   The case model is set on a hypothetical rural area that is protected by a ring of dikes which protects an area of 50 km^2 (see Figure 4.6). The dike has a typical slope of 1/3 (Jonkman et al., 2017) with grass revetments and perimeter length of 50 km. The grass cover is homogenous with a closed state as the initial condition.

2. **Time Length**
   The model has a monthly time reference. A single time-step is assumed to represent a monthly period. Furthermore, two different seasons is considered in the model, which will affect the degradation rate. The winter season starts from September until February where it is assigned only to degrade, and the summer starts from March until August which is set to improve slightly. The model is simulated until ten years or 120 months.

3. **Grass Degradation**
   The degrading performance of the grass revetment is demonstrated using the three states (closed, open, & fragmented). The degradation probability is presented as a transition matrix (see Table 4.3a and 6.2b, and obtained through SEJ in Chapter 3. It is important to acknowledge that the author determines some transition probability since not all transition probabilities were acquired in the expert judgment.

Table 4.3: Transition probability table for grass degradation

(a) Winter Degradation

P(S(t)|S(t+1))		S(t)		
		Closed	Open	Fragmented
S(t+1)	Closed	**0.888**	0	0
	Open	**0.069**	0.896	0
	Fragmented	**0.043**	0.104	1

(b) Summer degradation

P(S(t)|S(t+1))		S(t)		
		Closed	Open	Fragmented
S(t+1)	Closed	0.9	0.03	0.03
	Open	0.07	0.9	0.07
	Fragmented	0.03	0.07	0.9

4. **Costs and failure risk**
   In this hypothetical case, the maintenance has a fixed cost (CM) independent of the severity of the grass damage. The maintenance cost consists of both mobilization cost of personnel and equipment in inspection and maintenance. Both corrective and preventive are assigned to have an equal cost. If the organization decide not to intervene, the cost represents only the cost of inspection (see table 4.4). The value of maintenance cost is taken from Rijke and Hertogh (2014) report on investment on primary flood defences management. For every kilometer, an estimation of € 11500 is required every year. It includes both operation and management cost. In this report, there is no information on the average occurrence of maintenance. Hence, we made an assumption that the operational maintenance costs 2000 €/km and the inspection costs 1000 €/km.

Table 4.4: Utility for maintenance cost conditional to the maintenance decision

Maintenance Cost (€)	Maintenance Decision (MD_t)		
	Corrective	Preventive	Do Nothing
CM(t)×10^4	10	10	5

The consequences of system failure are dependent with the grass condition which is presented as cost of failure or risk cost (CR). In this research, risk costs are hypothetically determined. Using Rijkswaterstaat VNK Project (2015) economic risk map in Netherlands, the economic risk for dike with closed sod condition is assumed to be 10 €/ha (the total risk for 50 km2 equals 50000 €). To calculate the risk for open and fragmented sod, we intepret the failure probability based on a research from Klerk et al. (2018) on risk based inspection for grass revetments. We assume that fragmented sod has 10^{-3} probability, open sod has 10^{-5} probability and closed sod has 10^{-7} probability. Therefore, by using this assumption, we acquire the different risk cost for open and fragmented sod (see Table 4.5).

Table 4.5: Utility for risk cost(CR) conditional to the grass condition (S)

Risk Cost (€)	Grass condition at S_t		
	Closed	Open	Fragmented
$CR_t \times 10^4$	5	500	50000

These utility cost are applied over the time horizon to measure the model. All costs are discounted to their present value. The present value is the current value of a future sum of money given a specified discounting factor. We use a discount rate of 2% annually .

$$PV = \frac{FV}{(1+r)^n} \tag{4.10}$$

PV	Present value
FV	Future value
r	Discount rate
n	Number of periods

5. **Maintenance, Inspection and Decision**
Since this attempt focus on the most effective inspection and maintenance interval, an assumption is made where information is accurate, maintenance decision is ideal, and maintenance execution fully restores the grass condition. These nodes are computed using the value shown in Table 4.6,4.7, and 4.8

Table 4.6: CPT of Maintenance decision

Maintenance Decision	Grass Information (GI)		
	Closed	Open	Fragmented
Corrective	0	0	1
Do Nothing	1	1	0

Table 4.7: CPT of grass information

Grass Information at t (GI_t)	Grass State at t-1 (S_{t-1})		
	Closed	Open	Fragmented
Closed	1	0	0
Open	0	1	0
Fragmented	0	0	1

Table 4.8: CPT of maintenance execution

Maintenance Decision		Corrective			Do Nothing		
Grass State at t-1 (S_{t-1})		C	O	F	C	O	F
Grass Information at t (GI_t)	Closed (C)	1	1	1	0.888	0	0
	Open (O)	0	0	0	0.069	0.896	0
	Fragmented (F)	0	0	0	0.043	0.104	1

6. **Inspection and Maintenance Interval (Scenario)**
In this research, two different maintenance policy is applied, which are the annual and regular maintenance. Annual maintenance is an independent node, and the regular maintenance is conditional on the acquired information (see Equation 4.6). This chapter attempts to produce asset cost and performance from inspection and maintenance interval. The different maintenance interval is presented in Table 4.9. In practice, most of the annual maintenance is done at the beginning of spring. The annual maintenance is assigned in the network for every 12 time-steps (yearly).

Table 4.9: Scenario for optimal

Scenario Label	Maintenance Interval
A0	No Maintenance
A1	1-Month
A2	2-Month
A3	3-Month
A4	4-Month
A6	6-Month

- **Strategy analysis**
The goal is to measure the relative cost of asset cost and performance for different inspection and maintenance interval. This information should be useful for developing different asset management scenarios. There is two other supporting output of the model which are the asset cost (risk, maintenance, and relative change of total cost) and the asset performance (grass state probability) within the time horizon.

  1. **Asset performance**
  Throughout the time steps of the model, grass condition has a likelihood to degrade in time, and improve based on the maintenance action. The goal of this graph is to illustrate the interference and degradation of grass condition through probability. The grass performance is calculated using eq.4.3, eq.4.6, and eq.4.7 depending on the network at each time-steps.

  2. **Asset cost and Risk**
  Based on the grass condition probability, this output illustrates the total risk cost at every time-steps (see eq.4.8). The model also records the probability of maintenance and calculates the expected maintenance cost per time-steps (see eq.4.9). The cost is presented as a present value.

3. **Relative total cost**
   The relative cost is shown to identify the cost gap of different I&M interval.

$$RC(s=i) = \frac{\sum_{t=1}^{120} CT(s)_t - \sum_{t=1}^{120} CT(r)_t}{\sum_{t=1}^{120} CT(r)_t} \tag{4.11}$$

RC(s)	Relative total cost between scenario i and scenario 1 (no maintenance)
$CT(s)$	Utility cost of scenario i
$CT(r)$	Utility cost of scenario r where r is scenario 1
i	Scenario of maintenance interval
t	Time-steps

4.4. Results

The maintenance model was simulated using MATLAB. Part of the model is validated using the GeNie program, which is shown in Appendix C. The validation shows that the algorithm used in this research produces the same result as the GeNie program. The author did not validate all scenarios since the fundamental algorithm has already corresponded to the GeNie Program. Also, other scenarios only simulate with different CPT values or combination of network within the temporal-times where validation should not be a necessity.

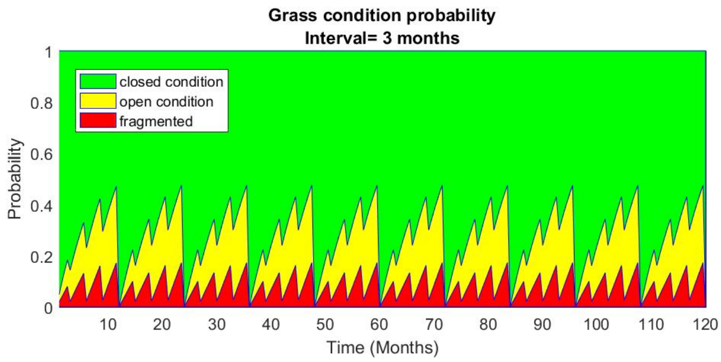
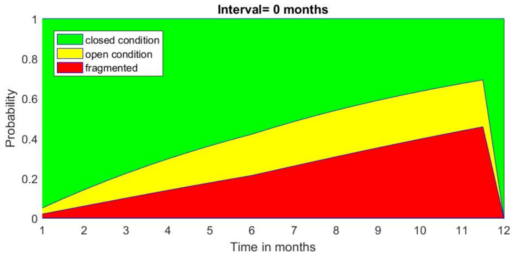


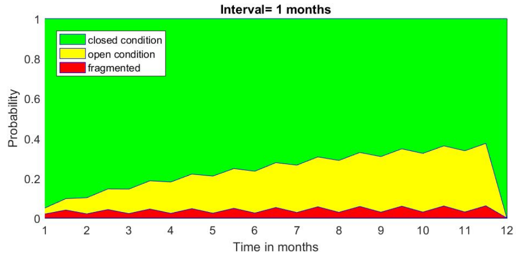
Figure 4.7: Grass condition over the time horizon for scenario A4 shows a repetition at every 12th time-steps. Annual maintenance policy influences the sudden drops of open and fragmented sod probability. The graph illustrates the changes in grass condition over the time horizon depending on the scenario.

The first result is the grass condition which presented using an area chart that depicts the grass condition probability over the time horizon. Fig.4.7 displays the impact of a maintenance interval (scenarios A4: 3-months maintenance interval) towards the grass degradation probability. In time, open and fragmented condition arises due to the transition probability assigned. A sudden decrease of open and fragmented sod is indicated at every 12-months, which represents the annual maintenance. Since we only consider a perfect restoration of grass condition, the grass condition reset at every 12th time-steps. Therefore, we could analyze the grass condition within the yearly period as shown in Figure 4.8.

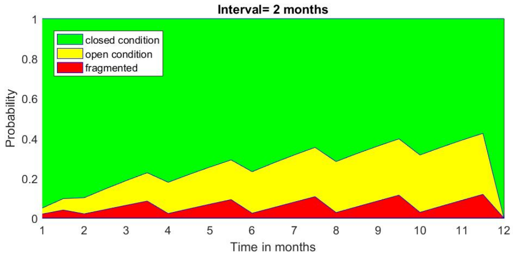
Figure 4.8 displays asset performance for different maintenance interval scenarios within a yearly period. The result shows a good representation of the influence of maintenance activities on a degrading asset. As expected, there is a significant difference between the "maintenance" and "no maintenance" policy where "no maintenance" policy has a higher probability of fragmented within the yearly period. The maintenance intervention can be seen from the saw-tooth shape in the chart. In a nutshell, the grass condition behaves as expected, where there is a significant impact on performing maintenance on a degrading asset. At each decline of the fragmented state, it indicates the causation of maintenance action.



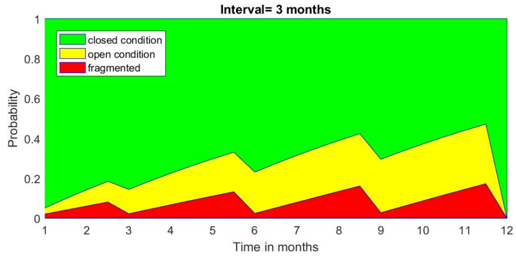
(a) Scenario A0



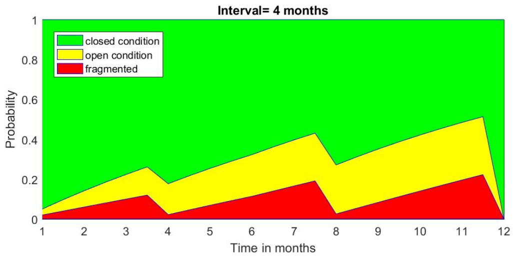
(b) Scenario A1



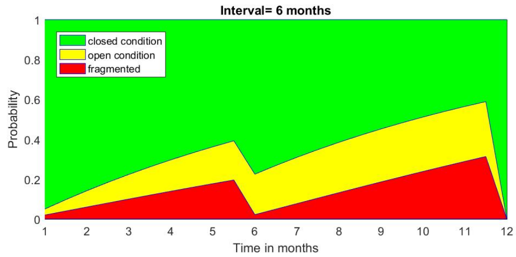
(c) Scenario A2



(d) Scenario A3



(e) Scenario A4

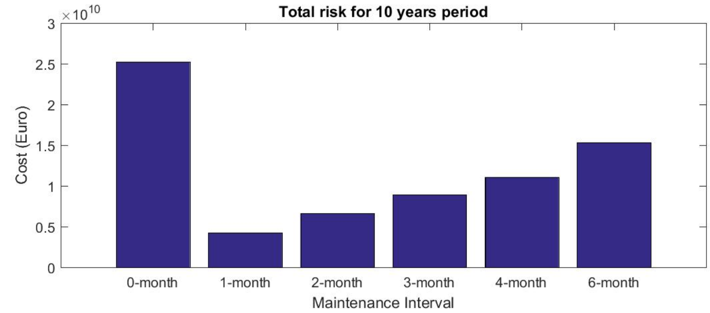


(f) Scenario A6

Figure 4.8: Grass state in a yearly period for different scenarios of maintenance interval

From Figure 4.8, the expected risk, and cost of maintenance can be interpreted. Both utilities have a relation with the grass condition. A higher probability of fragmented should indicates a higher risk. Meanwhile, a higher frequency of maintenance can be indicated by the saw-tooth shape of the grass condition probability chart which implies a lower probability of fragmented sod, hence produces a lower risk. Figure 4.9 illustrates the expected risk and maintenance cost. The utility results, shown in Figure 4.9a, indicates that scenario A1 has the lowest total risk and the highest total maintenance cost over the time horizon.

Overall, the model does illustrate the significance of maintenance activity. Figure 4.10 shows the combination of risk and maintenance cost produced in the model. We expected the result should indicate a distinction of asset cost and performance between maintenance intervals. The outcome indicates scenario A1 as the most effective maintenance interval with a relative change of approximately -80% compared to scenario A0. Another way to understand this graph is by comparing with the total maintenance cost and risk. For example, an organization has a maintenance policy which conducts inspection and maintenance every two months (Scenario A2). An additional investment, approximately 12000€/km (by increasing the maintenance frequency),is expected to improve asset performance by approximately 8%. Despite using a semi-hypothetical case and inputs, this method can indicate the significance of different maintenance policy.



(a) Total maintenance cost over 10 years period

(b) Total risk over 10 years period

Figure 4.9: Total risk and cost for different maintenance interval

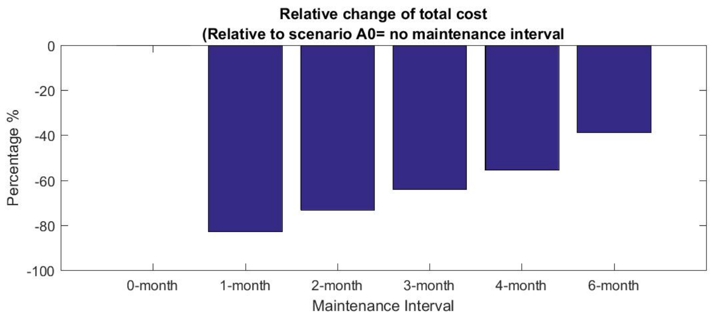


Figure 4.10: Relative cost for different interval

4.5. Conclusion

Dynamic Bayesian Network has been applied in maintenance modeling and has shown to be adaptable for this study. The model can replicate the inspection and maintenance of grass revetments while considering different maintenance interval. To recall, this chapter aims to answer the second research questions:

> *"What is the optimal inspection and maintenance strategy of grass revetment management?"*

Through DBN and different scenario of inspection and maintenance, the model can indicate the asset performance of different maintenance interval by measuring the expected risk and maintenance cost throughout the time horizon. The outcome of this model shows that a monthly period should be the most efficient strategy for grass revetment management. It is important to recall that the simulation was conducted by neglecting the influence of asset management capability nodes (GI, MD, ME), which will be applied in the next chapter.

There are several limitations in this simulation. First, the maintenance cost and risk are hypothetically determined. It can be improved by obtaining actual data. Second, several transition probabilities values of grass degradation are hypothetically determined by the developer. It is done due to the complexity of the issues and the availability of experts. Nonetheless, the missing values are determined with the basis of the SEJ outcome. Despite these limitations, the model has the ability to illustrate different asset performance under various scenarios. In the next chapter, the network is simulated under different set of scenarios that represent a particular management maturity. The simulation will be done by changing the CPT values and different combination of network elements.

5

Scenario Setup: Maturity Dimensions

This chapter objective is to answer the third research question:

"Which maturity model is suitable for infrastructure asset management, and how does it translate to the maintenance model?"

To answer this research question, this chapter begins by introducing maturity models that are related towards the flood defences. Then, the scenario is developed by using the known maturity dimension and relating it to the network elements. The result of this chapter should produce different set of model scenarios regarding different management maturity. The result of this chapter will be applied in the next chapter.

5.1. Maturity Models

Maturity models are used to quantify and compare management practice and levels to benchmark, identify strength and areas for improvement, and identify best practices. There are several maturity models which have a relevant application in various related to asset management (Gersonius et al., 2019; Volker et al., 2011; Williams, 2010; Zeb et al., 2013). For this research, we will focus on several maturity models that have been applied and developed towards asset management and flood defences. In the following sections, two maturity models are reviewed for their applicability to this study.

5.1.1. Infrastructure Management Maturity Model (IM3)

This maturity model is developed and implemented by Rijskwaterstaat (Volker et al., 2013). The development of this model is to perform a maturity check and focus on the development of internal quality improvement. The dimension or axis of asset management is divided into seven dimensions and five different levels. The asset dimension that is included in this model are shown in Table 5.1.

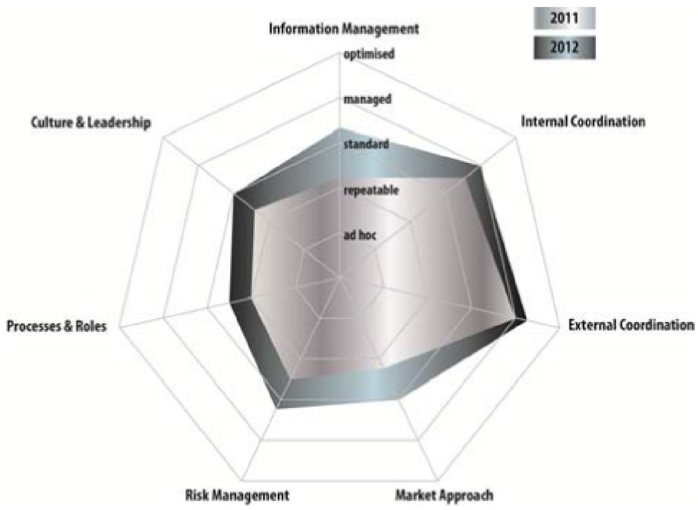


Figure 5.1: An example of IM3 maturity model. This example is an assessment of the asset management maturity in two different years. In 2012, the organization showed a significant improvement in every maturity dimension (Volker et al., 2013).

Table 5.1: IM3 Dimension

Information management	:	The availability to use of the static and dynamic database for decision making
Internal Coordination	:	Coordination and problem solving between the department of the organization
External Coordination	:	Coordination and problem solving between the different stakeholders of a project,including communication with users
Market Approach	:	Strategy about and implementation of integrated and performance-based contracting and innovative procurement methods
Risk Management	:	The use of risk management methods and life-cycle approach in the decision on strategic and operational asset management
Processes and Roles	:	Clarity, definition, and implementation of job responsibilities and roles within the organization
Culture and Leadership	:	Level of knowledge, application, and support of asset management related issues

Inspired by the CMM by Paulk et al. (1993), maturity is categorized in five different levels. The maturity levels are expressed as presented in Table 5.2

Table 5.2: IM3 Maturity Levels

Ad-hoc	:	The organization has limited experience and is at a learning and development stage
Repeatable	:	The organization can repeat what it has done before, but not necessarily define what it does
Standard	:	The organization can say what it does and how it goes about it
Well Managed	:	The organization can control what it does in the way of the process. It specifies requirements and ensures that these are met through feedback
Optimized	:	The organization is best practice, capable of learning, and adapting itself. It not only uses the experience to correct any problems but also uses the knowledge to change the way it operates

In a nutshell, this maturity model assesses the organization asset management by considering its consistency and efficiency of its management. IM3 has a stringer focus on the inclusion of stakeholders and communications (Gersonius et al., 2019). The advantage of this maturity model is the simplicity of its application for the organization which has been used in a Rijkswaterstaat which is shown in figure 5.1 (Volker et al., 2013).

5.1.2. FAIR Project

IM3 focus only on the fundamental aspects of asset management. Hence, FAIR project has updated the asset management maturity model for public infrastructure to incorporate and connect towards the proactive asset management framework (Gersonius et al., 2019).

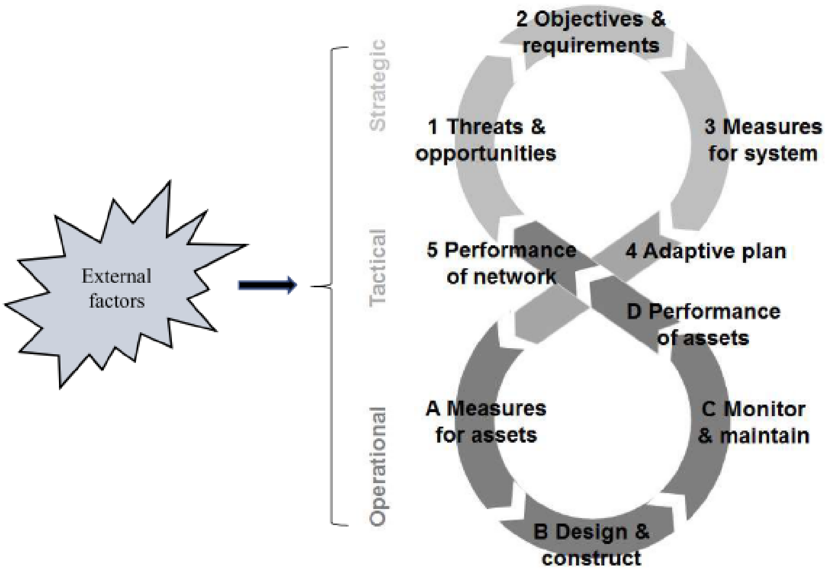


Figure 5.2: Proactive asset management framework showing the strategic, tactical and operational levels as well as how external factors indirectly impact what happens at each those stages Vlad (2017)

This framework of proactive asset management was designed by the FAIR scientific team from UNESCO-IHE, Van Hall Larenstein University and Deltares. It is a specific framework for the North Sea Region and user-friendly for the flood defence asset owners. It describes the process of asset management at three different levels, which are the strategic level, operational level, and tactical handshake. At every level, there will be key stages that are a relevant process in practice. These following key stages are developed by the Dutch scientific team (Vlad, 2017). This framework can be schematically represented in the form of the infinity symbol, as shown in Fig. 5.2. It represents the process of asset management from the strategic level, through tactical and implemented in the operational and back.

The strategic level is focusing on the long term planning of asset thus contains lower detail of asset information due to numerous uncertainty (Gersonius et al., 2016). At this level, the updated information is less frequent, in the scale of once every ten years, as needed for the top-level management. In the strategic level, organizations identify the potential threats and opportunities from the asset systems, setting the objective and the functional requirements, and acquire necessary measures towards the system of the asset.

The tactical handshake is bridging between the operational and strategic levels to ensure the consistency between two different levels. Tactical asset management can be seen as a connective process that allows the

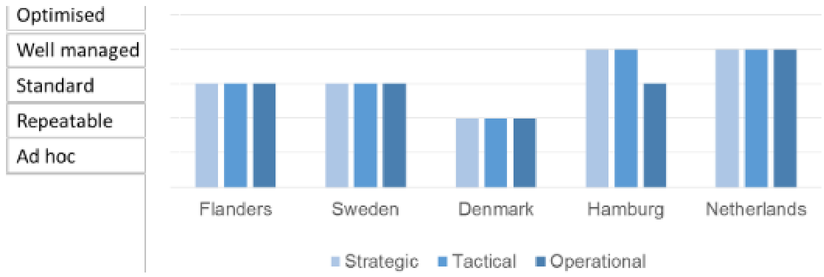


Figure 5.3: FAIR project maturity model for asset management process example (Gersonius et al., 2019)

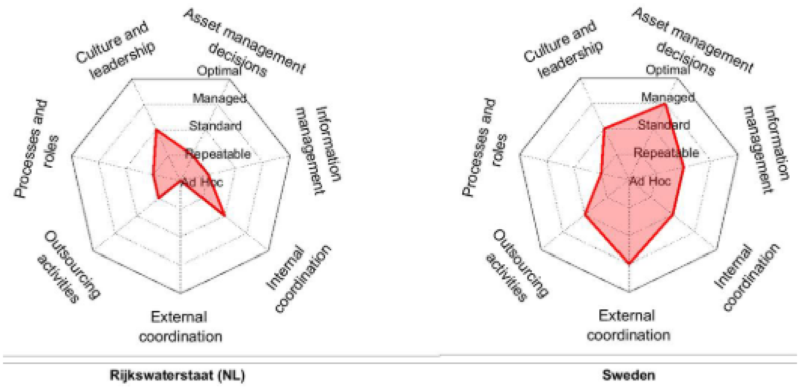


Figure 5.4: FAIR project maturity model for asset management dimension example (Gersonius et al., 2019)

asset manager to choose the best strategy from the strategic level for a particular situation that might be required at the operational level. In other words, a tactical handshake is an adaptive plan on a system level, translated to concrete measure for assets.

Operational perspective is the implementation of the strategy and focused on the short term planning of asset. Thus, it has a higher updating frequency than the strategic level. At this level, the asset owner is focusing on attaining the updated asset performance, monitors, and maintains the required performance.

Gersonius et al. (2019) develops a maturity model that not only assess the fundamental aspect of asset management but also the asset management process (strategic, tactical, and operational). The study was conducted towards different countries. Figure 5.3 and 5.4 demonstrates the result of the study. It shows the apparent difference between each country, and thereby, indicates opportunities to improve and share knowledge between the NSR countries.

5.2. Scenario

In the previous chapter, the result indicates that the network can be adjusted to resemble a particular scenario. By using the network elements, this section aims to translate the maturity dimensions into a particular scenario of maintenance that might be applicable in the developed model. Several network elements can be controlled and adjusted to explore different scenarios. Those elements are:

1. Inspection and maintenance policy (maintenance interval and annual maintenance)
2. The conditional probability of grass information $P(GI|S_t)$
3. The conditional probability of maintenance decision $P(MD|GI)$

4. The conditional probability of maintenance execution $P(S_{t+1}|MD)$

These scenarios can be adjusted to resemble a particular maturity dimension. In this research, we determine a particular maturity dimension that translates it to the relevant scenarios. Within the scenarios, sub-scenarios are assigned to explore the different asset cost and performance in different maturity levels as shown in Table 5.3. These are the scenarios:

Table 5.3: Implication towards maturity dimension scenario

No	Scenario	Maturity Dimension
1	Inspection and maintenance policy	Asset Management Decision
2	Perfect and Imperfect Information	Asset Information
3	Perfect and Imperfect Decision	Culture and Leadership
4	Perfect and Imperfect Maintenance Execution.	Internal Coordination

5.2.1. Scenario 1: Inspection and Maintenance Policy

The first scenario explores the different asset cost and performance conditional to the different inspection and maintenance schedule. In general, this scenario can be related to several relevant dimension of asset management, e.g., internal coordination or culture and leadership. In this scenario, only AM decision dimension is considered. Each maturity levels of AM decision dimension can be related a particular scenario of inspection and maintenance strategy. AM in practice applies risk analysis to evaluate the proposed alternatives. Therefore, the sub-scenario is developed with the basis of the importance of asset management decision and the application risk analysis. Table 5.4 shows the different scenario and maturity level description of asset management decision.

Table 5.4: Scenario 1: Asset Management Decisions

Maturity Levels	Asset Management Decision	Scenario Model
Ad-hoc	No attempt to analyse and make risk management decisions	Organizations does not have any inspection and maintenance schedule
Repeatable	AM decision is done without any reliable and structured evaluation process	Organization applies a periodical maintenance without applying risk analysis. Usually, organization performs maintenance based on the previous experience.
Standard	A systematic attempts on analysing risk and make risk management decisions	Organization applies a periodical maintenance and annual maintenance
Well-managed	The evaluation of risk and risk management decisions are supported based on cost analysis	A more cost-efficient schedule and implementing both annual and periodical maintenance
Optimized	Life-cycle costing is adopted to evaluate risk and risk management decisions	The most efficient period if inspection and performing annual maintenance

5.2.2. Scenario 2: Perfect and Imperfect Information

Information is an essential aspect of the decision process. The quality of a decision relies on the completeness and accuracy of the information. This concept has been discussed in numerous research on its application towards asset management. Perfect information occurs when the information structure provides clear and direct messages that identify precisely and unequivocally the state that occurs (Lawrence, 2012). Under perfect information, the information obtained by the organization is identical to the state space, and the posterior distribution is such that the probability of this event is one certain). Let us denote (a_{ω})) an action which is optimal for given perfect information ω and choice of action a_x. Hence, with perfect information, the decision-maker satisfies the optimal choice of decision and does not produce any opportunity loss (see Equation) which is expressed in Equation 5.1.

$$l_t(a,\omega) = \max u(a_\omega,\omega) - u(a_x,\omega) = 0 \tag{5.1}$$

Different information (imperfect information)may lead to a different choice of decision. Hence, this scenario focus on assessing the sensitivity of the imperfect information through the model. It allows us to understand the consequences of imperfect information. The input value will be differentiated based on the accuracy of information. Therefore, the sub-scenarios is developed considering the organization capability on acquiring information (e.g., inspection method, reporting, data management or information distribution) which is shown in Table 5.5

Table 5.5: Scenario 2: Asset Information

Maturity Levels	Asset Information	Scenario Model
Ad-hoc	No attempt on systematically acquiring and managing asset information within the organization	There is no actual or reliable information on asset condition (Accuracy : 0.33)
Repeatable	Couple of initiatives on acquiring and managing asset information which is conducted in an ad-hoc way	An informal and ineffective condition assessment which leads to inaccurate information. (Accuracy: 0.5)
Standard	A standardized approach on acquiring some of the required information and standardized data management within the organization	Information obtained by the organization are slightly more accurate and complete than repeatable. (Accuracy= 0.7)
Well-managed	Information are frequently updated through a standardized approach.	Information is slightly incomplete and inaccurate. (Accuracy=0.85)
Optimized	An optimal approach to acquiring and managing asset information	Information are complete and accurate (Accuracy=1)

5.2.3. Scenario 3: Maintenance Decision

The optimal choice for maintenance decision is conditional to the decision rule that tells the decision-maker how to respond to the acquired information. Since the quality of information has been covered in the previous scenario, this scenario only focuses on the maintenance decision rule from different management maturity. The ideal rule of maintenance is explained in Chapter 4. Different sub-scenarios are developed to assess the sensitivity of the imperfect decision towards the asset cost and performance by adjusting different CPT values of P(MD|GI). There are three different types of maintenance (corrective, preventive, and do nothing). These decisions are linked with the culture and leadership of an organization. It describes the organization consistency and initiatives in applying asset management to achieve asset objectives and goals.

Table 5.6: Scenario 3: Culture and Leadership

Maturity Levels	Culture and Leadership	Scenario Model
Ad-hoc	There is no initiatives on asset management application	Organization has lack of maintenance initiative.
Repeatable	Knowledge on asset management is present, and there are initiatives on bringing asset management to attention within the organization	The organization has an initiative of applying maintenance, but, the decision process is not thoroughly planned.
Standard	Asset management is applied within the organization. Various employee within the organization are following asset management studies	Maintenance are conducted due to the organization awareness of asset management. The rule of maintenance decision is improved by acknowledging different maintenance alternatives (preventive maintenance).
Well-managed	Asset Management is generally considered as one of the essential principles within the organization. The organization is familiar to the fundamental asset management practice	Management are aware of the different option of maintenance and more competent to evaluate and make a decision.
Optimized	AM is an integral component of the organizational culture. Management is adaptable towards new approach and proactive when it comes for improvement	Organization has an ideal rule of maintenance.

5.2.4. Scenario 4: Maintenance Execution

The quality of a maintenance action can be classified to the degree to which the operating condition of an asset is restored (Pham and Wang, 1996). Maintenance can perfectly restore the system operating condition (perfect maintenance), partially restore the system operating state between good as new and bad as old (imperfect maintenance), or undeliberately makes the system fail (worse repair). These different outcomes can be related to the management maturity. Therefore, this scenario elaborates different outcome of maintenance conditional to the internal coordination maturity of an organization.

Table 5.7: Scenario 4: Internal Coordination

Maturity Levels	Internal Coordination	Scenario Model
Ad-hoc	No initiatives on coordinating within the operational and strategical level.	Maintenance is done in an ad-hoc manner. There is no basis of analysis on which grass spots are required to maintain. The maintenance outcome of the grass condition might jeopardize grass in good condition.
Repeatable	There is coordination internally on an ad-hoc basis within the operational and between the tactical level	The outcome of maintenance is slightly better, but there is a high likelihood that other grasses are damaged or the damaged grass is not restored to the closed condition due to lack of internal coordination within the operational
Standard	A standardized coordination within the whole organization.	There is a small likelihood that the maintenance is done in the wrong grass spots.
Well-managed	The coordination has standard and has an initiative of evaluation within the organization	A higher likelihood that the grass is maintained to a closed sod condition. There is less misinformation through the evaluation initiative
Optimized	The coordination is optimal through continuous evaluation, and improvement	The maintenance are done on the correct grass spots and restored to most likely into a closed condition

5.3. Conclusion

This chapter aims to answer the third research question by exploring the different scenarios of the model elements within the maturity dimensions and levels. Through desk study, four different maturity dimensions are applied to the scenarios by considering different maturity model (see Table 5.3). This maturity dimension is inspired from the IM3 and FAIR maturity model. Within the scenarios, sub-scenarios are developed by considering the network elements, the chosen maturity dimensions, and different practical issues. These scenarios are applied in the next chapter to identify the loss and gain for different maturity dimensions and levels.

6

Relative Change of Total Cost for Different Maturity Levels

In IM3 or FAIR Maturity Model, maturity levels indicate the organization capability to manage assets. In times of restructuring policies and resources, maturity models offer organizations a structure to evaluate and improve their asset management performance. The maturity levels inform a general description of organization asset management capability. This information has shown a considerable learning curve for the organization (Volker et al., 2013). The use of maturity model results can be improved by adding the expected gain and loss for each AM maturity improvement or decline. By using the maintenance model developed in Chapter 4, the network can be adjusted to portray organization management capability using scenarios. This chapter aims to show the implementation of different AM scenarios towards the maintenance model. In total, 20 scenarios have been constructed which can be categorized into four management maturity. This chapter aims to process all of the findings from the previous chapter and answer the last research question:

"What is the expected gain of different asset management maturity levels?"

This chapter covers the model parameters, result, and analysis of every scenario developed in Chapter 3. The scenarios are translated as a model input which will be simulated and analyzed. There are four scenarios of maturity dimension, and within, five sub-scenarios is assigned to indicate the different asset cost and performance of every maturity levels.

6.1. Scenario Translation to Model Parameters

This scenario has been developed in the previous chapter. Each scenario covers different elements of management and its interpretation of asset management capability. There are four scenarios which consist of different asset management dimension. This section focuses on the development of maintenance model input conditional to the scenarios. At each scenario, only a few parameters are controlled, and other parameters are set to have a standard maturity. In order to be consistent, this assessment uses the same semi-hypothetical case study as in Chapter 4.

1. **Semi-Hypothetical Case Study**
   The case study is a typical grass revetment on the inner dike. The dike is located on a hypothetical rural area which is protected by a ring of dike with an area of 50 km^2. The dike has a typical slope of 1/3 (Jonkman et al., 2017) with grass revetments and perimeter length of 50 km. The grass cover is homogenous with a closed state as the initial condition. The dike ring is owned by an organization which is responsible for the serviceability of structure. As discussed in this research, the efficiency of asset management is crucial. Fragmented sod can be vulnerable to dike safety. Hence, this simulation aims to unveil the different gain/loss at each maturity dimension. The organization initial maturity level is

assumed to have standard maturity in all four management dimensions. This assessment follows the case parameters as shown in Table 6.1.

Table 6.1: Summary on the case parameters for management maturity scenario assessment

No	Case Parameters	Description
1	Case	Grass revetment management on a dike ring
2	Dimension of the Dike	Area= 50 km2; Dike total length= 25 km; Slope= 1/3
3	Time length of the model	10 years (1 timesteps= 1 month)
4	Grass degradation	- Degradation is modeled through three states (Closed, Open, Fragmented) - Two degradation transition probability is assigned for different seasons (see Table 6.2a) - Part of transition probabilities are obtained through SEJ
5	Maintenance cost	For each kilometer of dike length, an average of 11500 Euros is invested throughout the year. If maintenance occurs within a month, an expected of 2000 Euro/km.
6	Cost of failure	Assuming that the protected land has an expected risk of 1000 Euro/km2. Hence, the expected risk for closed condition is approximated to be 50000 Euro. For open and fragmented sod, the risk is elaborated to be: 5×10^6 Euro for open sod and 5×10^8 Euro for fragmented sod.
7	CPT Nodes GI, MD & ME	These nodes are adjusted based on the scenario. The initial condition of the organization management maturity is Standard.
8	Maintenance Policy	- The maintenance policy is adjusted depending on the scenario.
9	Outputs	The total cost (risk and maintenance) within the time horizon (10 years)

Table 6.2: Transition probability table for grass degradation

(a) Winter Degradation

P(S(t)|S(t+1))		S(t)		
		Closed	Open	Fragmented
S(t+1)	Closed	**0.888**	0	0
	Open	**0.069**	0.896	0
	Fragmented	**0.043**	0.104	1

(b) Summer degradation

P(S(t)|S(t+1))		S(t)		
		Closed	Open	Fragmented
S(t+1)	Closed	0.9	0.03	0.03
	Open	0.07	0.9	0.07
	Fragmented	0.03	0.07	0.9

2. **Scenario 1: Asset Management Decision Maturity and Inspection and Maintenance Schedule**

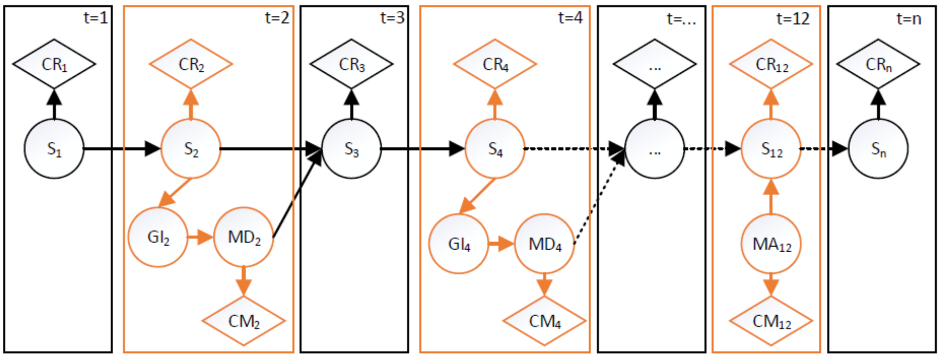


Figure 6.1: Schematization of maintenance network considering the first scenario (Orange lines are the controlled variables)

The first scenario is the influence of AM decision maturity towards the inspection and maintenance schedule. There are five sub-scenarios which represents each maturity levels. The variable changes are the inspection and maintenance interval and the application of annual maintenance (MA). Each sub-scenario are translated into model parameters in Table 6.3. The organization prior AM Decision maturity has a standard maturity where they are aware of the importance of maintenance and annual maintenance. Different sub-scenario is developed by fitting the maturity description in Table 5.4.

Table 6.3: Sub-scenarios for scenario 1 involving maintenance interval and annual maintenance

Maturity Levels	Maintenance Interval	Annual Maintenance
Ad-hoc	Random	No
Repeatable	Every 3 Months	No
Standard	Every 3 Months	Yes
Well-Managed	Every 2 Months	Yes
Optimized	Every 1 Month	Yes

3. **Scenario 2: Asset Information Maturity and Grass Information Node**

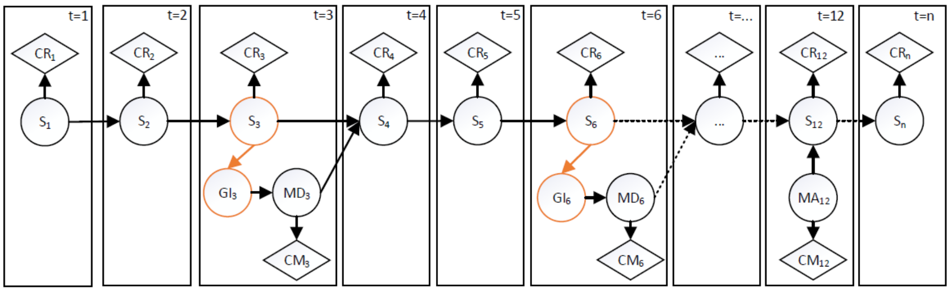


Figure 6.2: Schematization of maintenance network considering the second scenario (Orange lines are the controlled variables)

The second scenario covers the organization capability of acquiring reliable and accurate information on their asset. As discussed in 5, this scenario involves the accuracy of information obtained by the organization. Through the maintenance network, each maturity is assigned to have a different conditional probability. The lower maturity levels are assigned to have random information on its grass condition. Meanwhile, a higher maturity level is assumed to have a perfect information where the accuracy of information resembles in reality. The values are presented in table 6.4.

Table 6.4: The conditional probability of grass information for different sub-scenario. (C: Closed, O: Open, F: Fragmented)

Maturity		Ad-hoc			Repeatable			Standard			Well-Managed			Optimized		
Grass condition (St)		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
GIt	C	0.34	0.33	0.33	0.5	0.25	0.25	0.7	0.15	0.15	0.85	0.1	0.05	1	0	0
	O	0.33	0.34	0.33	0.25	0.5	0.25	0.15	0.7	0.15	0.05	0.85	0.1	0	1	0
	F	0.33	0.33	0.34	0.25	0.25	0.5	0.15	0.15	0.7	0.05	0.1	0.85	0	0	1

4. **Scenario 3: Culture Leadership Maturity and Maintenance Decision**

The third scenario investigates the influence of culture and leadership maturity towards the overall performance through the maintenance decision. There are three types of maintenance in the model; corrective, preventive, and do nothing maintenance. For ad-hoc and repeatable, it is assumed that the organization does not have initiative to conduct preventive maintenance. As the maturity level matures, the decision becomes inline with the ideal rule of maintenance.

5. **Scenario 4: Internal Coordination Maturity and Maintenance Execution**

The fourth scenario investigates the significance of internal coordination maturity towards the overall

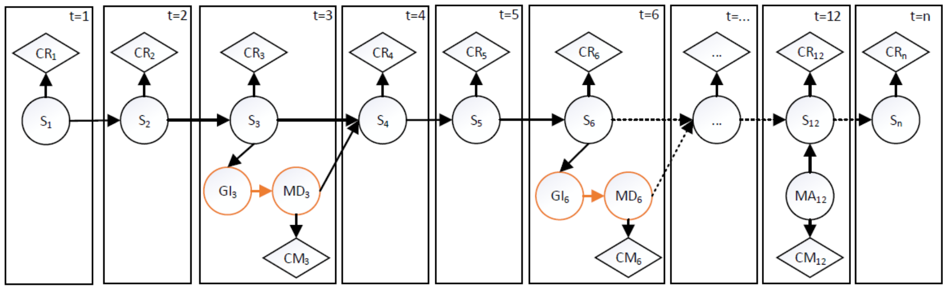


Figure 6.3: Schematization of maintenance network considering the third scenario (Orange lines are the controlled variables)

Table 6.5: CPT for maintenance decision conditional to grass information at every sub-scenario

Maturity		Ad-hoc			Repeatable			Standard			Well-Managed			Optimized		
Grass Condition (Gt)		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
MDt	Corrective	0	0.1	0.2	0.1	0.1	0.6	0.05	0	0.75	0	0.05	0.9	0	0	1
	Preventive	0	0	0	0	0	0	0.05	0.7	0.125	0	0.85	0.1	0	1	0
	Nothing	1	0.9	0.8	0.9	0.9	0.4	0.9	0.3	0.125	1	0.1	0	1	0	0

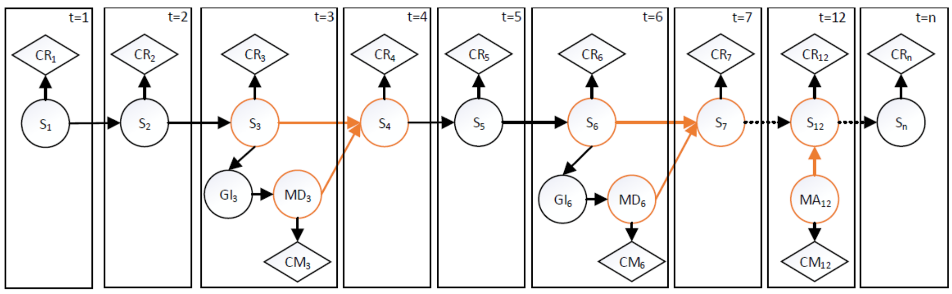


Figure 6.4: Schematization of maintenance network considering the fourth scenario (Orange lines are the controlled variables)

asset performance through maintenance execution node. During maintenance, the organization is required to coordinate between strategic and operational level. This scenario variates the outcome of maintenance execution depending on the maturity of organization internal coordination. These values are hypothetically developed based on the description discussed in Table 5.7.

Table 6.6: CPT of grass condition conditional on the maintenance and asset management maturity scenario

Maturity		Ad-hoc			Repeatable			Standard			Well-Managed			Optimized		
Maintenance Execution		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
St+1	C	0.34	0.34	0.34	0.5	0.5	0.5	0.75	0.75	0.75	0.9	0.9	0.9	1	1	1
	O	0.33	0.33	0.33	0.3	0.3	0.3	0.1875	0.1875	0.1875	0.09	0.09	0.09	0	0	0
	F	0.33	0.33	0.34	0.2	0.2	0.2	0.0625	0.0625	0.0625	0.01	0.01	0.01	0	0	0

6.2. Results and Analysis

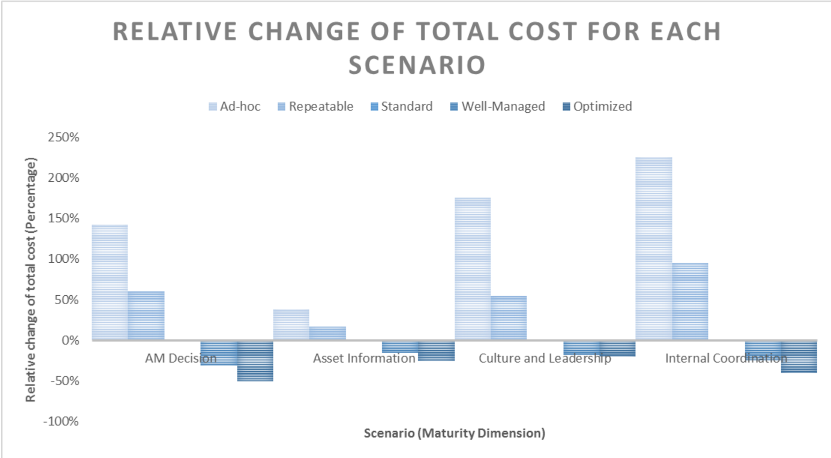
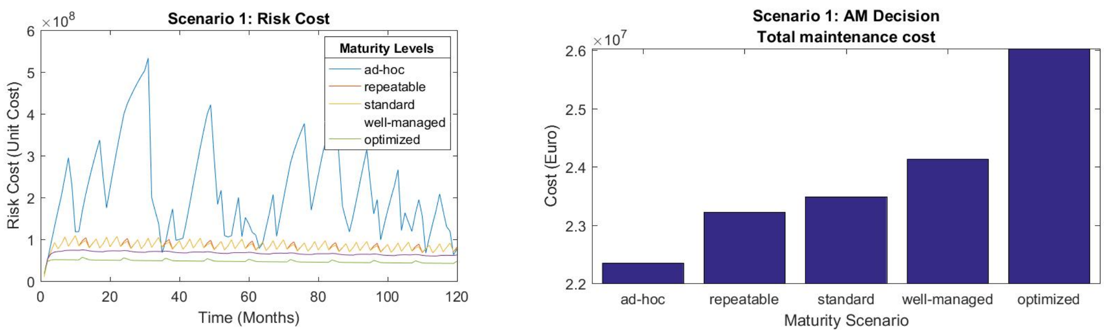


Figure 6.5: The relative change of the overall asset cost for different maturity dimension and level with respect to Standard maturity level at each scenario

The simulation was done using MATLAB by fitting the network with respect to the scenario. The network has been validated using the GeNIe Program which is shown in Appendix C. The result, shown in Figure 6.5, reveals a similar trend for each scenario where a higher maturity level produces the lowest total cost. The total cost is the summation of both risk and maintenance cost over the time-horizon. Each scenario has different significance towards the overall cost which will be discussed concisely in this section separately. All the figures and results can be also seen in Appendix D.

1. **Scenario 1: Asset Management Decision**



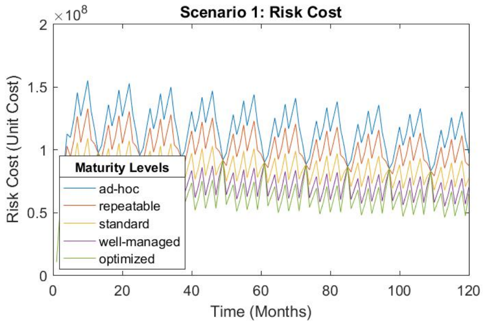
(a) The risk cost over the time horizon for scenario 1

(b) The total cost of maintenance for scenario 1

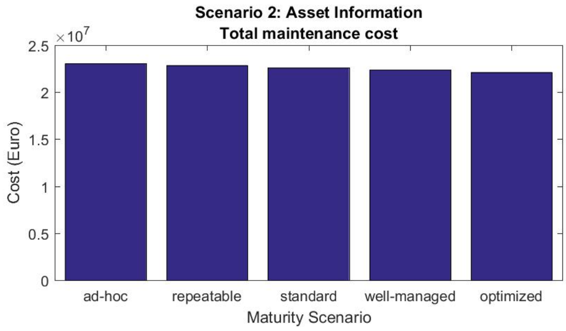
Figure 6.6: Output for scenario 1

The maintenance role is essential towards the asset cost and performance. As it is shown in Chapter 4, different maintenance interval may result in different asset performance. The ad-hoc maturity shows By applying different scenarios of maintenance interval and annual maintenance for each maturity levels, we can distinguish each maturity levels with respect to its asset cost and performance. Figure 6.6a shows the risk over the time-horizon for different sub-scenarios of maturity levels. Based on the assigned scenario, there is a clear distinction of asset performance at each maturity levels. At ad-hoc level, we assume that the organization does not have clear long-term planning of its asset and has a random maintenance interval. Therefore, due to inconsistent and inefficient timing of maintenance, the ad-hoc level has the highest risk (see Figure 6.6a). The tests has also revealed that the application of annual maintenance (between repeatable and standard) has a significant gain towards the overall asset performance (20%). It is because the annual maintenance is assigned to be regularly performed without any dependence on the maintenance decision. The result has also illustrates the different performance between repeatable and standard maturity levels. As expected, both well-managed and optimized maturity levels have the lowest overall risk and a higher maintenance cost (see 6.6b).

2. **Scenario 2: Asset Information**



(a) The risk cost over the time horizon for scenario 2

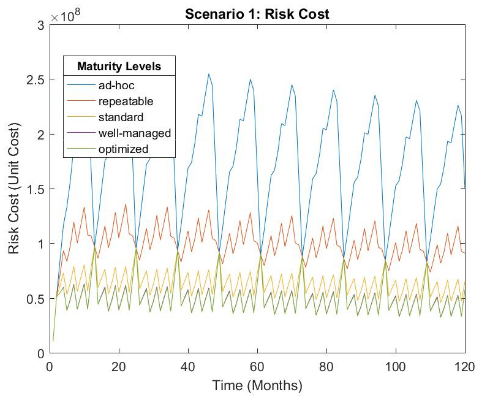


(b) The total cost of maintenance for scenario 2

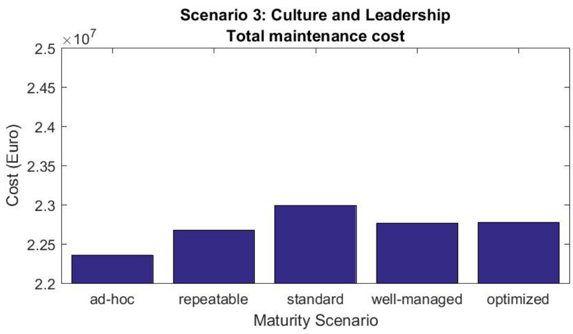
Figure 6.7: Output for scenario 2

The second scenario discusses the influence of the information accuracy towards the asset overall performance. As shown in Figure 6.7a, the result shows an agreement on the concept of perfect information. Over time, higher information accuracy leads to a lower risk. Interestingly, the maintenance cost is higher in the lower maturity level. In other words, it is expected that ad-hoc maturity level of asset information would maintain its asset more frequently. Despite the frequency of maintenance, the CPT of Asset Information shows that there is still a higher probability that the organization misinformed, which lead to a higher probability of fragmented sod. The overall result is dependent on the MD and ME nodes.

3. **Scenario 3: Culture and Leadership**



(a) The risk cost over the time horizon for scenario 3

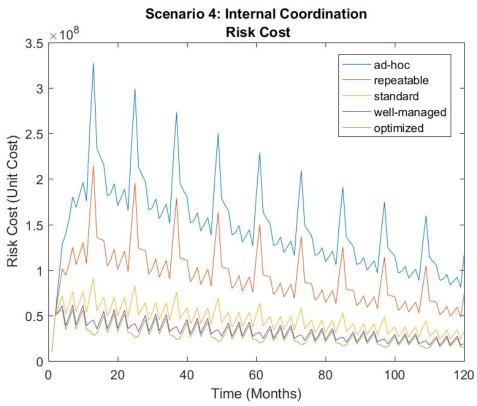


(b) The total cost of maintenance for scenario 3

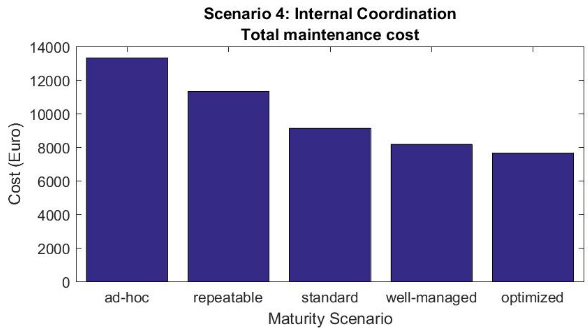
Figure 6.8: Output for scenario 3

The third scenario discusses the significance of AM awareness towards the overall cost-performance through the maintenance decision. For different maturity levels, an organization may have a different level of asset management application. It is illustrated that a low maturity level would have a lack of initiative for maintenance and have lack ability to make a perfect decision. MD node is essential, which illustrate the probability of maintenance. As expected, Figure 6.8a indicates that an ad-hoc and repeatable maturity level has the highest risk. The result shows an agreement with the importance of AM. Meanwhile, other maturity levels have relatively a similar overall cost. This can be distinct by analyzing both the risk and maintenance cost separately. As shown in Figure 6.8b, the cumulative maintenance cost between the two highest maturity levels are in a similar range. Meanwhile, the standard maturity has the highest cost of maintenance. Based on the CPT, the CP for standard maturity shows that there is a relatively high likelihood that organization decides not to intervene in any condition. There is slightly more frequent maintenance for standard maturity (since the organization will face more frequent deteriorated grass). As the decision resembles the ideal rule of maintenance, the decision becomes more efficient which can be seen by comparing both risk and maintenance cost for well managed and optimized scenario. Both scenarios slightly perform better than standard scenario, but, the maintenance cost shows that both optimized and well-managed require less investment than the standard scenario. Based on the result, the organization should consider improving their culture and leadership maturity by applying AM as one of the organization main principles. Hence, divisions and employee will be more aware of the importance of AM.

4. **Scenario 4: Internal Coordination**



(a) The risk cost over the time horizon for scenario 3



(b) The total cost of maintenance for scenario 3

Figure 6.9: Output for scenario 3

This scenario explores the outcome of different maintenance execution in relation to the organization internal coordination. The CPT shown in Table 6.6 implies that a higher maturity will restore the grass state into closed condition. Meanwhile, imperfect maintenance can be found on the lower maturity. Figure 6.9a illustrate that the risk is significantly higher for the lower maturity levels. Based on the CP, the lower maturity will constantly generate fragmented sod as the outcome of maintenance. As shown in Figure 6.9b, the lower maturity levels have a higher expected cost of maintenance. Based on this scenario, it implies that the lower maturity constantly generates a fragmented sod; hence, a higher likelihood of performing maintenance.

6.3. Conclusion

This chapter unveils the different asset cost and performance for different maturity levels using scenarios and maintenance model. The network is exploited to fit a particular scenario of asset management. The result was shown as a relative change of the overall cost with respect to the standard maturity level. The maintenance developed in this model is capable of predicting and illustrating the different asset cost and performance for different maturity levels as shown in Figure 6.5. It is important to remind that this result is the implication of the scenario which is subjectively developed by the author.

For the asset decision, the scenario was developed in relation to the inspection and maintenance policy. In ad-hoc decision making, the organization is simulated without a specific policy (unplanned maintenance interval). The relative change is around 142% higher than the standard level. It shows the significance of applying a standardize maintenance policy. Meanwhile, the effect of annual maintenance is shown between standard and repeatable level. Annual maintenance is an effective regime to maintain the grass condition, which will improve the asset cost and performance by 50%.

In the asset information maturity dimension, an ad-hoc maturity will lead to a risk reduction. At ad-hoc, the organization does not have a clear inspection design or information on grass condition. Due to the low degradation rate, the organization misinformed continuously on the decision process, which leads to a higher probability of performing maintenance than the optimized level where information is perfectly captured. Despite that, the grass cover is expected to be effectively restored in the optimized maturity levels. In other words, by obtaining more accurate information, the organization can effectively decide at which moment the grass required maintenance.

In the culture maturity dimension, the scenario was developed in relation to the awareness of maintenance. In ad-hoc maturity, the organization tends to have a lack of awareness of maintenance. Therefore, a low probability of maintenance is assigned, which leads to a 170% loss compared to standard. Meanwhile, the application of preventive maintenance increases the performance by 55%, which is shown from the relative change of repeatable maturity and standard maturity. Other than that, there is no significant gain or loss if preventive is maintenance is applied (see Figure 6.9a between standard, well-managed, and optimized). The difference can be found on the total investment cost at each scenario. Both well-managed and optimized has a lower investment and produces a better asset performance. It implies that the well-managed and optimized conducts an effective and efficiency of the maintenance decision which is beneficial towards the asset performance.
Lastly, in internal coordination, the scenario was developed in relation to the maintenance execution. An assumption was made where a lower maturity does not have a clear maintenance plan; therefore, maintenance regimes would have lower probability to restore grass to a closed condition. Meanwhile, a higher maturity level would likely restore grass to closed condition. The results show a significant difference between the total cost of optimized, standard and ad-hoc maturity.

7 Discussion

This chapter discusses the journey leading to the final result. First, we will discuss the development of expert judgment questionnaires and the performance of the participating expert. Then, the development of the maintenance model and scenarios are discussed. This chapter highlights the achievement and limitation of the conducted study.

Expert Judgment

Expert judgment was conducted to determine the degradation probability of grass revetments, which will be used in the Dynamic Bayesian Network. The choice for expert judgment as the method is to provide a fair approximation of the target variables. Seed questions (SQ) were created to calibrate the experts' ability to approximate uncertainty. Unfortunately, there are no quantitative data available that resembles the target question and can be utilized as seed questions. Therefore, this study uses sod cover measurement and wave overtopping experiment on grass revetments as seed questions.

A plausible source of unreliability might be in the conduction of the expert elicitation. Ideally, experts are gathered in the same room where the SEJ guidelines can be well informed. Due to the limitation of time and resources, expert elicitation was conducted online. It is plausible that this limitation could have influenced the results. The inconsistency in the target variables can be one of the examples, as mentioned in section 3.6. Some experts did not express their uncertainty or deviate from the common trend. For example, an overall degradation of grass revetment should have a lower probability than grass spot degradation. Some experts express differently, which may be caused by the indirect feedback. Another example is shown in the target variables, Exp.3 express in a narrow range of uncertainty in several target questions. Based on other questions, Exp.3 express his uncertainty well; therefore, confidence or lack of apprehension of the question might be the reason for the narrow range of uncertainty. However, in general, most of the experts did express their uncertainty.

After obtaining experts' distributions, experts' performance is measured using Cooke's Classical Model. By using a cut-off value of 0.05, only one expert was considered in the assessment where a high overall calibration was found. However, the goal of this method is to assess uncertainty by considering multiple experts. Therefore, the assessment uses a cut-off value of 0.001 to consider four experts. Other weighting system was also considered. The result shows that the DM Global has a lower calibration(0.007) than the DM Equal (0.493) and DM Optimized (0.707).

Based on the itemwise robustness, in general, all item has relatively a similar significance towards the overall scores except SQ8. By neglecting SQ8 in the assessment, the overall calibration scores increase by order of 10. The sudden increases of calibration are the result of a heavier weight on Exp.3 (the best expert). It can be seen from the Exp.3 distributions on the seed questions. By excluding SQ8, Exp.3 distribution closely resembles the theoretical distributions (see Figure 7.1) In the assessment, Exp. 3 scores the highest calibration (0.7) and the highest calibration, which indicates his confidence. Precisely, in SQ8, Exp.3 did not correctly predict while other contributing experts did. Therefore, by neglecting SQ8, Exp.3 is given a heavier weight which increases the overall calibration.

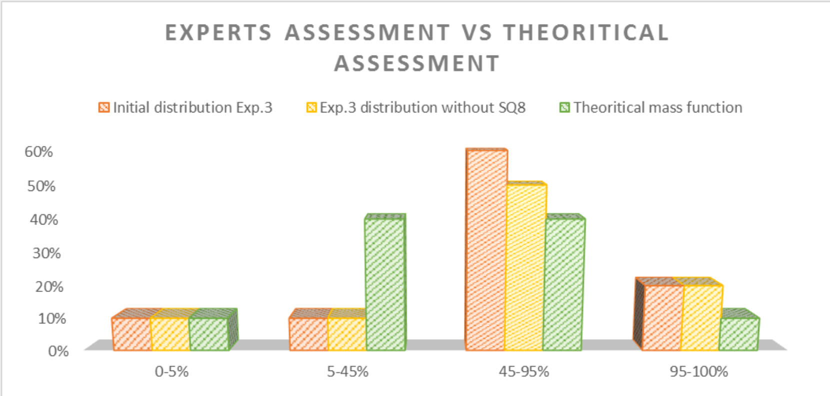


Figure 7.1: Distributions of the Exp.3 intervals compared to the exclusion of seed question 8 and theoretical mass distribution

Another assessment was conducted to analyze the consistency of expert performance in the target variables. The elicitation of target variables was conducted in three different groups of questions. Each group of question utilizes different unit of references (time, probability and spatial). The target questions were compared through different scenarios which consist of different combination of target question. Experts are not informed about the discrepancy analysis strategy to avoid bias elicitation. The result shows that most experts are more comfortable to express their uncertainty using degradation time as can be seen in the range of uncertainty. On the other hand, experts seem to have difficulties in expressing their uncertainty using spatial and probability. It can be seen by the inconsistency and narrow range of uncertainty. Therefore, for this research, degradation time is applied to represent the grass degradation rate.
To sum up, our work has led to a degradation probability distribution based on the experts' judgment. Our finding seems to demonstrate a low probability of degradation as expected. Although the SEJ interviews were not conducted in an ideal situation, we still believe that it produces valuable information based on the various range of uncertainty expressed by the participant given the performance and information of experts. At last, based on the assessment, DM Optimized is utilized as the virtual assessor for unveiling the grass degradation rate in time. Despite the inconsistency of Exp.3 in the target question, most of the inconsistency was found in the second and third group of questions (probability and spatial). Therefore, it is acceptable to use DM Optimal as the decision-maker. After the SEJ assessment, the result is applied in the DBN as the transition probability of grass for each time-slices.

Maintenance Model

Development of the Network
DBN was chosen as the method to develop maintenance model on a degrading grass revetment. In Chapter 4, the maintenance model was constructed by considering different elements of asset management, which are the asset information, asset decision, maintenance delivery, and asset degradation. It is constructed in such a way that it produces asset cost and performance based on a different combination of the element network. Asset degradation is illustrated as a Markov Process. We are aware that using Markov Chains, we limit the degradation process as a random deterioration between states.

As the first attempt in Chapter 4, different scenarios of maintenance interval was assigned to find the different asset cost and performance. In the model, the degradation transition probability uses the distribution from

the Expert Judgment and other conditional probabilities are set to be ideal (assigning perfect information, effective decision, and perfect maintenance). The network has been calibrated and validated in Appendix C. The validation was done using two essential networks which are the grass degradation and grass condition conditional to maintenance and prior condition. The result shows an equivalent outcome in both scenarios with respect to the GeNie Program.
A limitation was found in determining the cost of maintenance and risk. Through desk research, a hypothetical cost was assigned to the model where the cost of maintenance is lower than the risk. Hence, it is evident from the result that a higher maintenance frequency leads to higher asset performance as the preferable option. To summarize, the network does capture the different asset cost and performance based on different maintenance interval as expected. One downside regarding using DBN as maintenance model is the discrete function for maintenance decision. The decision network is a discrete function for different grass states. Therefore, it does not capture the severity or the magnitude of maintenance required.

Translating maturity dimensions to maintenance network
In order to include maturity dimensions and levels to the maintenance model, different scenarios of asset management were created. Four scenarios were created to replicate the asset management maturity dimension through the network elements. Each scenario consists of five different sub-scenarios that represent a certain maturity dimension and levels. Maturity dimension is a component of asset management that can be implied to different practical cases of management. For example, culture and leadership maturity dimension can be related in both maintenance decision process and the quality of information distributed in the organization. There are many ways to interpret maturity dimensions. Therefore, for the simplicity of the model, the scenario is built by restricting the influence of maturity dimension to a single network element. This restriction is considered as a limitation on this research.

Four components of the model are associated with a maturity dimension.Most of the existing maturity model defines a general idea of an aspect of management. Therefore, we have created four maturity dimensions which focus only around the maintenance process. It was developed by using both IM3 and FAIR Project maturity model as a benchmark. The scenario is then translated as model input. The model inputs were determined by the developer with regards to the translated scenario. We are aware of the subjectivity of this approach. The determination can also be done by involving expert elicitation to eliminate bias or conducting research focusing on a maturity dimension where inputs and scenario can be further studied.

Relative change of total cost for different maturity levels
Based on the result, it is possible to capture a particular different asset cost and performance for different asset management capabilities, which is shown in Figure 6.5. As far as we are aware, this is the first time that the different asset cost and performance for different maturity levels are predicted. Despite its limitation, this result shows the potential expansion use of maturity model. The result enables us to understand the different gain and loss at different maturity dimension and levels. The quality of the result is dependent on the input and the development of the scenarios. In this study, we developed different scenarios based on the author's perspectives.

8
Conclusion and Recommendation

The goal of this research is to assess the effect of different asset management maturity levels to cost and performance on grass revetment. We have presented an approach on predicting different asset cost and performance in different maturity levels by using Dynamic Bayesian Network. In the process, expert judgment is applied to unveil the grass degradation probability, which will be useful for the DBN maintenance model. In this study, scenarios and sub-scenarios are developed to represent a particular maturity dimension and level. Several model parameters are tweaked to recreate a specific scenario.

This study has developed a maintenance model that is able to depict asset cost and performance from different management maturity using Dynamic Bayesian Network. The method can be generalised, but, for other case study, the developer might have to adjust the boundary conditions and input variables. Taken together, this information and method can improve the use of maturity levels in the decision process.

Conclusions

The main research objective is:

"Assess the effect of different management maturity levels to cost and performance of a flood defences asset"

This objective has been addressed indirectly throughout the research with the help of four research questions. Each research question has been addressed and discussed in a separate chapter. The answers to the research questions are summarized below:

1. *What is the deterioration rate of grass revetments?*
   This question has been addressed in chapter 3 by unveiling the degradation probability using expert judgment. Seven experts participated in the assessment in which was done using an online questionnaire. The majority of experts are operational-oriented, and others have a background as a research and consultancy. The assessment consists of twenty-five questions (ten seed question and fifteen target variables). The result shows that few of the seven experts are able to estimate the uncertainty. Only one expert has calibration scores higher than 0.05. Furthermore, DM Optimized (0.707) and DM Equal (0.493) scores a higher calibration than the DM Global and DM Item. After a thorough assessment of robustness and discrepancy analysis, DM Optimized is chosen and used as a virtual expert to solve the deterioration rate of grass revetment (see table 3.9).

2. *What is the most effective inspection and maintenance interval of grass revetment management?*
   This question has been addressed in chapter 4 through a simulation of DBN on grass maintenance. The simulation was done using different scenario of maintenance interval. The transition probability is determined by using the result of chapter 3. The network was simulated for 120 time-steps, which refers to a monthly period at each time-steps. The cost and risk cost are determined based on the semi-hypothetical case. The result indicates asset cost and performance for different maintenance interval.

There are several limitations found in this assessment. One of the limitations was the transition probability of the grass revetments. In the SEJ, only a few combinations were elicited due the limited time. Another limitation was the determination of maintenance cost and risk. In this research, both maintenance cost and risk were determined using the semi-hypothetical case. The risk is significantly higher than the maintenance cost hence more frequent maintenance is always beneficial. This limitation can be resolved by collecting an existing study case. In summary, the result shows a distinction of asset cost and performance for different maintenance interval in which monthly interval is indicated as the most effective.

3. *Which maturity model is suitable for infrastructure asset management and applicable for translating it into asset performance indicators?*
Chapter 5 addresses the implication of maturity model towards grass revetment inspection and maintenance. Through literature reviews, two maturity model stands out in which are the IM3 and the FAIR project maturity model. Then, four scenarios are developed and implicated towards a maturity dimension. These scenarios are the maintenance policy related to the asset decision maturity dimension, the accuracy of inspection related to the asset information maturity dimension, the maintenance decision related to the culture of the organization, and the quality of maintenance execution which is related to the internal coordination. These scenarios are translated into the maintenance model in chapter 6. The result indicates the asset cost and performance for different scenarios. It implies that it is possible to implicate the maturity dimension and levels to the asset cost performance by developing scenarios.

4. *What is the expected gain of different asset management maturity levels?*
This research question aims to identify the gain and losses of asset cost and performances for different management maturity. Based on the scenario developed in chapter 5, the relative change of total cost for different management maturity is obtained by using the Dynamic Bayesian Network. The result successfully indicates the gain and loss of each scenario (see figure 6.5). Each maturity dimension has a different effect on asset performance. In general, all scenarios resulted in a similar trend where asset performs better as management matures. In general, the network succeeds depict asset cost and performance for each maturity dimension and levels scenario and obtain the relative change of cost for each maturity levels. The result may not be generalized for any flood defences asset due to the subjectivity of the developed scenario.

Recommendation for Future Research

Further work needs to be done to establish a better approximation of asset cost and performance for each maturity level. These are the recommendations:

Recommendation 1. The interrelation between different maturity dimension in a network element
The development of the scenario was limited to connect one network element towards a maturity dimension. It is important to recognize that a maturity dimension can influence several network elements. For example, asset management decision management covers the ability of an organization to evaluate its alternatives in the decision process. This capability can be associated with other significant activities in the network elements such as asset information, maintenance decision, and maintenance execution. This assessment can be done by creating a comprehensive conditional probability table that is conditional to the maturity dimension and level. For example, a conditional probability of acquired information (P($GI_t|S_t|$)) is conditional on AM decision maturity and asset information maturity. Therefore, we will obtain 25 sets of combination of CPT.

Recommendation 2. Structured judgment on grass degradation probability
This study uses sod cover measurement and waves overtopping experiments as seed questions. The finding shows that most of the experts give a higher range of uncertainty on the wave overtopping experiment. Meanwhile, due to a given range in the seed questions, the sod cover measurement is doubted to clearly measures the expert ability in predicting uncertainty. If another SEJ on grass degradation is conducted, we recommend using actual data of grass degradation rate for seed questions. If there are no data available, wave overtopping

experiment is recommended since it gives expert room to express their uncertainty.

Recommendation 3. Apply different other flood defence asset as case study
One of the interesting output of this study is the relative change in total cost for different management maturity. The result was obtained by using Dynamic Bayesian Network and different network scenarios. The development of the scenario is subjectively assigned by considering practical problems in grass revetment management. Further development using different flood defences should be applied. Therefore, the relative change of total cost from different management maturity can be generalized by comparing the different result from different flood defence asset.

Recommendation 4. Improving the conditional probability for different management maturity
In this research, the translation of the scenario to the model inputs was determined based on the author's judgment. Further study is required to obtain reliable input. The translation can be improved by conducting or associating to existing research on the reliability of different management strategy or capability. For example, in inspection, there are different method to inspect grass revetments, which is the visual inspection or the root strength measurement. The accuracy of each method is different. Therefore, the CP can be improved by associating the reliability of different inspection method to the scenario. Another option is to study further on the reliability of information accuracy conditional to the inspector experience. Different inspector experience may result in different information accuracy. The result of this study can be associated with a scenario of the model.

A

Appendix A Expert Judgment Questionnaire

WELKOM BIJ DE TWEEDE VRAGENLIJST VERANDERING VAN KWALITEIT VAN GRASBEKLEDINGEN

Namens het onderzoeksteam wil ik u bedanken voor uw beschikbaarheid en bijdrage aan deze studie. In het kader van mijn afstudeeronderzoek wil ik kijken naar de optimale inspectie- en onderhoudsstrategie voor grasbekledingen. Het doel van deze vragenlijst is om aan de hand van inschattingen van experts inzicht te krijgen in de verandering van grasbekledingen in de tijd. Daarbij is het uitdrukkelijk niet de bedoeling om 1 getal te geven, maar de onzekerheid van uw inschatting weer te geven.

De vragenlijst bestaat uit twee hoofdonderdelen:

1. Het eerste deel is om in te schatten hoe u zelf uiting geeft aan uw onzekerheid (de zogenaamde 'seed questions').
2. Het tweede deel bestaat uit het inschatten van gegevens t.a.v. de doelvariabelen (verandering/achteruitgang van graskwaliteit). Dit zijn de 'target questions'.

Instructie

Bij het beantwoorden moet het volgende in gedachten worden gehouden:

1. Vertrouw jezelf. Deze methode is geen examen maar bedoeld om inschattingen van experts boven water te krijgen. Er zijn dus ook geen foute antwoorden
2. Zoek geen antwoorden op; we verwachten niet dat je precies gelijk hebt; we willen weten hoe je je onzekerheid uitdrukt.
3. Druk uw onzekerheid uit in drie verschillende reeksen:

    - 5%: je inschatting van de ondergrens, de waarde die het minimaal is.
    - 50%: de waarde die je verwacht
    - 95%: je inschatting van de bovengrens

Voorbeeldvraag:
Wat is de de gemiddelde temperatuur in de zomer van 2019? Antwoord:5%: 20 graden, 50%: 23 graden, 95%: 27 graden

A.1. Seed Question 1-6 Conditie van een Grasmat

In dit gedeelte geven we u verschillende foto's van grasbedekking in een bepaalde toestand. We zouden graag willen dat u door gebruik te maken van getallen tussen 1-9, uw geloof in de toestand van het gras in de afbeeldingen hieronder schat. De getallen 1-9 vertalen zich als volgt naar de gebruikelijke zodeklassen:

- 1: Gefragmenteerd
- 5: Open
- 9: Closed

Een cijfer 3 betekent dus dat een zode zowel gefragmenteerd als open kan zijn. Uiteraard wordt wederom om waarden voor ondergrens/verwachting/bovengrens gevraagd.

(a) Seed Question 1: Closed Sod

(b) Seed Question 2: Open Sod

(c) Seed Question 3: Fragmented Sod

(d) Seed Question 4: Closed Sod

(e) Seed Question 5: Closed Sod

(f) Seed Question 6: Closed Sod

Figure A.1: Seed question 1-6 for grass condition)

A.2. Seed question 7-10: Golfoverslag bij grasbekledingengolfoverslag

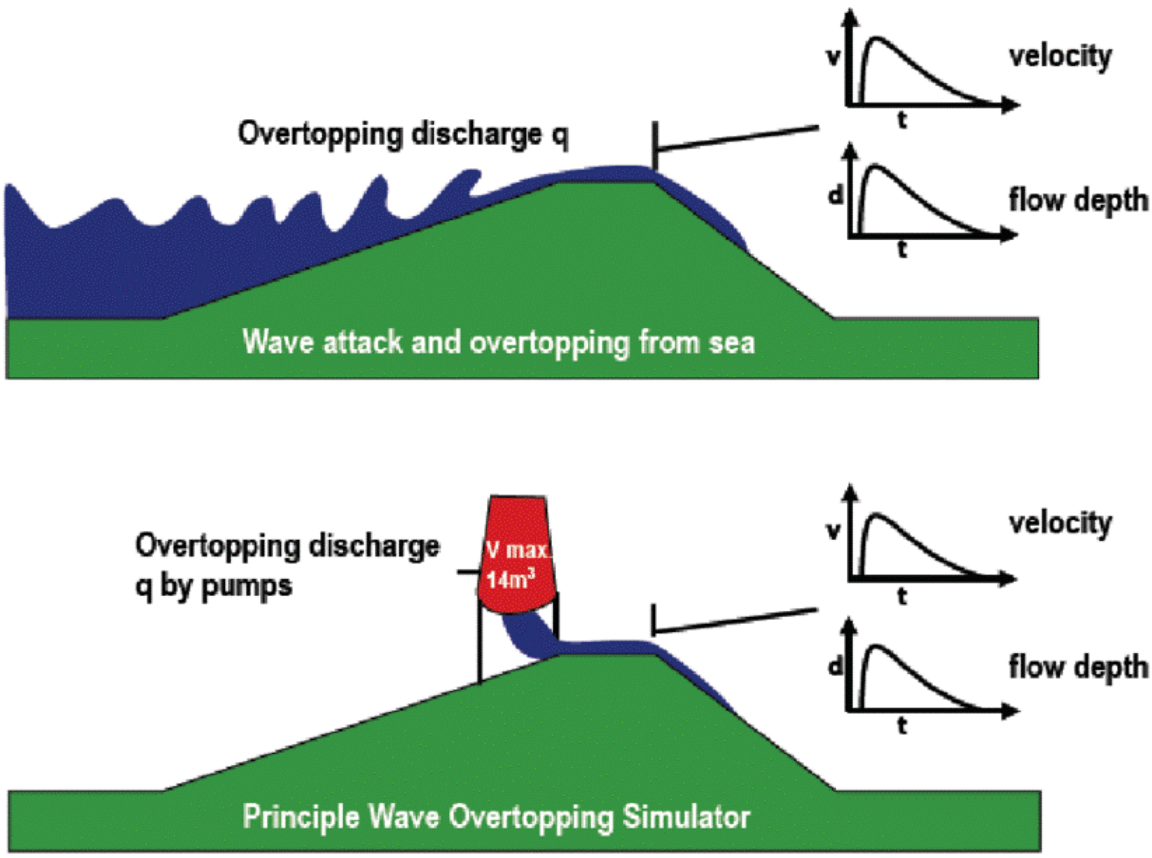


Figure A.2: Golfoverslagschets op dijk

Golfoverslag is een van de mogelijke oorzaken van schade aan grasbekledingen. Een bepaald overslagdebiet met een bepaalde duur veroorzaakt een zekere hoeveelheid schade, uiteraard afhankelijk van de kwaliteit van de belaste grasbekleding. In het verleden zijn meerdere experimenten uitgevoerd om hier meer inzicht in te krijgen. Voor de volgende vier vragen zullen er steeds twee foto's worden gegeven. De eerste foto is de oorspronkelijke toestand van het gras. De tweede foto is de toestand van het gras op een bepaald moment tijdens het experiment. Daarnaast wordt een grafiek gegeven met het overslagdebiet gedurende de proef. De vraag aan u is om aan te geven op welk tijdstip u verwacht dat de bekleding het beeld uit de tweede foto vertoonde, uiteraard inclusief onzekerheid.

Seed question 7

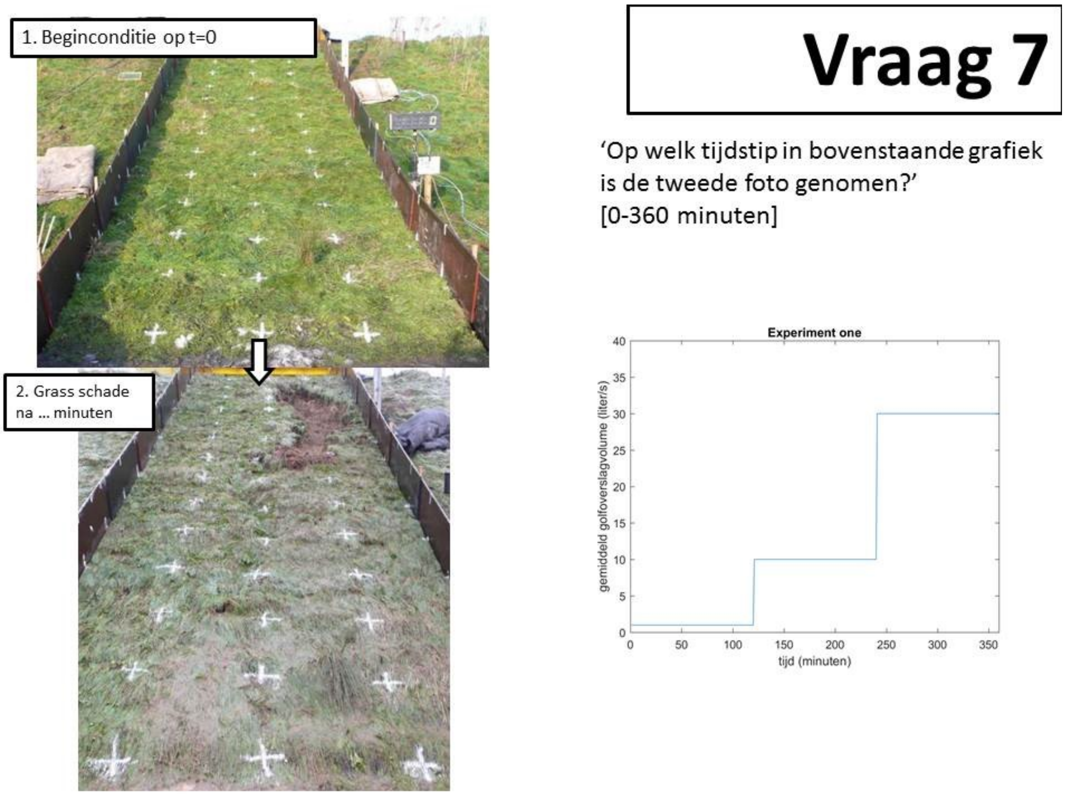


Figure A.3: Target Question 7

Een experiment werd uitgevoerd op een dijkvak van 1:2,5 helling met een grasbekleding als in bovenstaande figuur. De grasmat heeft een ongelijke grasmat, ruige vegetatie en een eerste kale plek. Het verloop van het overslagdebiet in de tijd is in de grafiek weergegeven. Het testprogramma was als volgt:

- 2 uur (120 min) storm met golfoverslagvolume van 1 l / s / m;
- 2 uur (120 min) storm met golfoverslagvolume van 10 l / s / m;
- 2 uur (120 min) storm met golfoverslagvolume van 30 l / s / m.
- Totale experimenttijd: 360 minuten

Schat in op welk tijdstip de tweede foto (met schade) is gemaakt?
Geef uw inschatting op de volgende wijze: "ondergrens/verwacht/bovengrens" in minuten [0-360 min]:

5%.....|50%......|95%......

Answer: 120+120+25=265 minutes (Peeters et al., 2012)

Seed question 8

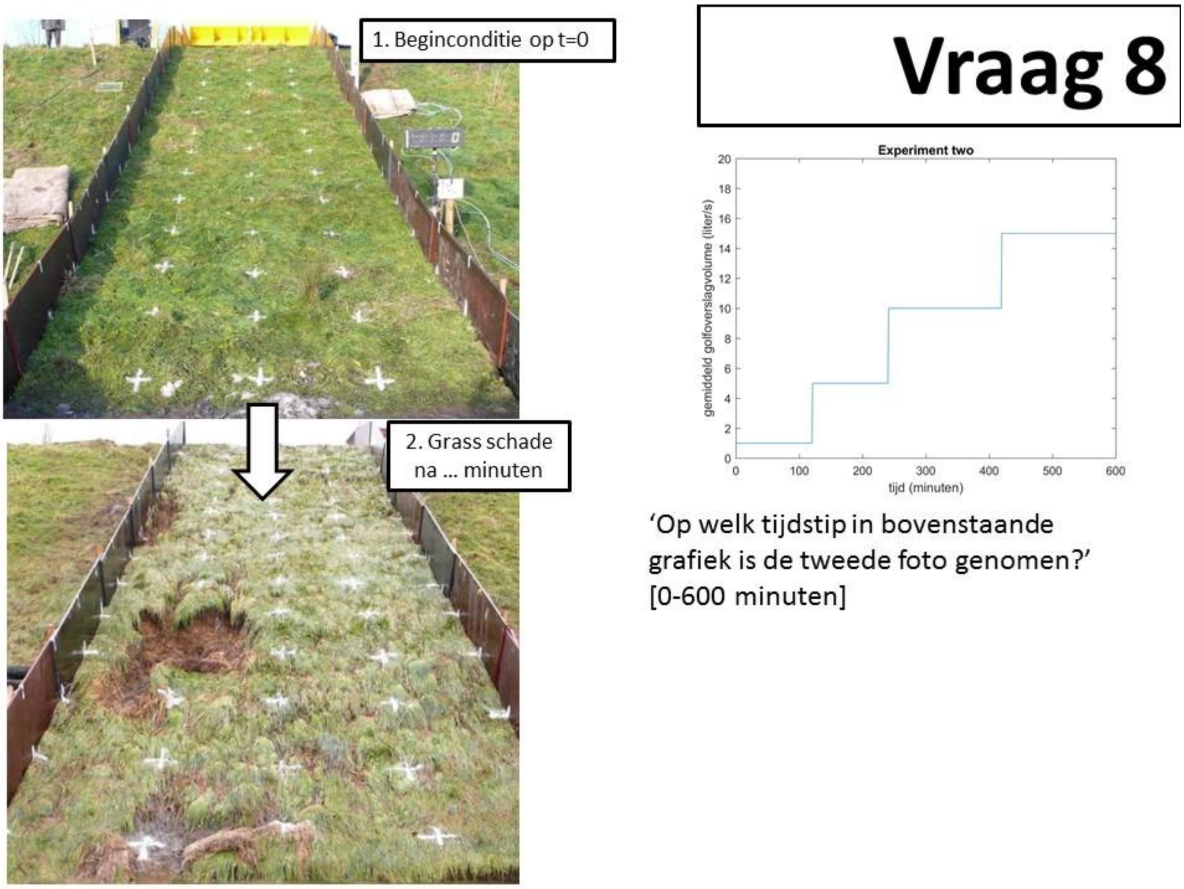


Figure A.4: Target Question 8

Een ander experiment werd uitgevoerd op een dijkvak van 1: 2,5 helling met regelmatige uniforme grasmat met enkele beginnende kale plekken (zie Figure 19-1). Het verloop van het overslagdebiet is weergegeven in de grafiek. Het testprogramma was als volgt:

- 2 uur storm met golfoverslagvolume van 1 l / s / m;
- 2 uur storm met golfoverslagvolume van 5 l / s / m;
- 3 uur storm met golfoverslagvolume van 10 l / s / m;
- 3 uur storm met golfoverslagvolume van 30 l / s / m.

Schat in op welk tijdstip de tweede foto (met schade) is gemaakt?
Geef uw inschatting op de volgende wijze: "ondergrens/verwacht/bovengrens" in minuten [0-600 min]:

5%.....|50%......|95%......

Answer: 420 minutes (Peeters et al., 2012)

Seed question 9

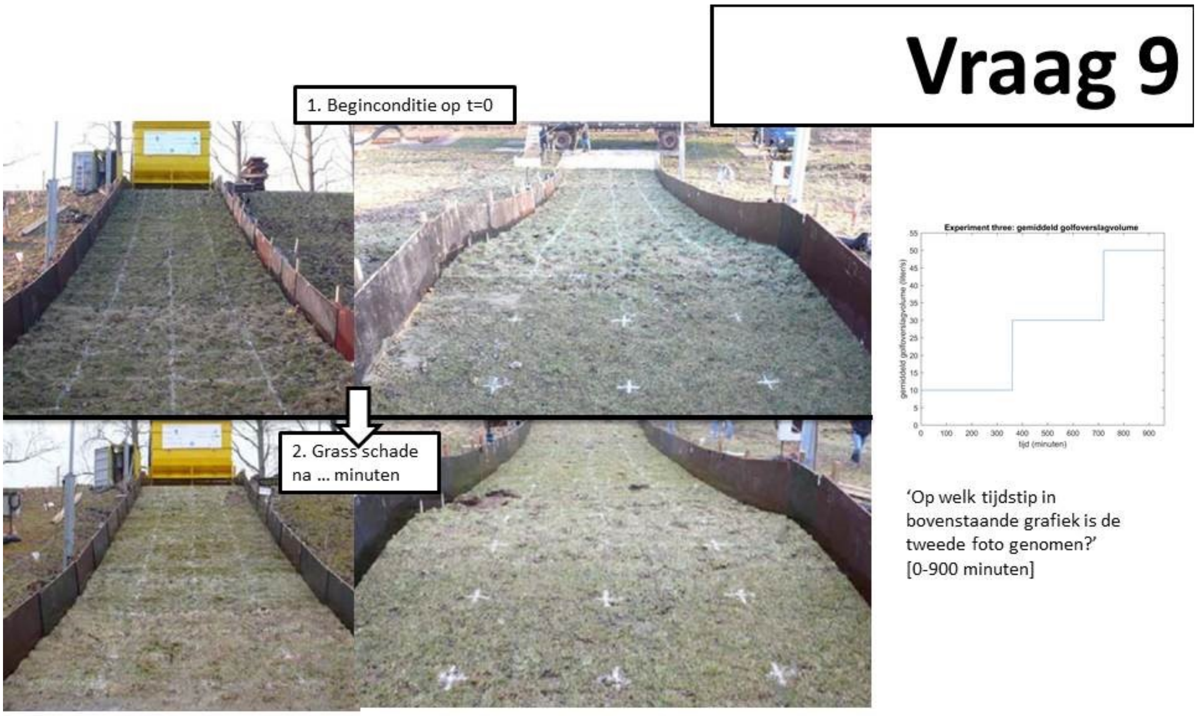


Figure A.5: Target Question 9

Experiment 3 werd uitgevoerd op een helling van 1:3,5. Het is bedekt met homogeen gras en mos. De grasmat was onregelmatig door graverij van mollen. Het testprogramma was als volgt:

- 6 uur storm met golfoverslagvolume van 10 l / s / m;
- 6 uur storm met golfoverslagvolume van 30 l / s / m.
- 2 uur storm met golfoverslagvolume van 50 l / s / m.
- Totale experimenttijd: 960 minuten

Schat in op welk tijdstip de tweede foto (met schade) is gemaakt?
Geef uw inschatting op de volgende wijze: "ondergrens/verwacht/bovengrens" in minuten [0-960 min]:

5%.....|50%......|95%......

Answer: 360+240=600 minutes (Steendam, Van der Meer, et al., 2012)

Seed question 10

1Bij experiment vier, is er een grote boom aanwezig op het talud van de dijk. . De grasmat was onregelmatigheden als gevolg graverij en gedeeltelijk verdwenen. Het testprogramma was als volgt:

- 6 uur (360 min) storm met golfoverslagvolume van 4 l / s / m;

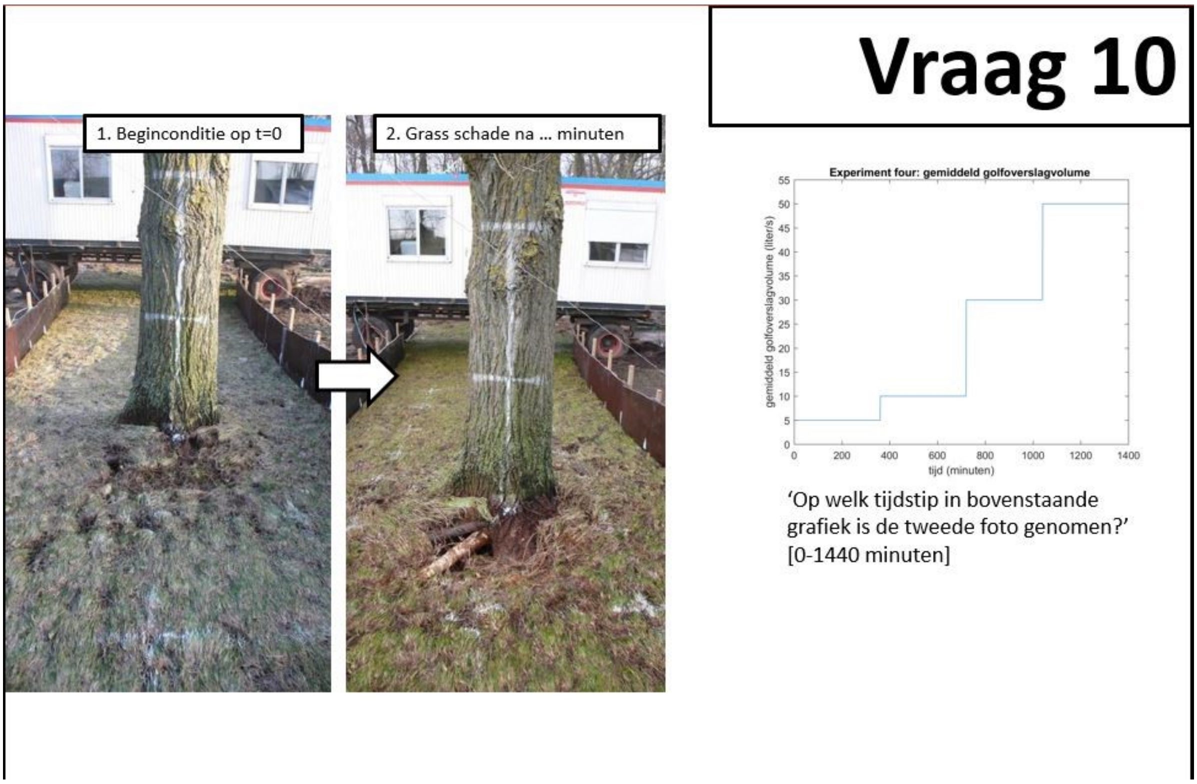


Figure A.6: Target Question 10

- 6 uur (360 min) storm met golfoverslagvolume van 10 l / s / m.
- 6 uur (360 min) storm met golfoverslagvolume van 30 l / s / m.
- 6 uur (360 min) storm met golfoverslagvolume van 50 l / s / m.
- Totale experimenttijd: 24 uur (1440 minuten)

Schat in op welk tijdstip de tweede foto (met schade) is gemaakt?
Geef uw inschatting op de volgende wijze: "ondergrens/verwacht/bovengrens" in minuten [0-1440 min]:

5%.....|50%......|95%......

Answer: 960 minutes (Steendam, Van der Meer, et al., 2012)

A.3. Target Variables: Verandering van kwaliteit van grasbekledingen

Gras vervult een belangrijke functie in het beschermen van waterkeringen tegen erosie.

Na verloop van tijd kan de kwaliteit van het gras achteruitgaan door natuurlijke verschijnselen. Droogte, overbegrazing, graverij, menselijk ingrijpen (denk aan rijsporen), haarden van probleemsoorten en ongezonde bodemgesteldheid (vervuiling) zijn bijvoorbeeld enkele van de oorzaken van achteruitgang. De degradatie van de graskwaliteit beïnvloedt de erosieweerstand van de waterkering en daarmee de veiligheid.

Doel van dit onderzoek is om te komen tot een algemene inschatting van de degradatiesnelheid. We zullen u verschillende vragen stellen die verband houden met de degradatiesnelheid van het gras.We onderscheiden twee soorten degradatie:

- Degradatie door het ontstaan van 1 of meer significante plekken (ca. 2 m2) met een lagere zodekwaliteit, bijvoorbeeld door schades en/of haarden van ongewenste soorten.

- Algehele degradatie van de grasmat op het dijkvak, bijvoorbeeld door verarming van de grond

We kijken ook naar het effect van het wel of niet meenemen van regulier onderhoud. Regulier onderhoud is het routineonderhoud conform uw eigen beheerpraktijk, zonder nood/spoedreparaties.

A.3.1. Tijd tot verslechtering: Target Question 11-17

We beschouwen een dijkvak van 100 meter lang met een grasbekleding op het binnentalud. De dijk bevindt zich in landelijk gebied, beschut (d.w.z. beperkte golfaanval) en met beperkte menselijke activiteit. Het is begin oktober.

We stellen een aantal vragen over de tijd totdat de grasbekleding is verslechterd, volgens de beide vormen van degradatie: algeheel en het ontstaan van probleemplekken. We maken in de vragen onderscheid tussen een dijk met regulier en zonder regulier onderhoud.

1. **Probleemplekken**
   Hoe lang duurt het voor op de grasbekleding met volledig gesloten toestand, 1 of meerdere plekken (ca. 2 m2) ontstaan met een lagere zodekwaliteit ‘open’ of ‘fragmentarisch’? (in maanden)

   (a) Voor een dijk **met regulier onderhoud** & **plekken met open zode:**

   5%.....|50%......|95%......

   (b) Voor een dijk **met regulier onderhoud** & **plekken met gefragmenteerde** zode:

   5%.....|50%......|95%......

   (c) Voor een dijk **zonder regulier onderhoud** & **plekken met open zode:**

   5%.....|50%......|95%......

   (d) Voor een dijk **zonder regulier onderhoud** & **plekken met gefragmenteerde** zode:

   5%.....|50%......|95%......

2. **Algehele degradatie van de grasmat**
   Hoe lang duurt het voor de grasbekleding zonder regulier onderhoud;

   (a) Degradeert van volledig gesloten zode naar een open zode? (in maanden)

   5%.....|50%......|95%......

   (b) Degradeert van volledig open zode naar een gefragmenteerd zode? (in maanden)

   5%.....|50%......|95%......

   (c) Degradeert van volledig gesloten zode naar een gefragmenteerd zode? (in maanden)

   5%.....|50%......|95%......

A.3.2. Kans op verslechteren: Target Questions 8-11

We beschouwen opnieuw een dijkvak van 100 meter lang met een grasbekleding op het binnentalud. De dijk bevindt zich in landelijk gebied, beschut (d.w.z. beperkte golfaanval) en met beperkte menselijke activiteit. Het is begin oktober.
We stellen een aantal vragen over de kans dat de grasbekleding is verslechterd na een bepaalde tijd voor beide soorten degradaties met en zonder onderhoud.

Probleemplekken

1. Wat is de kans dat de grasmat **met regulier onderhoud** na 6 maanden (oktober tot maart)
   (a) is verslechterd van **gesloten zode tot open zode** (1-100

   5%.....|50%......|95%......

   (b) is verslechterd van **open zode tot gefragmenteerde zode** (1-100

   5%.....|50%......|95%......

2. Wat is de kans dat de grasmat **zonder regulier onderhoud** na 6 maanden (oktober tot maart)
   (a) is verslechterd van **gesloten zode tot open zode** (1-100

   5%.....|50%......|95%......

   (b) is verslechterd van **open zode tot gefragmenteerde zode** (1-100

   5%.....|50%......|95%......

A.3.3. Aantal verslechterde dijkvakken: Target Questions 12-13

We beschouwen nu 10 km van dezelfde dijk waarbij geldt dat één dijkvak 100 meter lang is (in totaal zijn er dus 100 dijkvakken).

- De dijk bevindt zich in een landelijk gebied, beschut (d.w.z. beperkte golven) en er is beperkte menselijke activiteit.
- Aan het begin van oktober is de grasmat gesloten
- Verslechtering duidt hier opnieuw op het ontstaan van 1 of meer slechtere plekken van ca. 2 m2.

We stellen een aantal vragen over het aantal dijkvakken waar na het winterseizoen 1 of meer slechtere plekken van ca. 2 m2 zijn ontstaan.

Probleemplekken

1. Hoeveel dijkvakken zijn aan het einde van de winterperiode (maart
   (a) is verslechterd van **gesloten zode tot open zode** (1-100

   5%.....|50%......|95%......

   (b) is verslechterd van **open zode tot gefragmenteerde zode** (1-100

   5%.....|50%......|95%......

A.3.4. Invloed van menselijke activiteit: Target Questions 14-15

We beschouwen dezelfde situation als in de vorige vraag (10 km, dijkvakken van 100 meter dus 100 dijkvakken). Nu is er echter veel menselijke activiteit (bebouwing, verkeer, etc). De vragen zijn hetzelfde als bij het vorige deel.

Probleemplekken

1. Hoeveel dijkvakken zijn aan het einde van de winterperiode (maart
   (a) is verslechterd van **gesloten zode tot open zode** (1-100

   5%.....|50%......|95%......

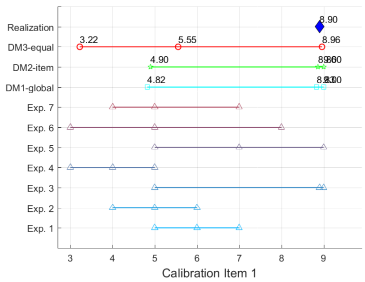
   (b) is verslechterd van **open zode tot gefragmenteerde zode** (1-100

   5%.....|50%......|95%......

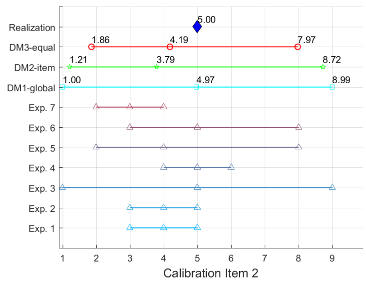
B

Appendix B SEJ Results

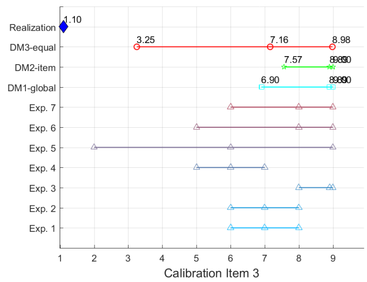
B.1. Seed variables



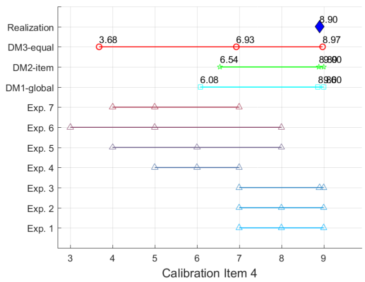
(a) Seed Question 1



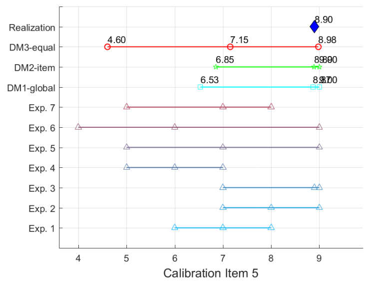
(b) Seed Question 2



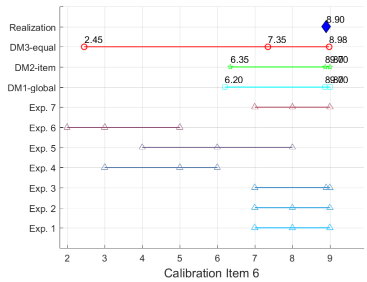
(c) Seed Question 3



(d) Seed Question 4

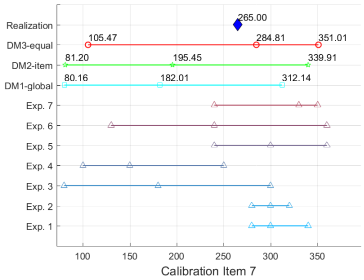


(e) Seed Question 5

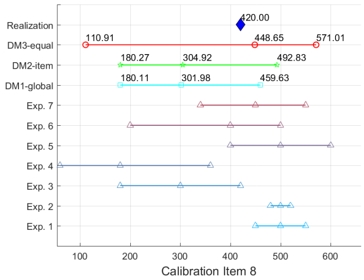


(f) Seed Question 6

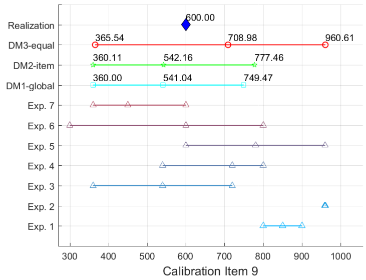
Figure B.1: Distributions for the first group of seed variables in context of the sod cover measurements by their 5th, 50th, and 95th percentiles for 7 experts and combined distributions (DM Global, DM Item and DM Equal)



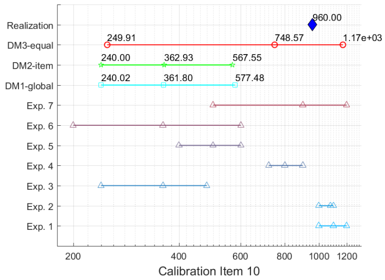
(a) Seed Question 7



(b) Seed Question 8



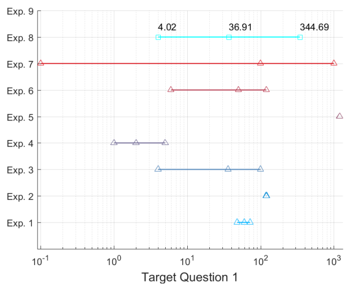
(c) Seed Question 9



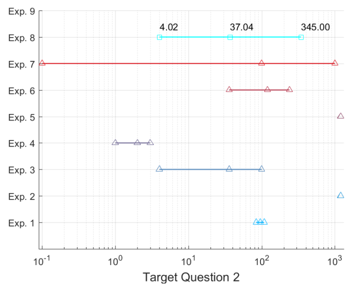
(d) Seed Question 10

Figure B.2: Distributions for the second group of seed variables in context of the wave overtopping experiment by their 5th, 50th, and 95th percentiles for 7 experts and combined distributions (DM Global, DM Item and DM Equal)

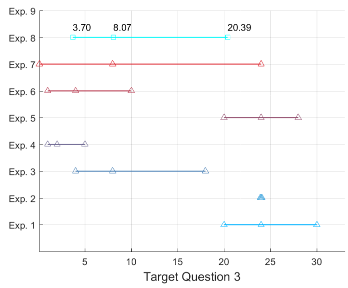
B.2. Target Variables



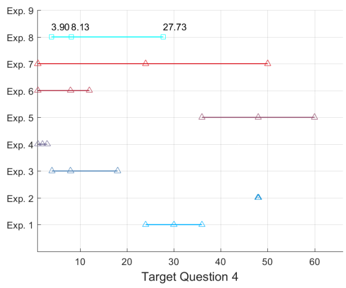
(a) Target question 1



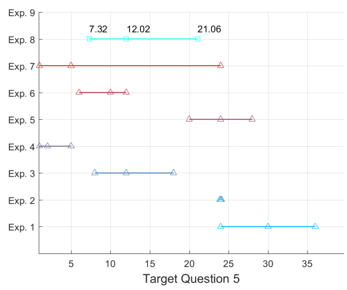
(b) Target question 2



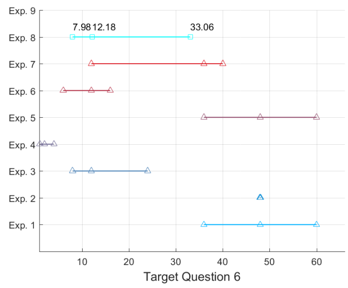
(c) Target question 3



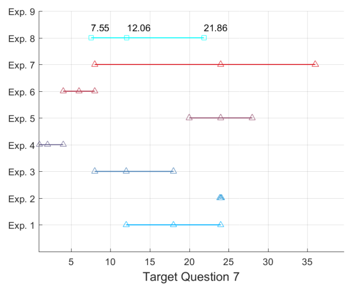
(d) Target question 4



(e) Target question 5

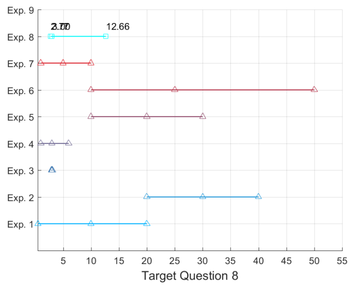


(f) Target question 6

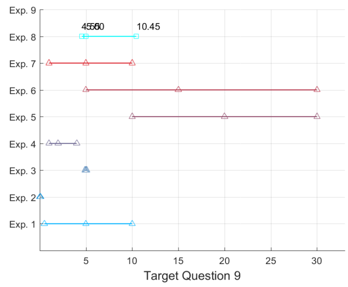


(g) Target question 7

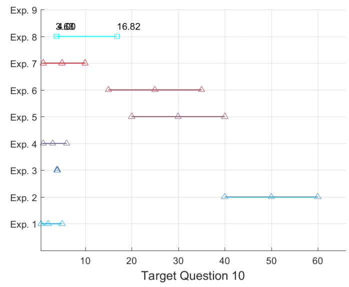
Figure B.3: Distributions for the first group of target variables in context of the deterioration time by their 5th, 50th, and 95th percentiles for 7 experts



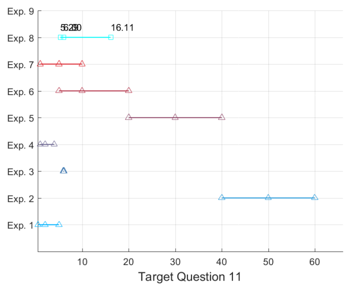
(a) Target question 8



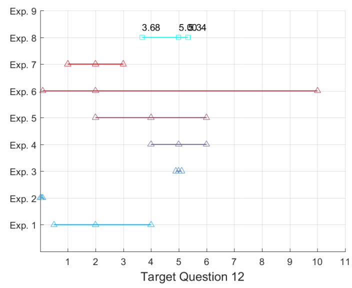
(b) Target question 9



(c) Target question 10

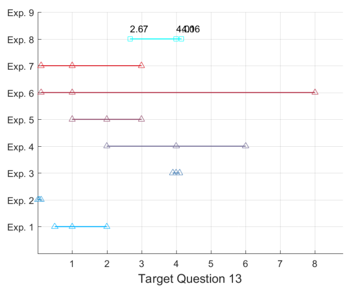


(d) Target question 11

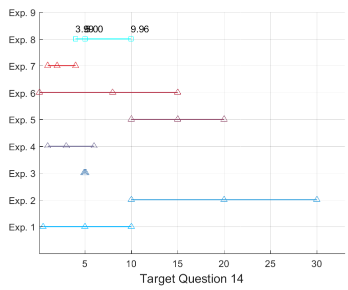


(e) Target question 12

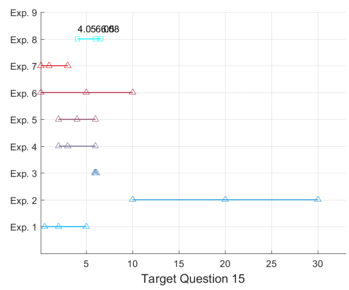
Figure B.4: Distributions for the second group of target variables in context of the deterioration probability by their 5th, 50th, and 95th percentiles for 7 experts



(a) Target question 13



(b) Target question 14



(c) Target question 15

Figure B.5: Distributions for the third group of target variables in context of the spatial degradation by their 5th, 50th, and 95th percentiles for 7 experts

C

Validation of the model

In this research, the model is developed using MATLAB program. The script is developed differently for each scenario. Therefore, the validation shown in this appendix only compares several algorithm that is commonly found in the maintenance network. There are two essential network that is considered in this validation. These network are the grass degradation and the the posterior grass condition conditional to maintenance decision and the prior grass condition. The algorithm will be compared using GeNie Program.

C.1. Grass degradation

The posterior grass condition is conditional to the prior condition as shown in Figure 4.5b. The algorithm shown below follows the equation 4.3. The transition probability of grass revetment is acquired through SEJ in Chapter 3. For this example, a simple transition probability is developed to better understand the results. The grass state has an equivalent result which is shown in Figure C.1, C.2, C.3 and Table C.1.

$$S(1,:) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} Closed & Open & Fragmented \end{bmatrix} \tag{C.1}$$

$$P(S_t|S_{t-1}) = Tr = \begin{bmatrix} 0.9 & 0 & 0 \\ 0.1 & 0.9 & 0 \\ 0.0 & 0.1 & 1 \end{bmatrix} \tag{C.2}$$

Algorithm C.1: GRASS STATE $(S_t|S_{t-1})$

Input: Grass degradation transition probability with an initial condition of closed sod
Output: Grass state over the time horizon

```
for t ← 1 to 10 do
    S(t,1)=S(t-1,1)*Tr(1,1)+S(t-1,2)*Tr(1,2)+S(t-1,3)*Tr(1,3)
    S(t,2)=S(t-1,1)*Tr(2,1)+S(t-1,2)*Tr(2,2)+S(t-1,3)*Tr(2,3)
    S(t,3)=S(t-1,1)*Tr(3,1)+S(t-1,2)*Tr(3,2)+S(t-1,3)*Tr(3,3)
```

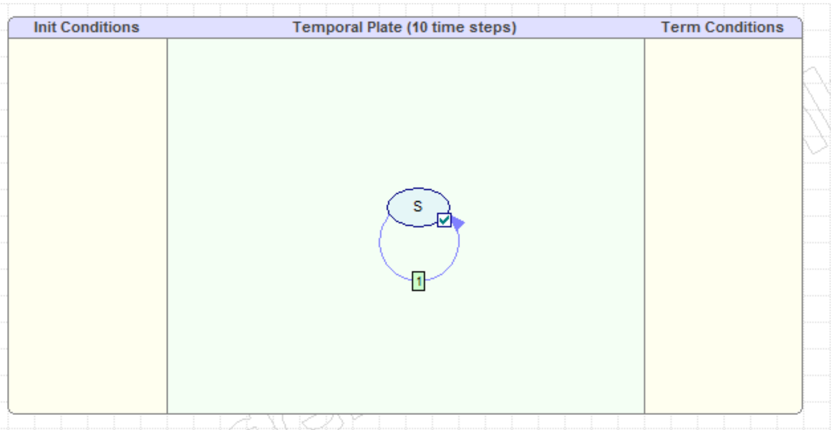


Figure C.1: Grass state probability over the time horizon through a simulation on grass degradation scenario by using GeNie program

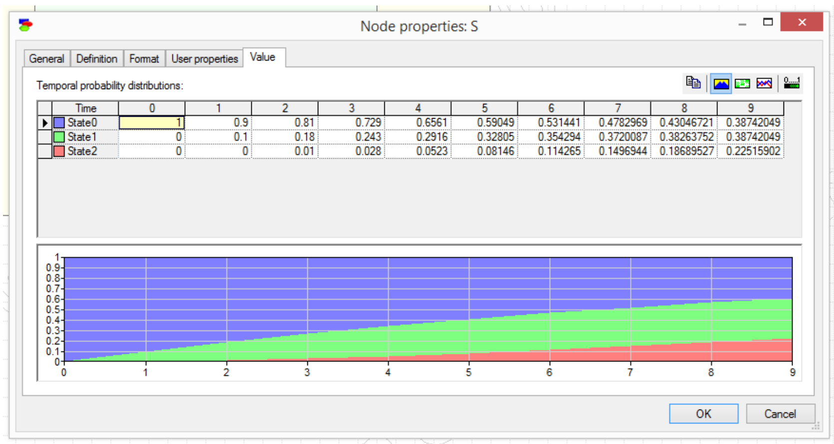


Figure C.2: Chart of grass state over the time horizon by simulating the grass degradation scenario using the GeNie program

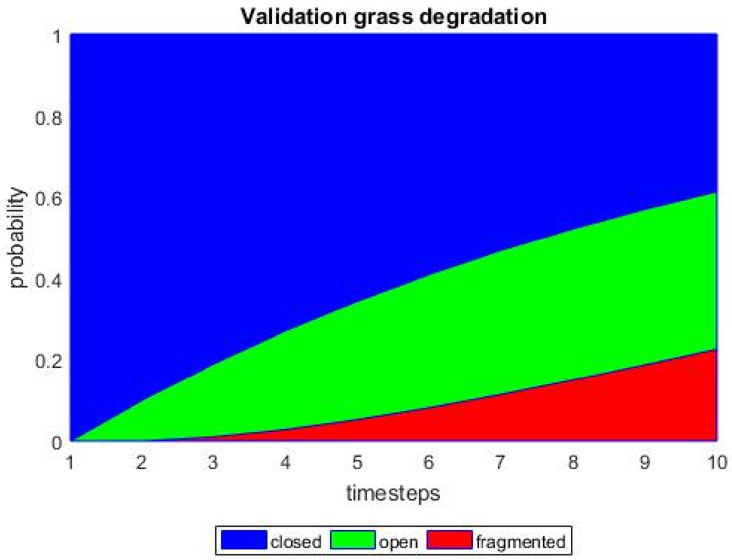


Figure C.3: Chart of grass state over the time horizon by simulating the grass degradation scenario using the MATLAB program

Table C.1: Validation 1: Grass state at every time-steps using MATLAB

Closed	Open	Fragmented
1,000	0,000	0,000
0,900	0,100	0,000
0,810	0,180	0,010
0,729	0,243	0,028
0,656	0,292	0,052
0,590	0,328	0,081
0,531	0,354	0,114
0,478	0,372	0,150
0,430	0,383	0,187
0,387	0,387	0,225

C.2. Grass condition conditional to maintenance and prior condition

The second validation investigates the posterior grass state conditional to the maintenance decision (MD), acquired information GI, and prior condition. This network is applied for every maintenance that required prior decision (see Chapter4). The grass degradation is conditional to the maintenance decision node *MD* and prior grass state *S(t-1)*. Meanwhile, the maintenance decision is conditional to the grass information GI. By assuming a rule of maintenance without preventive maintenance, and has the same degradation probability as the previous example. Therefore, we obtain Algorithm C.2 where S is the grass state, Tr is the transition probability, MD is the maintenance decision node, and MW is the CPT of posterior grass condition.

Table C.2: CPT Maintenance Decision (MD) as a validation input

Acquired Information GI		Closed	Open	Fragmented
Maintenance Decsion MD	Corrective	0.8	0.1	0.1
	Preventive	0.1	0.8	0.1
	Do Nothing	0.1	0.1	0.8

Table C.3: CPT Acquired Information GI as a validation input

Grass Condition St		Closed	Open	Fragmented
Acquired Information GI (t)	Closed	0.8	0.1	0.1
	Open	0.1	0.8	0.1
	Fragmented	0.1	0.1	0.8

Table C.4: CPT for posterior grass state conditional to the maintenance decision and prior grass condition

Maintenance Decision MD		Corrective			Preventive			Do Nothing		
Prior Grass State S(t-1)		C	O	F	C	O	F	C	O	F
Posterior Grass State S(t)	C	1	1	1	1	1	1	0.9	0	0
	O	0	0	0	0	0	0	0.1	0.9	0
	F	0	0	0	0	0	0	0	0.1	1

Algorithm C.2: GRASS STATE $(S_t|S_{t-1})$

Input: CPT of $P(S_t|S_{t-1}, MD_t$ (see Table C.4), CPT of $P(MD_t GIt)$ (see Table C.2) and CPT of $P(GI_t|S_{t-1})$ (see Table C.3)

Output: Grass state over the time horizon

```
for s ← 1 to 3 do
    MC(1,s)=(MW(s,1,1)*MD(1,1)+MW(s,1,2)*MD(2,1)+MW(s,1,3)*MD(3,1))
    MC(2,s)=(MW(s,1,1)*MD(1,2)+MW(s,1,2)*MD(2,2)+MW(s,1,3)*MD(3,2))
    MC(3,s)=(MW(s,1,1)*MD(1,3)+MW(s,1,2)*MD(2,3)+MW(s,1,3)*MD(3,3))
    MC(4,s)=(MW(s,2,1)*MD(1,1)+MW(s,2,2)*MD(2,1)+MW(s,2,3)*MD(3,1))
    MC(5,s)=(MW(s,2,1)*MD(1,2)+MW(s,2,2)*MD(2,2)+MW(s,2,3)*MD(3,2))
    MC(6,s)=(MW(s,2,1)*MD(1,3)+MW(s,2,2)*MD(2,3)+MW(s,2,3)*MD(3,3))
    MC(7,s)=(MW(s,3,1)*MD(1,1)+MW(s,3,2)*MD(2,1)+MW(s,3,3)*MD(3,1))
    MC(8,s)=(MW(s,3,1)*MD(1,2)+MW(s,3,2)*MD(2,2)+MW(s,3,3)*MD(3,2))
    MC(9,s)=(MW(s,3,1)*MD(1,3)+MW(s,3,2)*MD(2,3)+MW(s,3,3)*MD(3,3))
    end
for t ← 1 to 10 do
    G(t,1)=S(t-1,1)*GI(1,1)+S(t-1,2)*GI(1,2)+S(t-1,3)*GI(1,3)
    G(t,2)=S(t-1,1)*GI(2,1)+S(t-1,2)*GI(2,2)+S(t-1,3)*GI(2,3)
    G(t,3)=S(t-1,1)*GI(3,1)+S(t-1,2)*GI(3,2)+S(t-1,3)*GI(3,3)
    M(t,1)=G(t,1)*MD(1,1)+G(t,2)*MD(1,2)+G(t,3)*MD(1,3)
    M(t,2)=G(t,1)*MD(2,1)+G(t,2)*MD(2,2)+G(t,3)*MD(2,3)
    M(t,3)=G(t,1)*MD(3,1)+G(t,2)*MD(3,2)+G(t,3)*MD(3,3)
    S(t,1)=(S(t-1,1)*(GI(1,1)*MC(1,1)+GI(2,1)*MC(2,1)+GI(3,1)*MC(3,1)))+(S(t-
      1,2)*(GI(1,2)*MC(4,1)+GI(2,2)*MC(5,1)+GI(3,2)*MC(6,1)))+(S(t-
      1,3)*(GI(1,3)*MC(7,1)+GI(2,3)*MC(8,1)+GI(3,3)*MC(9,1)))
    S(t,2)=(S(t-1,1)*(GI(1,1)*MC(1,2)+GI(2,1)*MC(2,2)+GI(3,1)*MC(3,2)))+(S(t-
      1,2)*(GI(1,2)*MC(4,2)+GI(2,2)*MC(5,2)+GI(3,2)*MC(6,2)))+(S(t-
      1,3)*(GI(1,3)*MC(7,2)+GI(2,3)*MC(8,2)+GI(3,3)*MC(9,2)))
    S(t,3)=(S(t-1,1)*(GI(1,1)*MC(1,3)+GI(2,1)*MC(2,3)+GI(3,1)*MC(3,3)))+(S(t-
      1,2)*(GI(1,2)*MC(4,3)+GI(2,2)*MC(5,3)+GI(3,2)*MC(6,3)))+(S(t-
      1,3)*(GI(1,3)*MC(7,3)+GI(2,3)*MC(8,3)+GI(3,3)*MC(9,3)))
```

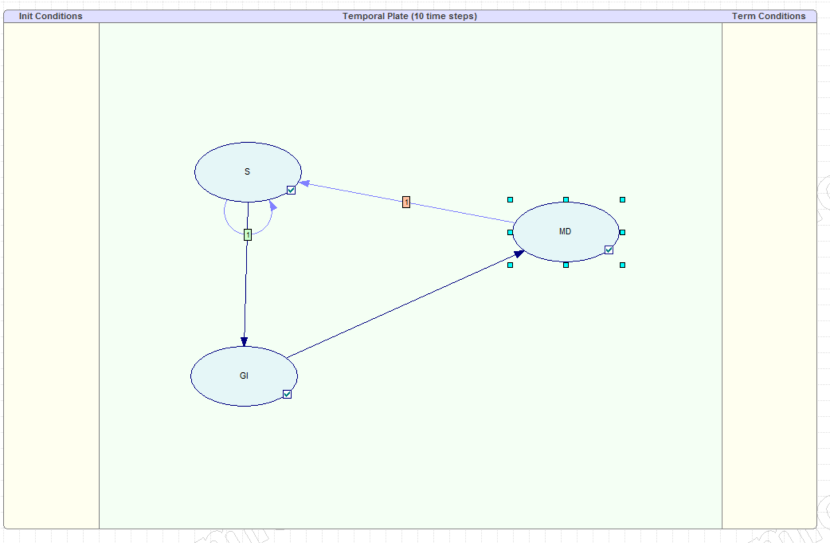


Figure C.4: Schematic network of the second validation scenario on grass maintenance

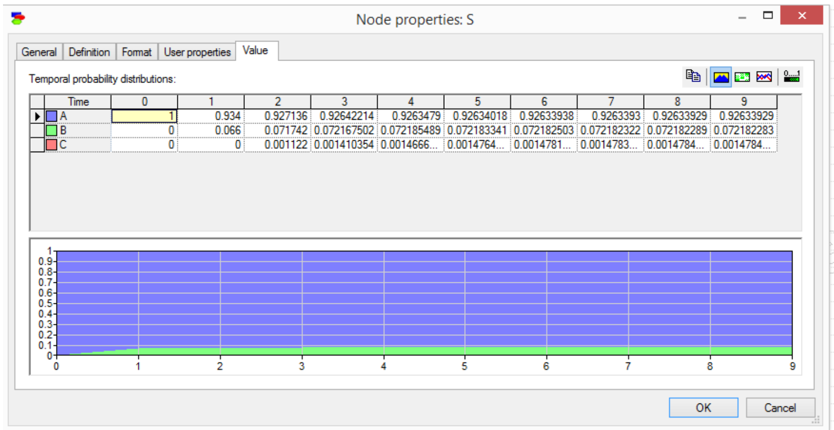


Figure C.5: Validation 2: Grass state at every time-steps using Genie

Table C.5: Validation 2: Grass state at every time-steps using MATLAB

Closed	Open	Fragmented
1,000	0,000	0,000
0,934	0,066	0,000
0,927	0,072	0,001
0,926	0,072	0,001
0,926	0,072	0,001
0,926	0,072	0,001
0,926	0,072	0,001
0,926	0,072	0,001
0,926	0,072	0,001
0,926	0,072	0,001

D
Model Results

This appendix is an additional information of each scenario results which is shown as figures and graph

1. Scenario 1: Asset Management Decision

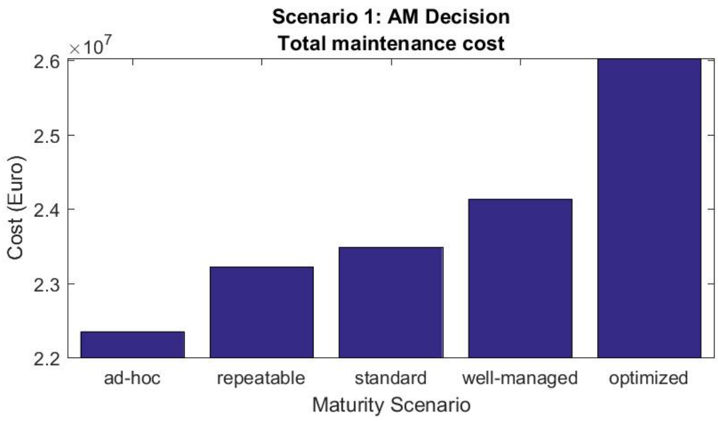


Figure D.1: Total expected maintenance cost over the time horizon for scenario 1

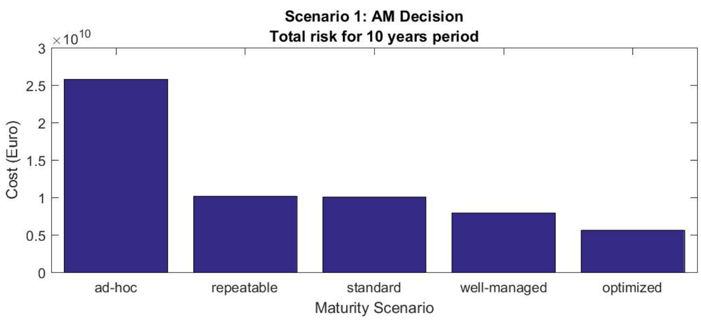


Figure D.2: Total expected risk over the time horizon for scenario 1

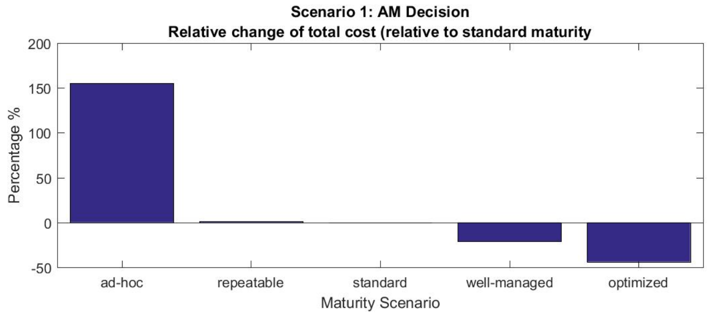


Figure D.3: Relative change of total cost (relative to total cost of standard maturity) over the time horizon for scenario 1

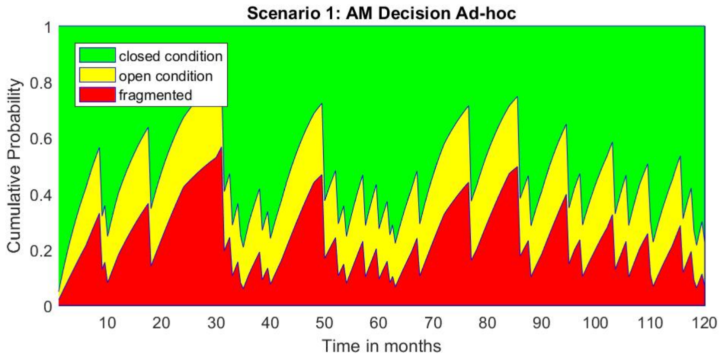


Figure D.4: Grass condition over the time horizon for scenario 1 ad-hoc maturity

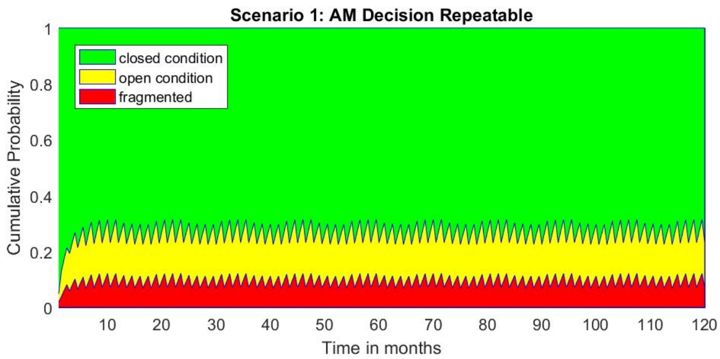


Figure D.5: Grass condition over the time horizon for scenario 1 repeatable maturity

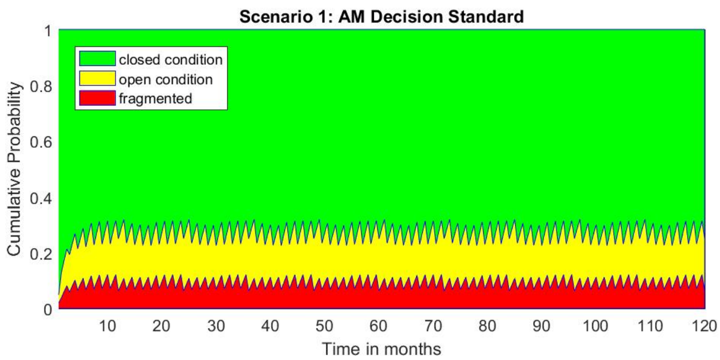


Figure D.6: Grass condition over the time horizon for scenario 1 standard maturity

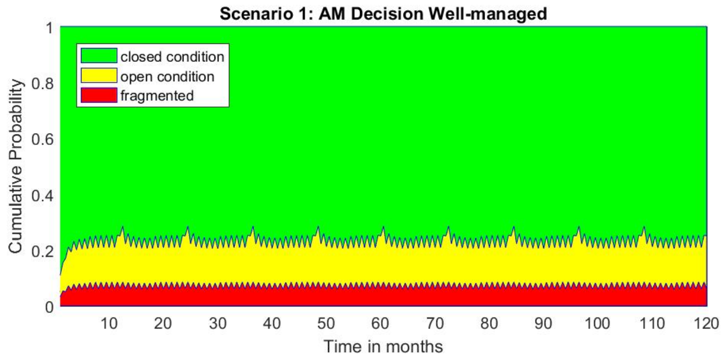


Figure D.7: Grass condition over the time horizon for scenario 1 well-managed maturity

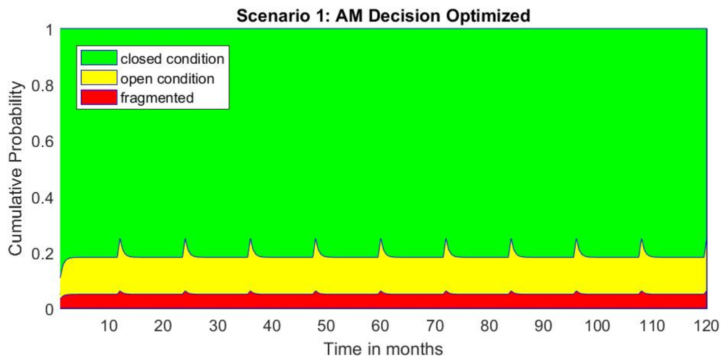


Figure D.8: Grass condition over the time horizon for scenario 1 optimized maturity

2. Scenario 2: Asset Information

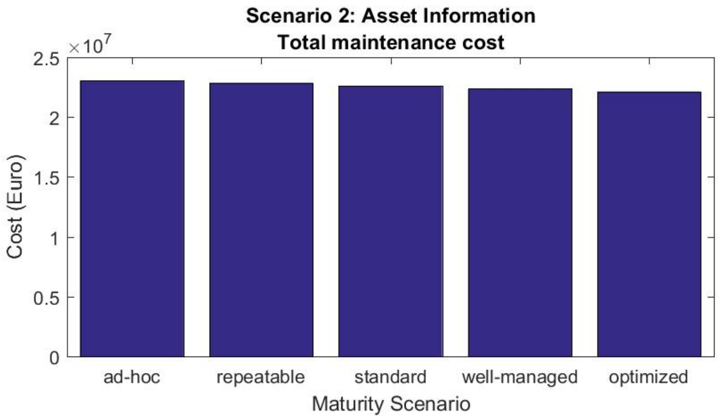


Figure D.9: Total expected maintenance cost over the time horizon for scenario 2

[h!]

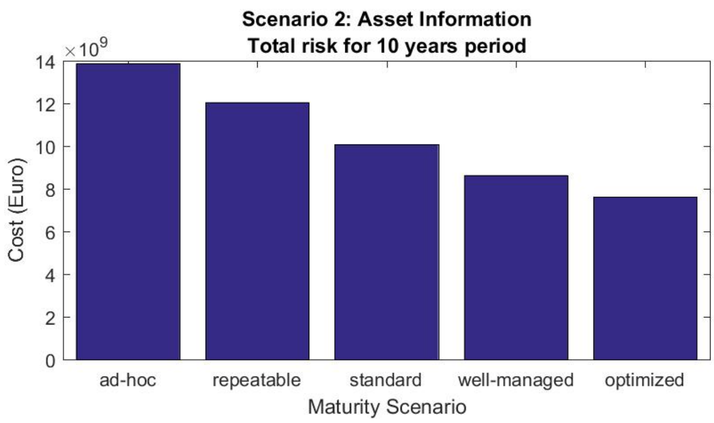


Figure D.10: Total expected risk over the time horizon for scenario 2

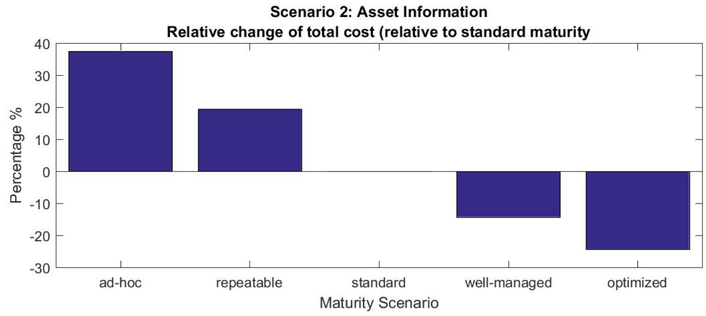


Figure D.11: Relative change of expected total cost (relative to total cost of standard maturity) over the time horizon for scenario 2

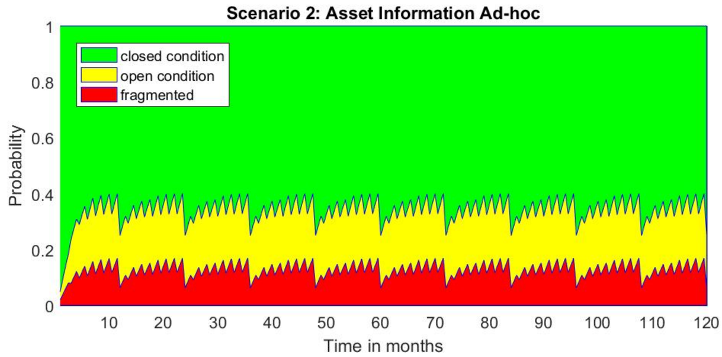


Figure D.12: Grass condition over the time horizon for scenario 2 ad-hoc maturity

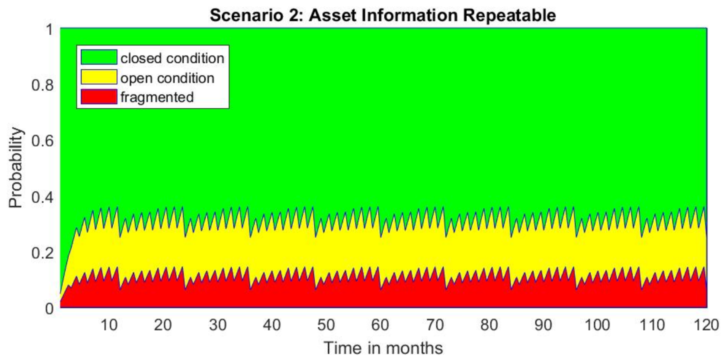


Figure D.13: Grass condition over the time horizon for scenario 2 repeatable maturity

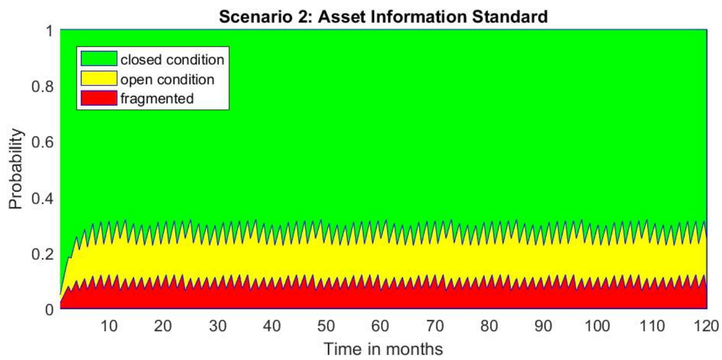


Figure D.14: Grass condition over the time horizon for scenario 2 standard maturity

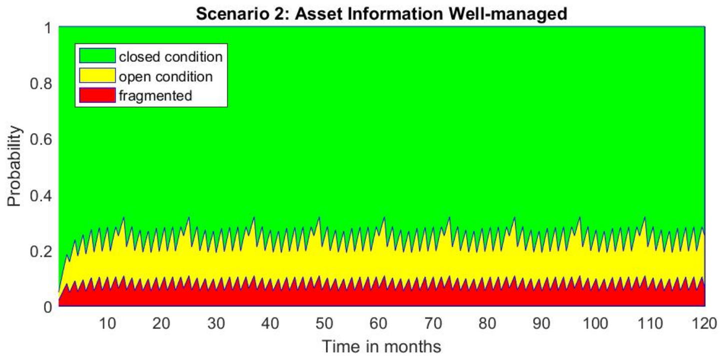


Figure D.15: Grass condition over the time horizon for scenario 2 well-managed maturity

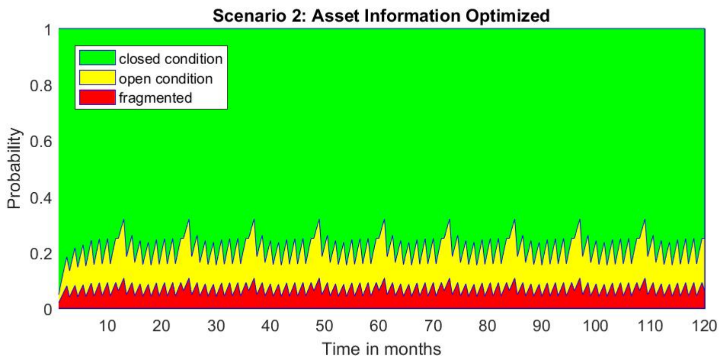


Figure D.16: Grass condition over the time horizon for scenario 2 optimized maturity

3. Scenario 3: Culture and Leadership

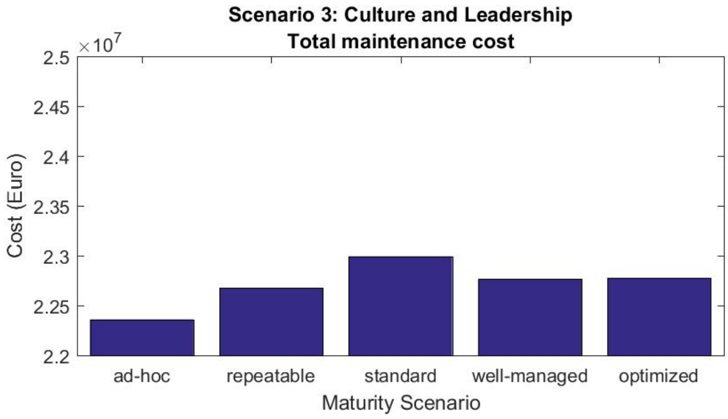


Figure D.17: Total expected maintenance cost over the time horizon for scenario 3

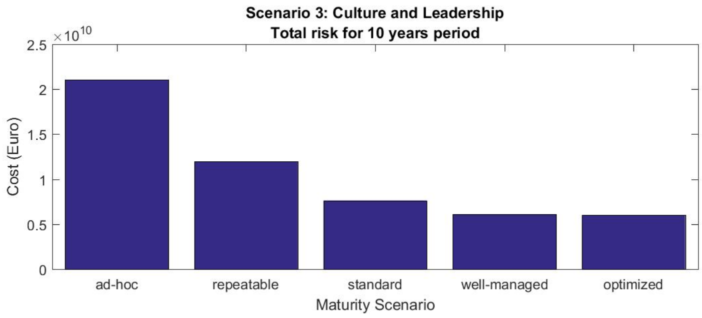


Figure D.18: Total expected risk over the time horizon for scenario 3

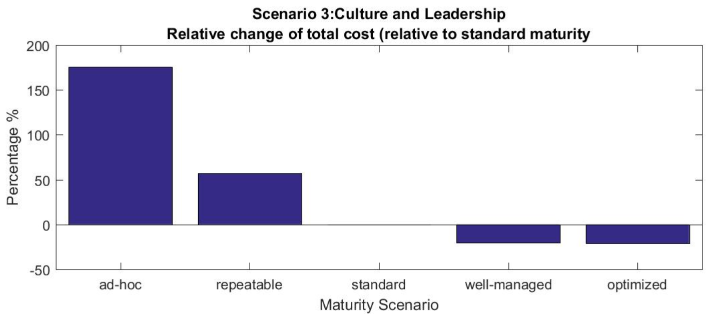


Figure D.19: Relative change of expected total cost (relative to total cost of standard maturity) over the time horizon for scenario 3

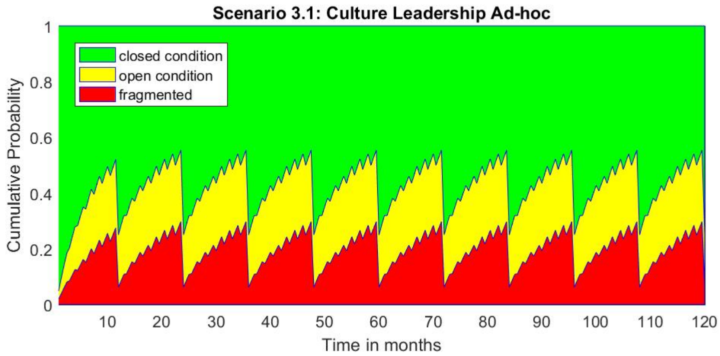


Figure D.20: Grass condition over the time horizon for scenario 3 ad-hoc maturity

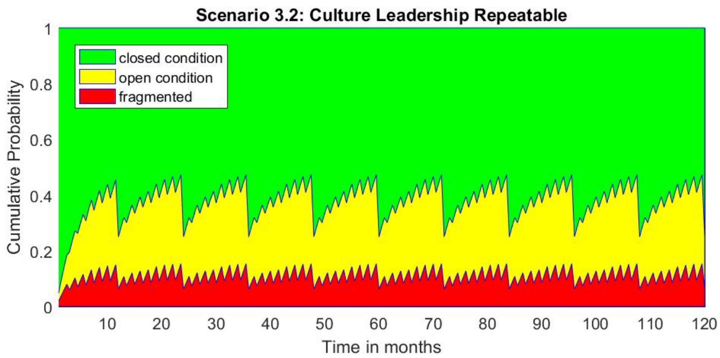


Figure D.21: Grass condition over the time horizon for scenario 3 repeatable maturity

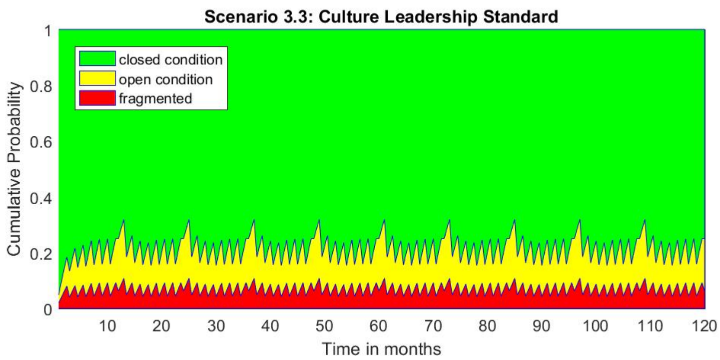


Figure D.22: Grass condition over the time horizon for scenario 3 standard maturity

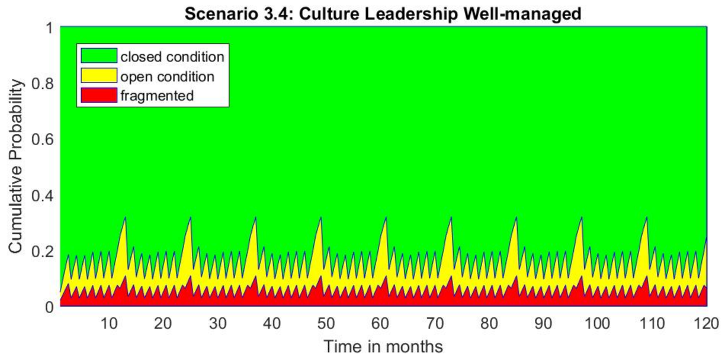


Figure D.23: Grass condition over the time horizon for scenario 3 well-managed maturity

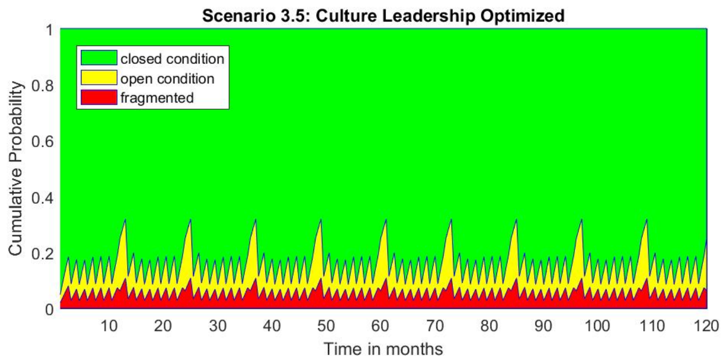


Figure D.24: Grass condition over the time horizon for scenario 3 optmized maturity

4. Scenario 4: Internal Cooordination

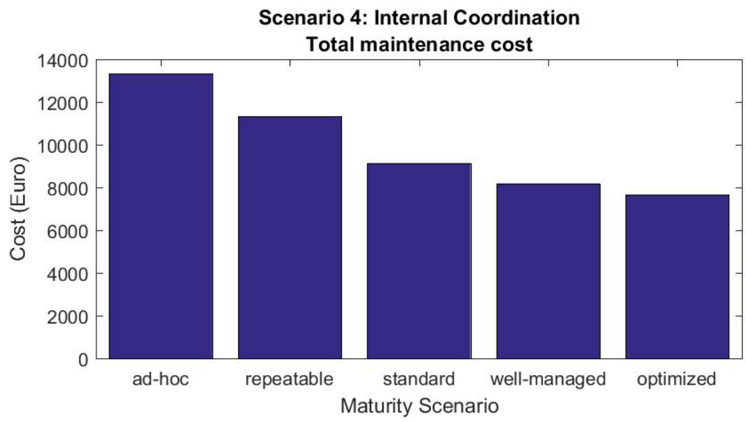


Figure D.25: Total expected maintenance cost over the time horizon for scenario 4

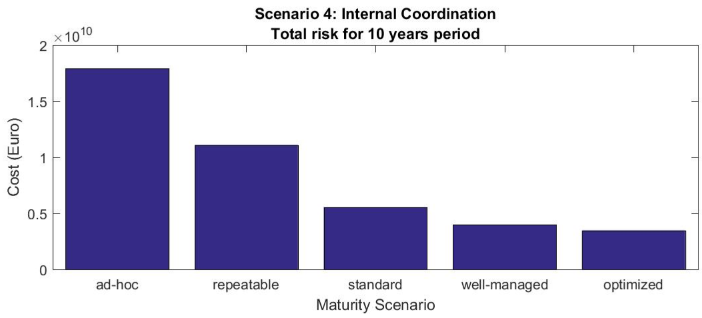


Figure D.26: Total expected risk over the time horizon for scenario 4

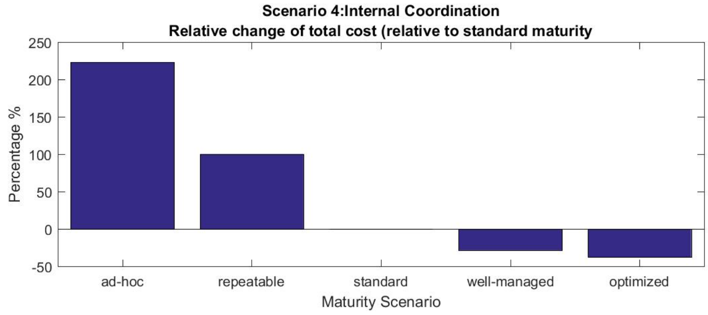


Figure D.27: Relative change of expected total cost (relative to total cost of standard maturity) over the time horizon for scenario 4

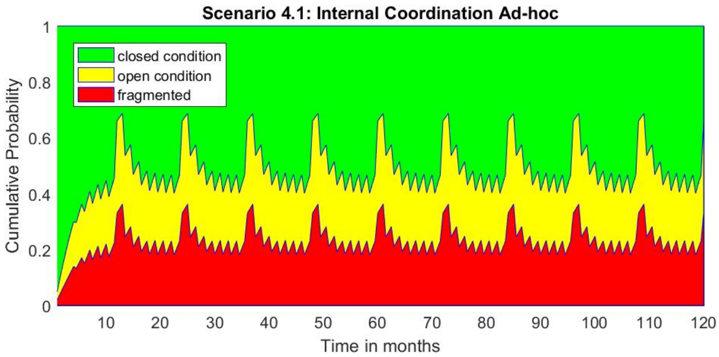


Figure D.28: Grass condition over the time horizon for scenario 4 ad-hoc maturity

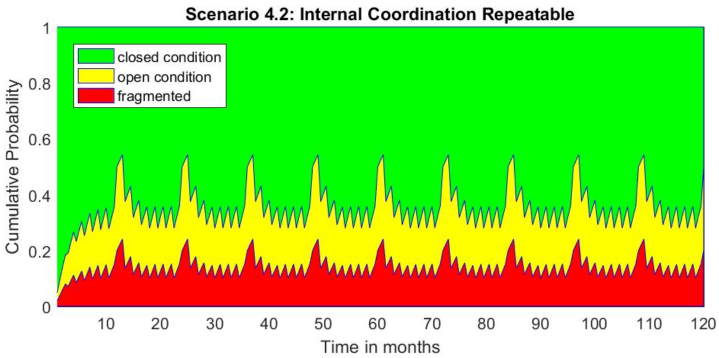


Figure D.29: Grass condition over the time horizon for scenario 4 repeatable maturity

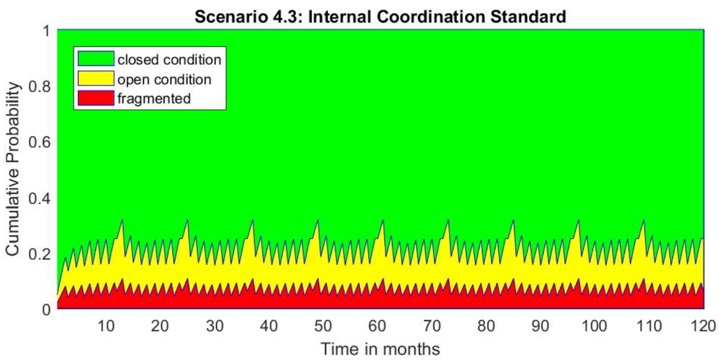


Figure D.30: Grass condition over the time horizon for scenario 4 standard maturity

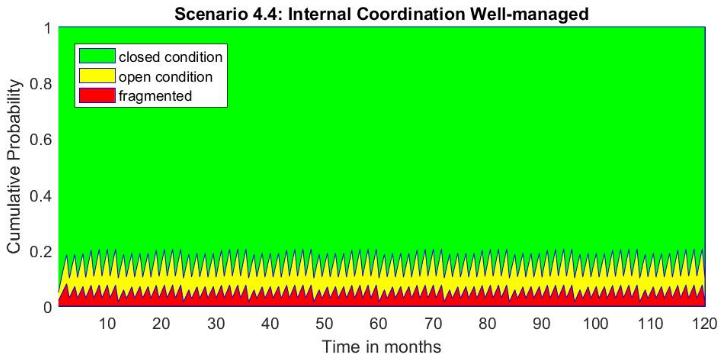


Figure D.31: Grass condition over the time horizon for scenario 4 well-managed maturity

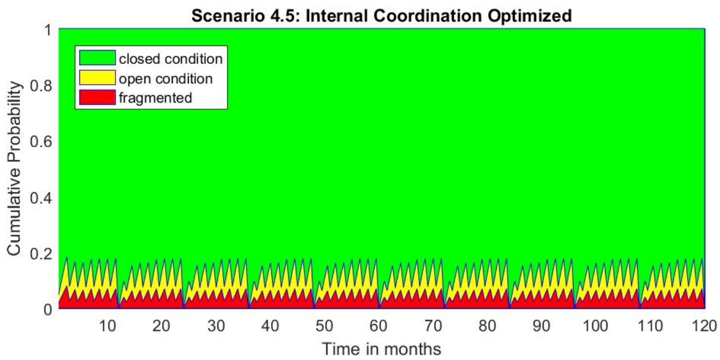


Figure D.32: Grass condition over the time horizon for scenario 4 optimized maturity

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